GEY203

INTRODUCTION TO PETROLOGY

Course Code: GEY 203

Course title: Introduction to Petrology

Units: 2 Units

List of Series

Series 1: Foundations of Igneous Petrology

Series 2: Systematic Study of Metamorphic Rocks

Series 3: Textures and Minerals in Metamorphism

Series 4: Introduction to Sedimentary Petrology

Series 5: Classification of Igneous, Metamorphic, and Sedimentary Rocks

1.1 Origin and Formation of Igneous Rocks

- 1.1.1 Magma generation and sources

- 1.1.2 Processes of crystallisation and solidification

- 1.1.3 Geological settings of igneous activity

1.2 Occurrence and Geologic Setting of Igneous Rocks

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- 1.4.2 Major categories: felsic, intermediate, mafic, ultramafic

- 1.4.3 Common classification schemes (e.g., TAS diagram, modal classification)

Introduction

Igneous rocks form the very foundation of the Earth's crust, shaping landscapes and providing vital clues about the planet's internal processes. From the fiery eruptions of volcanoes to the slow cooling of magma deep underground, these rocks record the dynamic history of Earth's geological activity. As learners of petrology, gaining a clear understanding of how igneous rocks originate, occur, and are classified will prepare you to explore the broader study of rocks and their role in Earth systems.

The aim of this Series is to equip you with the knowledge and skills to explain the origin and formation of igneous rocks, describe their occurrence and geologic settings, and apply systematic methods for their description and classification.

We shall commence this Series by examining the origin and formation of igneous rocks, focusing on magma generation, crystallization, and geological settings. Next, we will explore their occurrence and distribution within extrusive and intrusive environments, considering the role of plate tectonics. Following that, we will move on to the systematic description of igneous rocks, paying attention to their textures, mineral composition, and identification methods. Finally, we will wrap up by studying the classification of igneous rocks, highlighting the basis of classification and the major categories used in petrology.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- SLO 1.1 define the processes involved in the origin and formation of igneous rocks,

- SLO 1.2 explain the occurrence and geologic settings of igneous rocks in both extrusive and intrusive environments,

- SLO 1.3 describe the textural features and mineral composition of igneous rocks using systematic methods, and

- SLO 1.4 classify igneous rocks accurately based on texture, mineralogy, and established classification schemes.

1.1 Origin and Formation of Igneous Rocks

1.1.1 Magma generation and sources

The study of igneous rocks begins with magma, which is molten rock material found beneath the Earth's surface. Magma is generated when parts of the mantle or crust melt due to changes in temperature, pressure, or the addition of volatiles such as water. The mantle is the thick layer of solid rock beneath the crust, and it is the primary source of most magmas.

Magma generation occurs in specific tectonic settings, including mid-ocean ridges, subduction zones, and hotspots.

Fill in the blank: Magma is produced when parts of the _____ or crust melt due to changes in physical conditions.

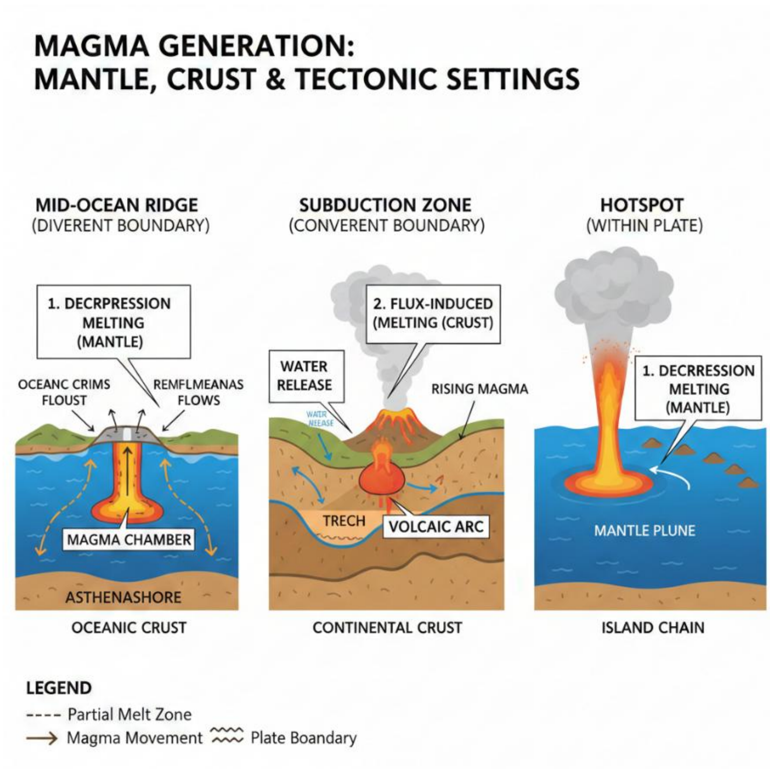

Figure 1.1: Magma generation zones in the Earth's interior

1.1.2 Processes of crystallization and solidification

Once magma is generated, it begins to cool and undergoes crystallization, which is the process by which minerals form from the cooling melt. The rate of cooling determines the texture of the igneous rock. Slow cooling deep underground produces coarse-grained rocks such as granite, while rapid cooling at the surface produces fine-grained rocks such as basalt. Solidification refers to the complete transformation of magma into solid rock.

Fill in the blank: Slow cooling of magma produces -grained igneous rocks, while rapid cooling produces fine-grained rocks.

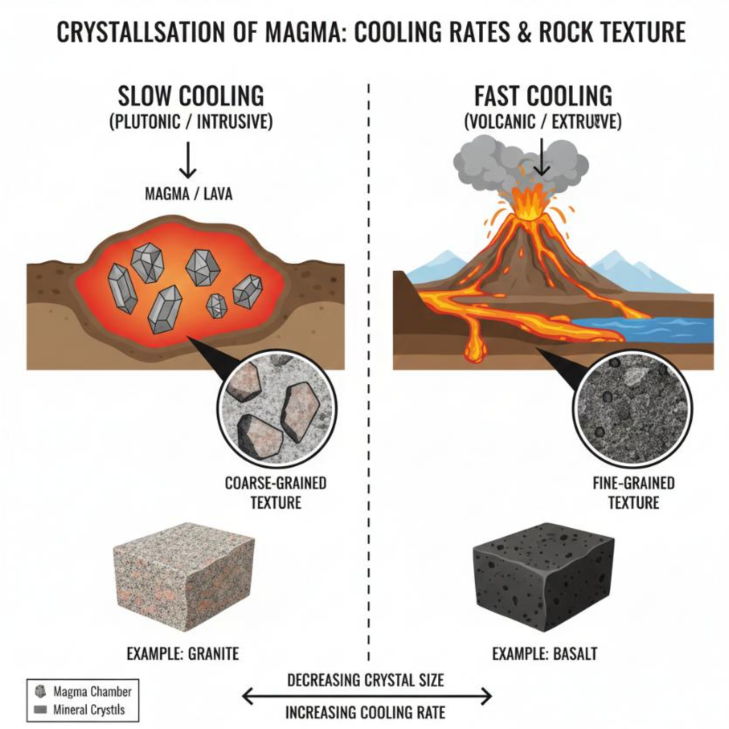

Figure 1.2: Crystallization and cooling of magma

1.1.3 Geological settings of igneous activity

Igneous activity occurs in diverse geological settings. At mid-ocean ridges, magma rises to form new oceanic crust. In subduction zones, melting occurs as oceanic plates descend into the mantle, producing volcanic arcs. At hotspots, plumes of hot mantle material rise to the surface, creating isolated volcanic centers such as Hawaii. These settings explain the distribution and diversity of igneous rocks across the Earth.

Fill in the blank: Volcanic arcs are typically formed in ______ zones where oceanic plates descend into the mantle.

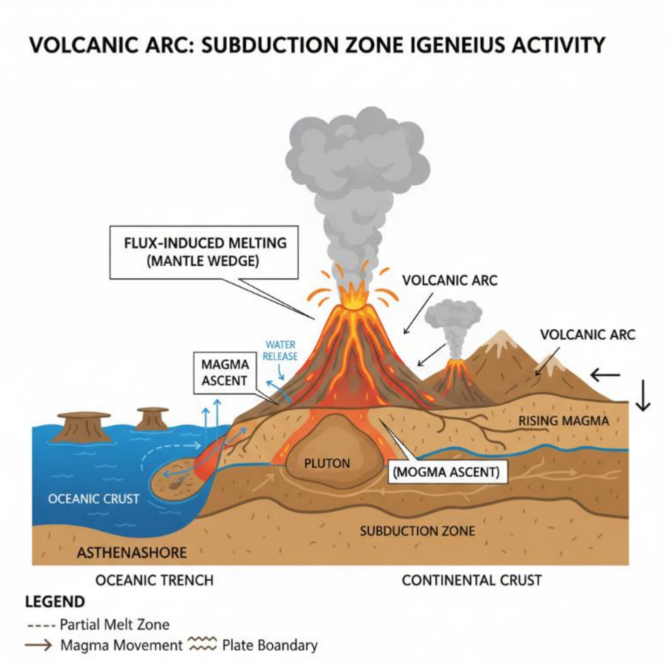

Plate 1.1: Volcanic arc formed at a subduction zone

Pilot questions 1.1

1. Which part of the Earth is the primary source of most magmas?
2. What is crystallization in the context of igneous rocks?
3. How does cooling rate affect the texture of igneous rocks?
4. Name two geological settings where magma generation occurs.
5. What type of volcanic feature is associated with hotspots?

1.2 Occurrence and Geologic Setting of Igneous Rocks

1.2.1 Extrusive and intrusive environments

Igneous rocks occur in two main environments: extrusive and intrusive. Extrusive rocks are formed when magma erupts onto the Earth's surface as lava and cools rapidly, producing fine-grained textures. Examples include basalt and rhyolite. Intrusive rocks, on the other hand, form when magma cools slowly beneath the surface, producing coarse-grained textures such as granite and gabbro. These environments determine not only the texture but also the overall appearance and distribution of igneous rocks.

Fill in the blank: Igneous rocks that cool slowly beneath the Earth's surface are called ______ rocks.

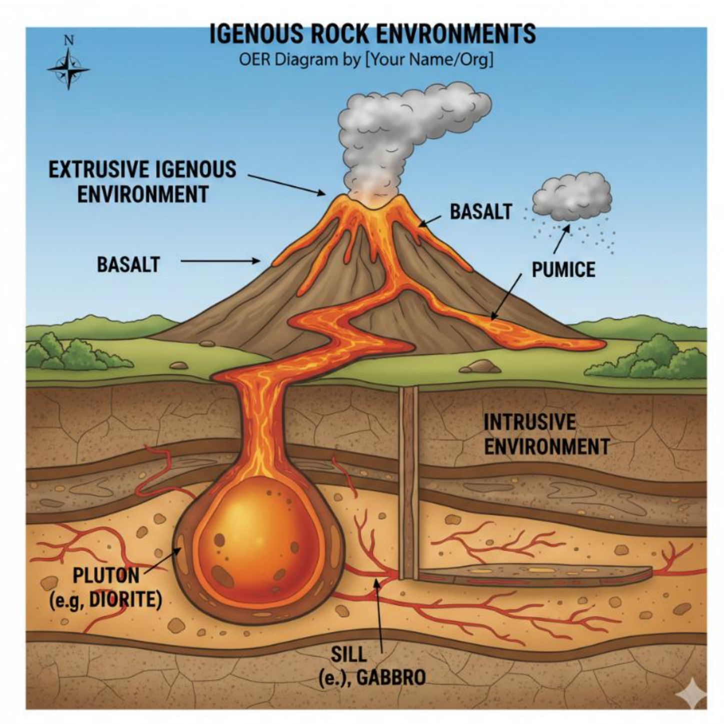

Figure 1.3: Comparison of extrusive and intrusive igneous settings

1.2.2 Distribution of igneous bodies in the crust

Igneous bodies are distributed throughout the Earth's crust in various forms. Plutons are large intrusive bodies that crystallize deep underground, while dykes and sills are smaller intrusions that cut across or lie parallel to existing rock layers. At the surface, volcanic flows and pyroclastic deposits represent extrusive igneous activity. The distribution of these bodies provides important information about past geological processes and helps geologists reconstruct the history of crustal development.

Fill in the blank: A tabular igneous intrusion that cuts across existing rock layers is called a_______.

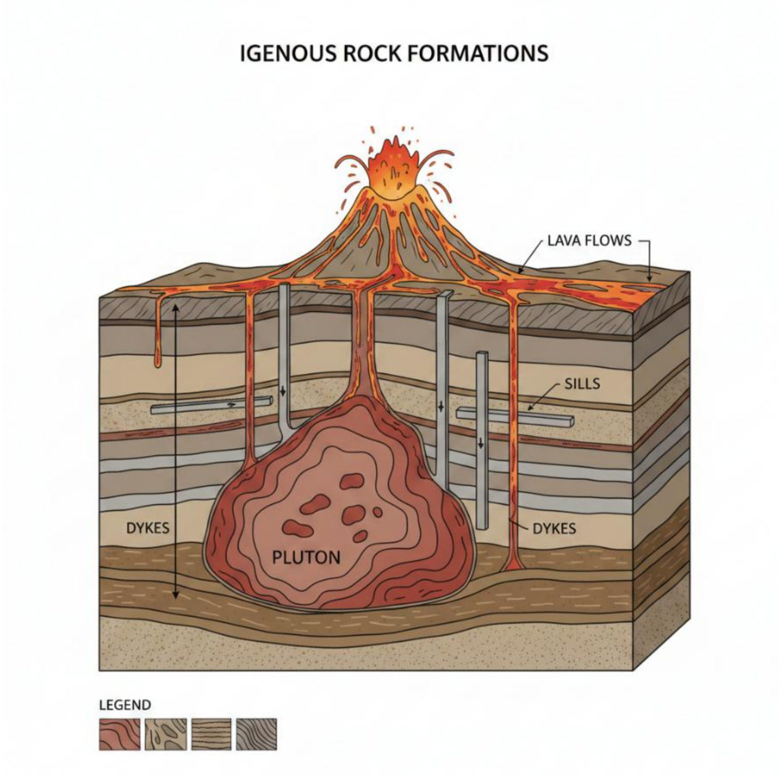

Figure 1.4: Distribution of igneous bodies in the crust

1.2.3 Plate tectonic context of igneous rocks

The occurrence of igneous rocks is closely linked to plate tectonics, which refers to the movement and interaction of large plates that make up the Earth's lithosphere. At divergent boundaries, magma rises to form new crust at mid-ocean ridges. At convergent boundaries, subduction leads to melting and the formation of volcanic arcs. At hotspots, mantle plumes generate isolated volcanic centers. Understanding these tectonic contexts helps explain why igneous rocks are found in specific regions and why their composition varies.

Fill in the blank: New oceanic crust is formed at _____ boundaries where plates move apart.

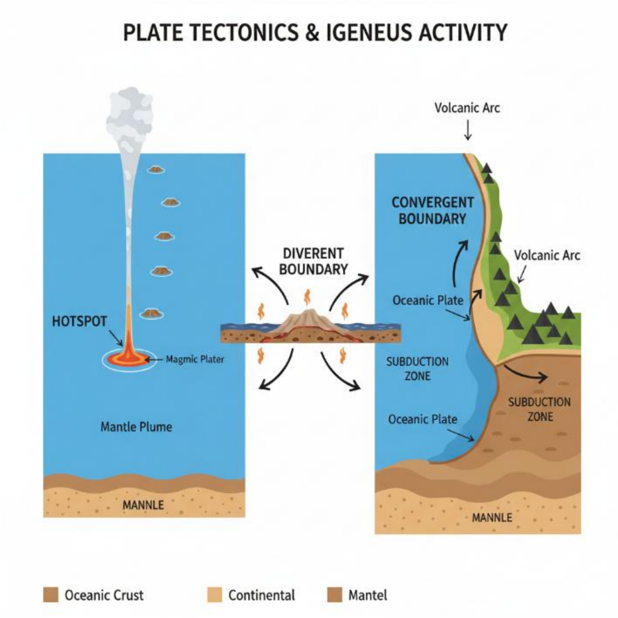

Figure 1.5: Plate tectonic settings of igneous rocks

Pilot questions 1.2

1. What is the main difference between extrusive and intrusive igneous rocks?
2. Give one example of an intrusive igneous rock.
3. What type of igneous intrusion cuts across existing rock layers?
4. Which tectonic setting is associated with volcanic arcs?
5. At what type of plate boundary is new oceanic crust formed?

1.3 Systematic Description of Igneous Rocks

1.3.1 Textural features of igneous rocks

The texture of an igneous rock refers to the size, shape, and arrangement of its mineral grains. Texture provides important clues about the cooling history of the magma. For example, phaneritic texture describes rocks with large crystals formed by slow cooling underground, while aphanitic texture refers to fine-grained rocks formed by rapid cooling at the surface. Other textures include porphyritic, where large crystals are embedded in a finer matrix, and glassy, which results from extremely rapid cooling with no crystal formation.

Fill in the blank: Rocks with large crystals formed by slow cooling underground are described as having _______ texture.

Figure 1.6: Common textural features of igneous rocks

1.3.2 Mineral composition of igneous rocks

The mineral composition of igneous rocks depends on the chemical makeup of the magma and the conditions under which it crystallizes. Rocks rich in silica form felsic compositions, such as granite and rhyolite, which are light-colored and contain minerals like quartz and feldspar. Rocks with lower silica content form mafic compositions, such as basalt and gabbro, which are darker and contain minerals like pyroxene and olivine. Intermediate and ultramafic compositions also exist, representing a spectrum of chemical variation.

Fill in the blank: Igneous rocks rich in silica and light-colored minerals are classified as___.

Category	Silica (SiO2) %	Primary Mineralogy	Color/Tone	Intrusive Example	Extrusive Example
Felsic (Silicic)	>65%	Quartz, K-Feldspar, Muscovite	Light (Pink, White, Gray)	**Granite**	**Rhyolite**
Intermediate	55% - 65%	Amphibole, Na/Ca-Plagioclase	"Salt & Pepper" / Medium Gray	**Diorite**	**Andesite**
Mafic	45% - 55%	Pyroxene, Ca-Plagioclase	Dark (Black, Dark Gray)	**Gabbro**	**Basalt**
Ultramafic	<45%	Olivine, Pyroxene	Very Dark (often Greenish)	**Peridotite**	**Komatite**

Table 1.1: Mineral composition of igneous rocks

1.3.3 Field and laboratory identification methods

The identification of igneous rocks involves both field methods and laboratory techniques. In the field, geologists observe rock color, grain size, and texture, often using a hand lens for closer inspection. Laboratory methods include thin section petrography, where rocks are sliced into thin sections and examined under a microscope to identify minerals and textures. Chemical analysis, such as X-ray fluorescence, provides precise information about the rock's composition. These methods together ensure accurate classification and description.

Fill in the blank: A thin section of rock examined under a microscope is used in ______ petrography.

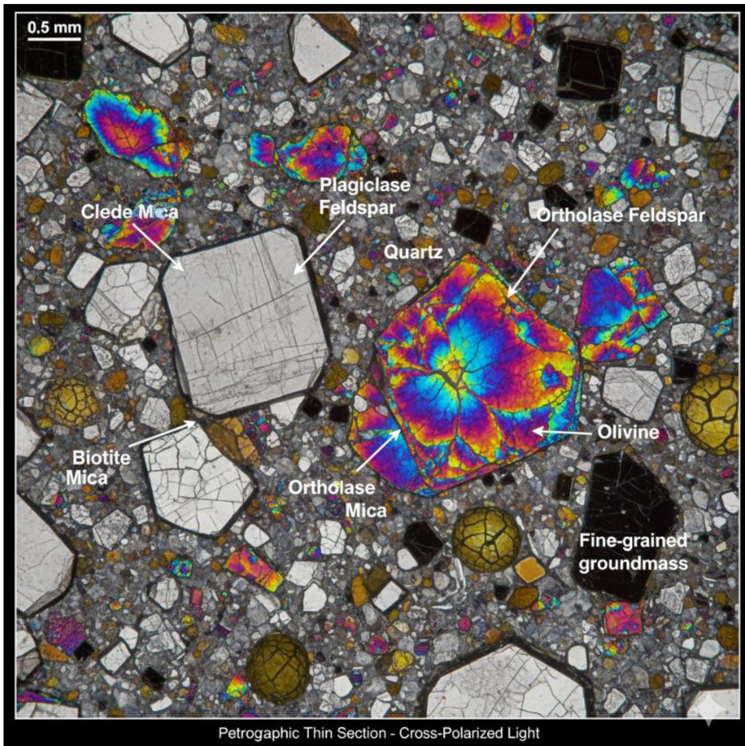

Plate 1.2: Thin section view of igneous rock minerals

Pilot questions 1.3

1. What does the texture of an igneous rock reveal about its cooling history?
2. Which texture describes rocks with large crystals formed by slow cooling underground?
3. Name two minerals commonly found in felsic igneous rocks.
4. What type of igneous rocks are darker and contain pyroxene and olivine?
5. Which laboratory method involves slicing rocks into thin sections for microscopic study?

1.4 Classification of Igneous Rocks

1.4.1 Basis of classification: texture and mineralogy

The classification of igneous rocks is primarily based on texture and mineralogy. Texture refers to the size, shape, and arrangement of mineral grains, which reflects the cooling history of the magma. Mineralogy refers to the types and proportions of minerals present in the rock, which are controlled by the chemical composition of the magma. Together, these two features provide a systematic way to group igneous rocks into meaningful categories.

Fill in the blank: The two main features used to classify igneous rocks are _____ and mineralogy.

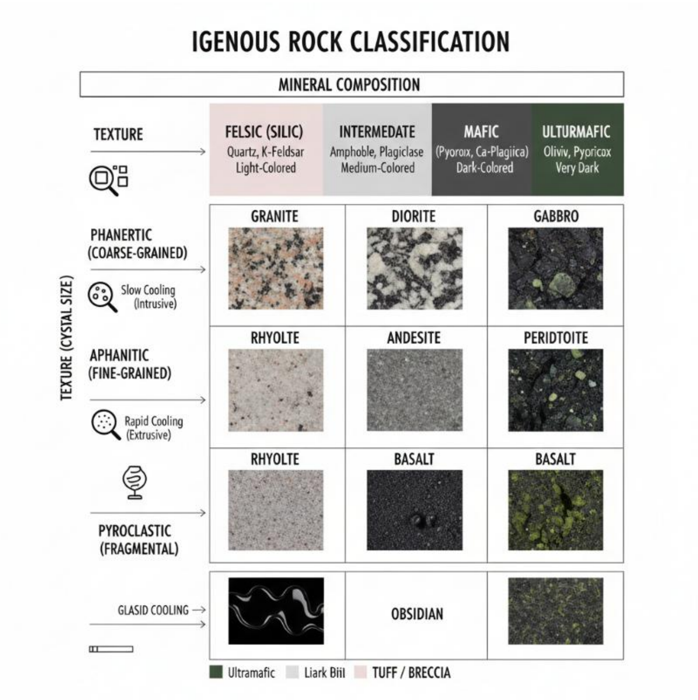

Figure 1.7: Basis of igneous rock classification

1.4.2 Major categories: felsic, intermediate, mafic, ultramafic

Igneous rocks are grouped into four major categories according to their mineral composition. Felsic rocks are rich in silica and light-colored minerals such as quartz and feldspar. Intermediate rocks contain moderate silica and minerals like amphibole and feldspar. Mafic rocks are darker, with lower silica content, and contain minerals such as pyroxene and olivine. Ultramafic rocks are very low in silica and dominated by olivine and pyroxene. These categories reflect the chemical diversity of magmas and the variety of igneous rocks formed.

Fill in the blank: Igneous rocks that are very low in silica and dominated by olivine are classified as ________.

Category	Silica (SiO2) %	Primary Mineralogy	Representative Minerals	Intrusive Example	Extrusive Example
Felsic	>65%	Quartz, K-Feldspar, Plagioclase	Muscovite, Biotite	**Granite**	**Rhyolite**
Intermediate	55% - 65%	Amphibole, Plagioclase	Pyroxene, Biotite	**Diorite**	**Andesite**
Mafic	45% - 55%	Pyroxene, Ca-Plagioclase	Olivine, Amphibole	**Gabbro**	**Basalt**
Ultramafic	<45%	Olivine, Pyroxene	Ca-Plagioclase	**Peridotite**	**Komatiite**

Table 1.2: Major categories of igneous rocks

1.4.3 Common classification schemes

Several schemes are used to classify igneous rocks systematically. The TAS diagram (Total Alkali-Silica diagram) is commonly used for volcanic rocks, plotting silica against alkali content to distinguish between basalt, andesite, dacite, and rhyolite. Modal classification is based on the relative proportions of minerals observed in thin sections, often used for plutonic rocks. These schemes provide geologists with standardized methods to compare and describe igneous rocks across different regions.

Fill in the blank: The TAS diagram classifies volcanic rocks based on their _____ and alkali content.

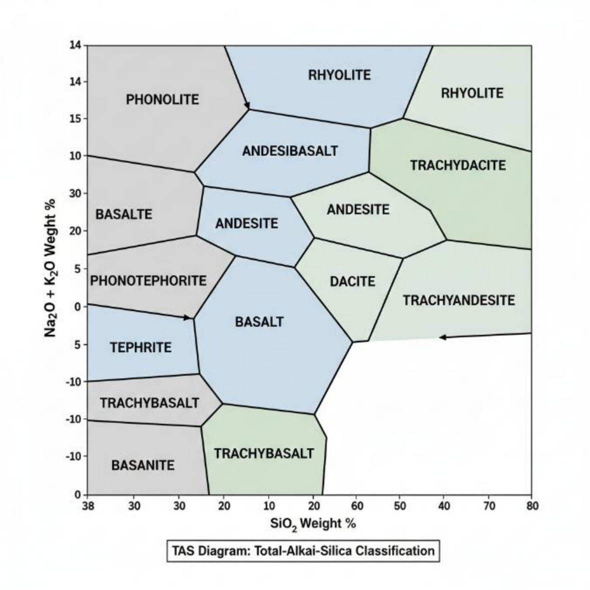

Figure 1.8: TAS diagram for volcanic rock classification

Pilot questions 1.4

1. What two features form the basis of igneous rock classification?
2. Which category of igneous rocks is rich in silica and light-colored minerals?
3. Name one example of a mafic igneous rock.
4. What type of classification scheme uses mineral proportions observed in thin sections?
5. In the TAS diagram, which two chemical components are plotted?

Series Summary

This Series introduced you to the foundations of igneous petrology, highlighting the importance of igneous rocks in understanding Earth's dynamic processes. We began by exploring the origin and formation of igneous rocks, focusing on magma generation, crystallization, and geological settings. We then examined their occurrence in both extrusive and intrusive environments, considering how igneous bodies are distributed within the crust and linked to plate tectonic activity. Following that, we studied the systematic description of igneous rocks, paying attention to their textures, mineral composition, and methods of identification. Finally, we concluded with the classification of igneous rocks, emphasizing the role of texture, mineralogy, and established schemes such as the TAS diagram and modal classification.

By completing this Series, you should now be able to define the processes involved in the origin and formation of igneous rocks (SLO 1.1), explain their occurrence and geologic settings (SLO 1.2), describe their textural features and mineral composition using systematic methods (SLO 1.3), and classify igneous rocks accurately based on texture, mineralogy, and recognized schemes (SLO 1.4). These skills provide a strong foundation for further study in petrology and will support your ability to analyze and interpret the role of igneous rocks in Earth's history and structure.

Glossary of Terms

Aphanitic texture: A fine-grained texture in igneous rocks where crystals are too small to be seen easily with the naked eye, formed by rapid cooling of magma at or near the Earth's surface.

Crystallization: The process by which minerals form from cooling magma, resulting in solid igneous rock.

Dyke: A tabular igneous intrusion that cuts across existing rock layers.

Extrusive rocks: Igneous rocks formed when magma erupts onto the Earth's surface as lava and cools quickly, producing fine-grained textures.

Felsic rocks: Igneous rocks rich in silica and light-colored minerals such as quartz and feldspar.

Hotspot: A location where a plume of hot mantle material rises to the surface, creating isolated volcanic centers.

Intrusive rocks: Igneous rocks formed when magma cools slowly beneath the Earth's surface, producing coarse-grained textures.

Lithosphere: The rigid outer layer of the Earth, consisting of the crust and the uppermost mantle, which is broken into tectonic plates.

Mafic rocks: Dark-coloured igneous rocks with lower silica content, containing minerals such as pyroxene and olivine.

Mantle: The thick layer of solid rock beneath the Earth's crust, which is the primary source of most magmas.

Modal classification: A method of classifying igneous rocks based on the relative proportions of minerals observed in thin sections under a microscope.

Phaneritic texture: A coarse-grained texture in igneous rocks where crystals are large enough to be seen easily with the naked eye, formed by slow cooling of magma underground.

Pluton: A large intrusive igneous body that crystallises deep underground.

Porphyritic texture: An igneous rock texture characterised by large crystals embedded in a finer-grained matrix, indicating two stages of cooling.

Pyroclastic deposits: Fragmented material ejected during volcanic eruptions, which solidifies to form extrusive igneous rocks.

Silica: A chemical compound (SiO_2) that is a major component of many minerals and influences the composition and classification of igneous rocks.

Solidification: The complete transformation of magma into solid rock after cooling.

Subduction zone: A tectonic setting where one plate descends beneath another into the mantle, often producing volcanic arcs.

TAS diagram: A classification scheme for volcanic rocks that plots total alkali content against silica content.

Texture: The size, shape, and arrangement of mineral grains in a rock, which reflects its cooling history.

Ultramafic rocks: Igneous rocks with very low silica content, dominated by minerals such as olivine and pyroxene.

This glossary provides clear definitions of the essential terms introduced in Series 1, supporting independent study and reinforcing the concepts linked to the Series Learning Outcomes.

Concept Check Questions [Series 1]

Objective Questions

1. Which part of the Earth is the primary source of most magmas? (Linked to SLO 1.1)

2. Igneous rocks that cool slowly beneath the Earth's surface are called rocks. (Linked to SLO 1.2)

3. Which texture describes igneous rocks with large crystals formed by slow cooling underground? (Linked to SLO 1.3)

4. In the TAS diagram, volcanic rocks are classified based on their silica and content. (Linked to SLO 1.4)

Short-Answer Questions

5. Define crystallization in the context of igneous rocks. (Linked to SLO 1.1)

6. Explain the difference between extrusive and intrusive igneous rocks. (Linked to SLO 1.2)

7. Identify two minerals commonly found in felsic igneous rocks. (Linked to SLO 1.3)

8. Name one example each of a mafic and an ultramafic igneous rock. (Linked to SLO 1.4)

Long-Answer Questions

9. Analyze how cooling rate influences the texture of igneous rocks, providing examples of different textures. (Linked to SLO 1.3)

10. Evaluate the role of plate tectonic settings in the occurrence of igneous rocks, with reference to divergent boundaries, convergent boundaries, and hotspots. (Linked to SLO 1.2)

11. Discuss the basis of igneous rock classification, explaining how texture and mineralogy are used to distinguish between felsic, intermediate, mafic, and ultramafic rocks. (Linked to SLO 1.4)

Answers to Concept Check Questions [Series 1]

Objective Questions

1. The mantle.

2. Intrusive rocks.

3. Phaneritic texture.

4. Alkali content.

Short-Answer Questions

5. Crystallization is the process by which minerals form from cooling magma, resulting in solid igneous rock.

6. Extrusive igneous rocks form when magma erupts onto the surface and cools quickly, producing fine-grained textures, while intrusive igneous rocks form when magma cools slowly beneath the surface, producing coarse-grained textures.

7. Quartz and feldspar.

8. Mafic: basalt; Ultramafic: peridotite.

Long-Answer Questions

9. Basic response: Cooling rate determines crystal size in igneous rocks. Slow cooling underground produces coarse-grained textures (phaneritic), while rapid cooling at the surface produces fine-grained textures (aphanitic). Extremely rapid cooling can result in glassy textures, and two-stage cooling produces porphyritic textures.

Value-added response: Cooling rate also influences rock porosity and mechanical strength. For example, volcanic glass (obsidian) is brittle due to rapid cooling, while granite's coarse texture makes it durable and widely used in construction.

10. Basic response: Plate tectonic settings control where igneous rocks occur. At divergent boundaries, magma rises to form new crust at mid-ocean ridges. At convergent boundaries, subduction produces volcanic arcs. At hotspots, mantle plumes generate isolated volcanic centers.

Value-added response: These settings also influence magma composition. Divergent boundaries typically produce mafic rocks such as basalt, convergent boundaries produce intermediate to felsic rocks such as andesite and rhyolite, and hotspots can produce diverse compositions depending on mantle source characteristics.

11. Basic response: Igneous rocks are classified based on texture and mineralogy. Texture reflects cooling history, while mineralogy reflects chemical composition. Felsic rocks are silica-rich and light-colored, intermediate rocks have moderate silica, mafic rocks are darker with lower silica, and ultramafic rocks are very low in silica and dominated by olivine and pyroxene.

Value-added response: Classification schemes such as the TAS diagram and modal classification provide standardized methods for comparing rocks globally. These schemes are essential in petrology for linking rock types to tectonic settings and understanding Earth's geological evolution.

Answers to Pilot Questions [Series 1]

Part 1: Origin and Formation of Igneous Rocks

1. The mantle.

2. Crystallization is the process by which minerals form from cooling magma.

3. Slow cooling produces coarse-grained textures, while rapid cooling produces fine-grained textures.

4. Mid-ocean ridges, subduction zones.

5. Hotspots.

Part 2: Occurrence and Geologic Setting of Igneous Rocks

1. Extrusive rocks cool rapidly at the surface, while intrusive rocks cool slowly underground.

2. Granite.

3. Dyke.

4. Convergent boundaries.

5. Divergent boundaries.

Part 3: Systematic Description of Igneous Rocks

1. Texture reveals the cooling history of magma.

2. Phaneritic texture.

3. Quartz and feldspar.

4. Mafic rocks: basalt; Ultramafic rocks: peridotite.

5. Thin section petrography.

Part 4: Classification of Igneous Rocks

1. Texture and mineralogy.

2. Felsic rocks.

3. Basalt.

4. Modal classification.

5. Silica and alkali content.

References and Attributions [Series 1]

All references and attributions listed below correspond to the instructional content, illustrations, and open educational resources (OERs) suggested in Series 1: Igneous Petrology: Origin, Occurrence, and Classification. The referencing style used here follows APA guidelines for clarity and consistency.

General References

- Winter, J. D. (2010). Principles of Igneous and Metamorphic Petrology (2nd ed.). Pearson Education.

- Marshak, S. (2019). Earth: Portrait of a Planet (6th ed.). W. W. Norton & Company.

- Open Educational Resources (OER) Commons. (n.d.). Retrieved from https://www.oercommons.org

Illustrations

Figure 1.1: Magma generation zones in the Earth's interior

- AI-generated suggestion: "Generate a labelled diagram showing magma generation in mantle, crust, and tectonic settings."

- Suggested OER search string: "OER diagram magma generation mantle crust tectonic settings."

Figure 1.2: Crystallisation and cooling of magma

- AI-generated suggestion: “Create a diagram illustrating crystallisation of magma with examples of coarse-grained and fine-grained rocks.”

- Suggested OER search string: “OER diagram crystallisation cooling magma igneous rocks.”

Plate 1.1: Volcanic arc formed at a subduction zone

- AI-generated suggestion: “Generate an image of a volcanic arc at a subduction zone with labelled features.”

- Suggested OER search string: “OER image volcanic arc subduction zone igneous activity.”

Figure 1.3: Comparison of extrusive and intrusive igneous settings

- AI-generated suggestion: “Generate a labelled diagram showing extrusive and intrusive igneous environments with examples of rocks.”

- Suggested OER search string: “OER diagram extrusive intrusive igneous rocks environments.”

Figure 1.4: Distribution of igneous bodies in the crust

- AI-generated suggestion: “Create a diagram illustrating plutons, dykes, sills, and lava flows in the Earth’s crust.”

- Suggested OER search string: “OER diagram igneous bodies plutons dykes sills lava flows.”

Figure 1.5: Plate tectonic settings of igneous rocks

- AI-generated suggestion: “Generate a diagram showing divergent boundaries, convergent boundaries, and hotspots with igneous activity.”

- Suggested OER search string: “OER diagram plate tectonics igneous rocks divergent convergent hotspot.”

Figure 1.6: Common textural features of igneous rocks

- AI-generated suggestion: “Create a labelled diagram illustrating igneous rock textures: phaneritic, aphanitic, porphyritic, and glassy.”

- Suggested OER search string: “OER diagram igneous rock textures phaneritic aphanitic porphyritic glassy.”

Table 1.1: Mineral composition of igneous rocks

- AI-generated suggestion: "Generate a table showing mineral composition categories of igneous rocks with examples."

- Suggested OER search string: "OER table igneous rock mineral composition felsic mafic intermediate ultramafic."

Plate 1.2: Thin section view of igneous rock minerals

- AI-generated suggestion: "Generate an image of a thin section of igneous rock under a microscope with labelled minerals."

- Suggested OER search string: "OER image thin section igneous rock petrography microscope."

Figure 1.7: Basis of igneous rock classification

- AI-generated suggestion: "Generate a diagram showing igneous rock classification based on texture and mineral composition."

- Suggested OER search string: "OER diagram igneous rock classification texture mineral composition."

Table 1.2: Major categories of igneous rocks

- AI-generated suggestion: "Create a table showing igneous rock categories with silica content, minerals, and examples."

- Suggested OER search string: "OER table igneous rock categories felsic mafic intermediate ultramafic."

Figure 1.8: TAS diagram for volcanic rock classification

- AI-generated suggestion: "Generate a TAS diagram showing volcanic rock classification based on silica and alkali content."

- Suggested OER search string: "OER TAS diagram volcanic rock classification silica alkali."

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Lists of Series

Series 1: Foundations of Igneous Petrology

Series 2: Systematic Study of Metamorphic Rocks

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Series 5: Classification of Igneous, Metamorphic, and Sedimentary Rocks

2.1 Metamorphism and its processes

- 2.1.1 Definition and causes of metamorphism

- 2.1.2 Types of metamorphism (contact, regional, dynamic)

- 2.1.3 Factors controlling metamorphism (temperature, pressure, fluids)

2.2 Description of metamorphic rocks

- 2.2.1 Field characteristics of metamorphic rocks

- 2.2.2 Common metamorphic rock types (slate, schist, gneiss, marble, quartzite)

- 2.2.3 Methods of identifying metamorphic rocks

2.3 Metamorphic minerals and textures

- 2.3.1 Index minerals and their significance

- 2.3.2 Textural features of metamorphic rocks (foliated and non-foliated)

- 2.3.3 Microstructures in metamorphic rocks

2.4 Classification of metamorphic rocks

- 2.4.1 Basis of classification (texture and mineralogy)

- 2.4.2 Foliated versus non-foliated categories

- 2.4.3 Common classification schemes

Introduction

In the last Series, we explored the foundations of igneous petrology, focusing on how igneous rocks originate, occur, and are classified. We now turn our attention to metamorphic rocks, which provide another vital perspective on Earth's dynamic processes. These rocks are formed when existing rocks undergo transformation under the influence of heat, pressure, and fluids, and they record the conditions deep within the crust. Understanding metamorphic rocks is essential because they reveal the history of tectonic activity, mountain building, and crustal evolution.

The aim of this Series is to equip you with the knowledge and skills to explain the processes of metamorphism, describe the features and types of metamorphic rocks, analyze their minerals and textures, and classify them systematically.

We shall commence this Series by examining metamorphism and its processes, including the causes, types, and controlling factors. Next, we will move on to the description of metamorphic rocks, considering their field characteristics, common types, and methods of identification. Following that, we will study metamorphic minerals and textures, paying attention to index minerals, foliated and non-foliated structures, and microstructures. Finally, we will wrap up by exploring the classification of metamorphic rocks, focusing on the basis of classification and the schemes used to distinguish between different categories.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- SLO 2.1 define metamorphism and explain the processes and factors that cause rocks to undergo metamorphic change,

- SLO 2.2 describe the field characteristics and common types of metamorphic rocks,

- SLO 2.3 analyze the role of index minerals and textural features in interpreting metamorphic conditions, and

- SLO 2.4 classify metamorphic rocks systematically based on texture, mineralogy, and recognized schemes.

2.1 Metamorphism and its Processes

2.1.1 Definition and causes of metamorphism

Metamorphism is the process by which existing rocks (igneous, sedimentary, or older metamorphic) are transformed into new rocks through changes in mineralogy, texture, and sometimes chemical composition, under conditions of heat, pressure, and chemically active fluids. Unlike melting, metamorphism occurs in a solid state, meaning the rock does not become magma but instead recrystallizes.

The causes of metamorphism include increased temperature from proximity to magma or deep burial, increased pressure from tectonic forces or burial, and the presence of fluids that accelerate chemical reactions. These factors work together to produce new mineral assemblages and textures that reflect the conditions of metamorphism.

Fill in the blank: Metamorphism occurs in the _______state, meaning rocks recrystallize without melting.

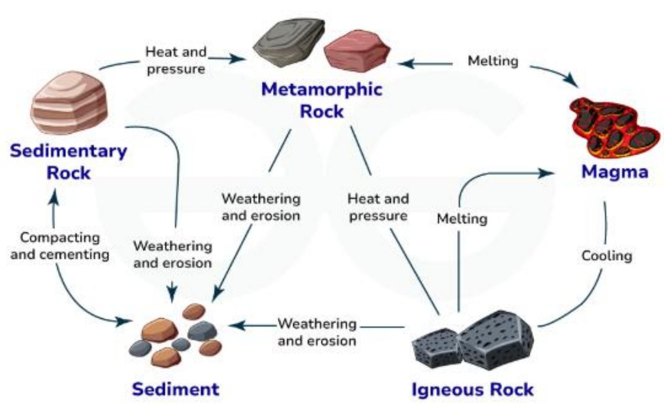

Figure 2.1: The metamorphic process in the rock cycle

2.1.2 Types of metamorphism (contact, regional, dynamic)

There are three main types of metamorphism:

- Contact metamorphism occurs when rocks are altered by heat from nearby magma intrusions. This produces fine-grained rocks called hornfels.

- Regional metamorphism takes place over large areas under high pressure and temperature, usually associated with mountain building. It produces foliated rocks such as schist and gneiss.

- Dynamic metamorphism results from intense pressure in fault zones, producing rocks with crushed or sheared textures, such as mylonite.

Fill in the blank: Contact metamorphism is caused mainly by ______ from nearby magma intrusions.

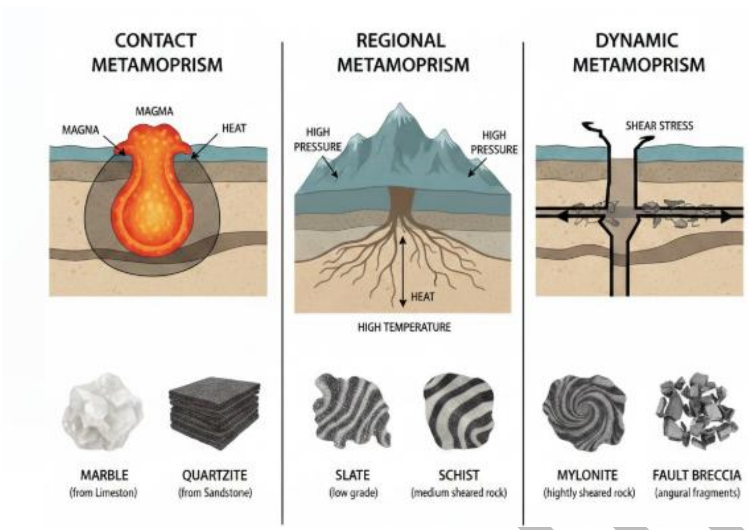

Figure 2.2: Types of metamorphism and their geological settings

2.1.3 Factors controlling metamorphism (temperature, pressure, fluids)

The outcome of metamorphism is controlled by three main factors:

- Temperature: Higher temperatures promote recrystallisation and the formation of new minerals.

- Pressure: Increased pressure, especially directed pressure, leads to the development of foliated textures such as slaty cleavage and schistosity.

- Fluids: Chemically active fluids, often water with dissolved ions, enhance mineral reactions and facilitate the growth of new minerals.

These factors interact to produce a wide variety of metamorphic rocks, each recording the specific conditions under which they formed.

Fill in the blank: Directed pressure during metamorphism often produces ______ textures such as schistosity.

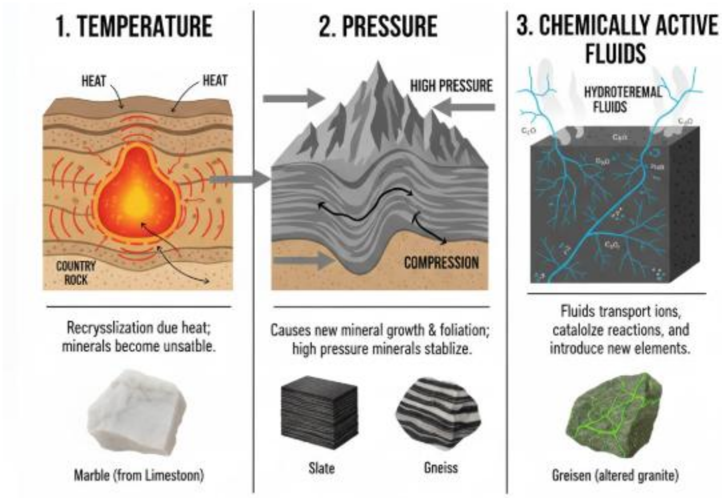

Figure 2.3: Factors controlling metamorphism

Pilot questions 2.1

1. What is metamorphism and how does it differ from melting?
2. Name the three main causes of metamorphism.
3. Which type of metamorphism is associated with mountain building?
4. What rock type is commonly formed by contact metamorphism?
5. Which factor of metamorphism often produces foliated textures?

2.2 Description of Metamorphic Rocks

2.2.1 Field characteristics of metamorphic rocks

Metamorphic rocks can be recognized in the field by their texture, mineral composition, and structures. Texture refers to the size, shape, and arrangement of minerals, while mineral composition reflects the types of minerals present. Common field features include foliation, which is the alignment of minerals due to directed pressure, and banding, which is the segregation of light and dark minerals into layers. These features help geologists distinguish metamorphic rocks from igneous and sedimentary rocks.

Fill in the blank: The alignment of minerals in metamorphic rocks due to directed pressure is called ________.

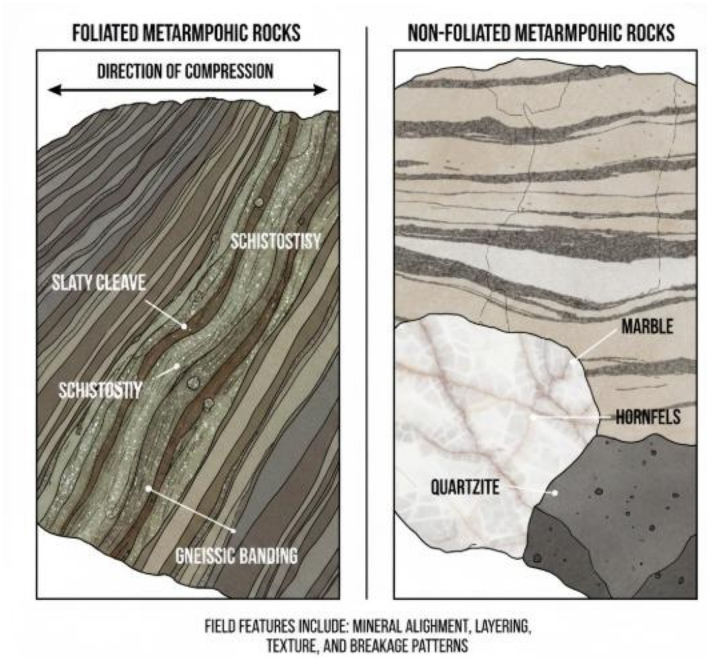

Figure 2.4: Field characteristics of metamorphic rocks

2.2.2 Common metamorphic rock types

Metamorphic rocks vary widely, but several common types are frequently studied:

- Slate: A fine-grained foliated rock formed from shale, characterized by slaty cleavage.
- Schist: A medium- to coarse-grained foliated rock with visible minerals such as mica.
- Gneiss: A coarse-grained rock with distinct banding of light and dark minerals.
- Marble: A non-foliated rock formed from limestone, composed mainly of calcite.
- Quartzite: A non-foliated rock formed from sandstone, composed mainly of quartz.

Fill in the blank: A metamorphic rock formed from limestone and composed mainly of calcite is called _________.

Metamorphic Rock	**Parent Rock (Protolith)**	**Key Features**
Slate	Shale, Mudstone	Foliated; very fine-grained; splits into flat, thin sheets (slaty cleavage).

Metamorphic Rock	Parent Rock (Protolith)	Key Features
Phyllite	Slate, Shale	Foliated; fine-grained; has a silky or "satiny" sheen; wavy rock surfaces.
Schist	Phyllite, Shale, Volcanic rocks	Foliated; medium-to-coarse grained; visible platy minerals (like mica) giving it a sparkly appearance.
Gneiss	Schist, Granite, Volcanic rocks	Foliated; coarse-grained; distinct dark and light mineral banding (gneissic banding).
Marble	Limestone, Dolostone	Non-foliated; crystalline texture; relatively soft (can be scratched by steel); reacts with HCl.
Quartzite	Quartz Sandstone	Non-foliated; very hard; composed of interlocking quartz grains; sugary appearance.
Anthracite	Bituminous Coal	Non-foliated; hard, black, and shiny; high carbon content; breaks with a conchoidal fracture.

Table 2.1: Common metamorphic rock types and their parent rocks

2.2.3 Methods of identifying metamorphic rocks

The identification of metamorphic rocks involves both field methods and laboratory techniques. In the field, geologists observe color, grain size, foliation, and hardness, often using a hand lens. Laboratory techniques include thin section petrography, where rocks are sliced into thin sections and examined under a microscope to identify minerals and textures. Chemical analysis, such as X-ray diffraction, can also be used to determine mineral composition. These methods together ensure accurate identification and classification.

Fill in the blank: Thin section petrography involves examining rocks under a _______ to identify minerals and textures.

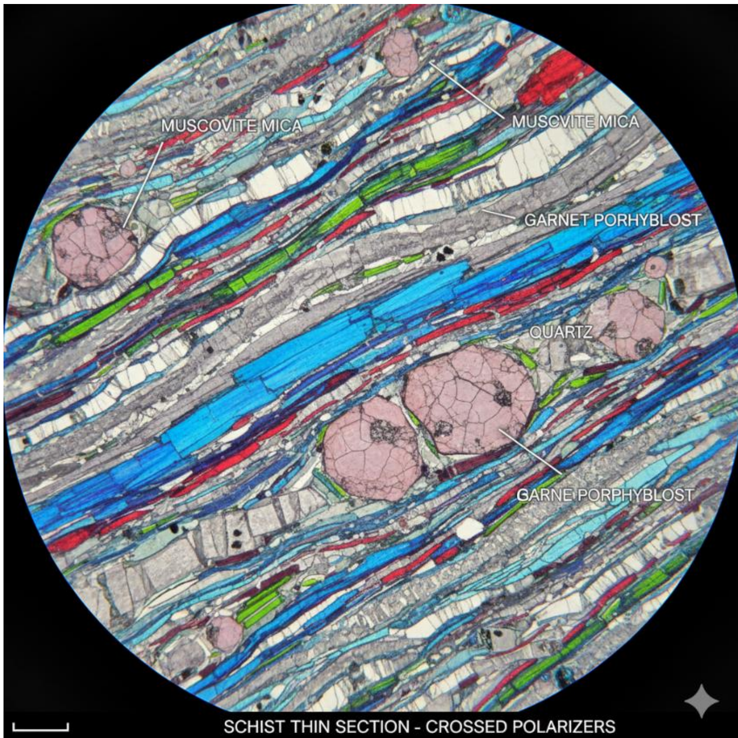

Plate 2.1: Thin section view of foliated metamorphic rock

Pilot questions 2.2

1. What field features help distinguish metamorphic rocks from igneous and sedimentary rocks?
2. Name one foliated and one non-foliated metamorphic rock.
3. Which metamorphic rock is formed from limestone?
4. What is the parent rock of quartzite?
5. Which laboratory method involves slicing rocks into thin sections for microscopic study?

2.3 Metamorphic Minerals and Textures

2.3.1 Index minerals and their significance

Index minerals are minerals that form under specific ranges of temperature and pressure during metamorphism. They are used by geologists to estimate the metamorphic grade of a rock. For example, chlorite typically indicates low-grade metamorphism, garnet represents medium-grade conditions, and sillimanite signals high-grade metamorphism. These minerals are important because they act as natural indicators of the conditions under which the rock was formed.

Fill in the blank: Garnet is an index mineral that usually indicates -grade metamorphism.

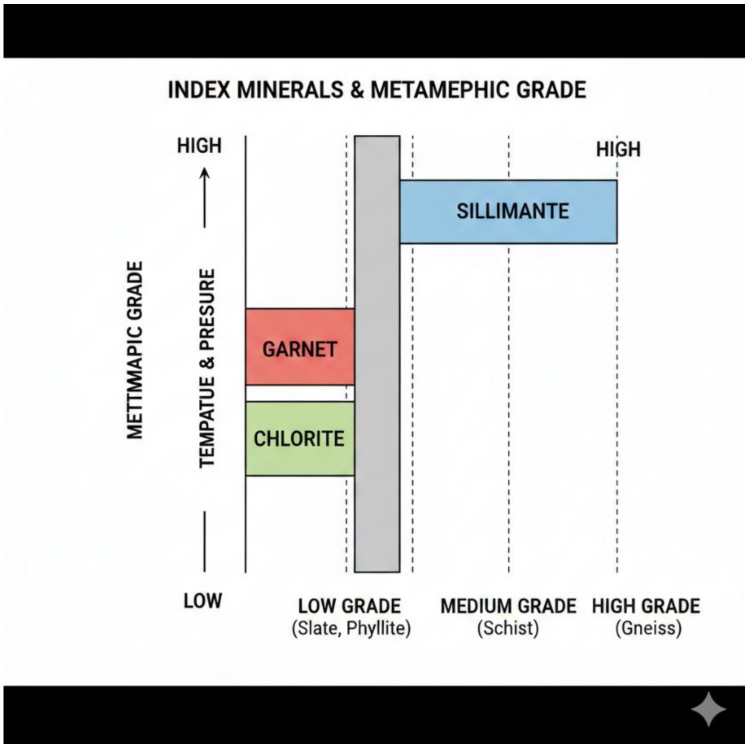

Figure 2.5: Index minerals as indicators of metamorphic grade

2.3.2 Textural features of metamorphic rocks (foliated and non-foliated)

The texture of metamorphic rocks refers to the arrangement of minerals and the overall appearance of the rock. Textures are broadly divided into two categories:

- Foliated textures: These show a layered or banded appearance due to the alignment of minerals under direct pressure. Examples include slaty cleavage in slate, schistosity in schist, and gneissic banding in gneiss.

- Non-foliated textures: These lack mineral alignment and appear massive or granular. Examples include marble and quartzite, which form under conditions where pressure is uniform or mineral composition prevents foliation.

Fill in the blank: Rocks such as marble and quartzite are examples of _______ metamorphic textures.

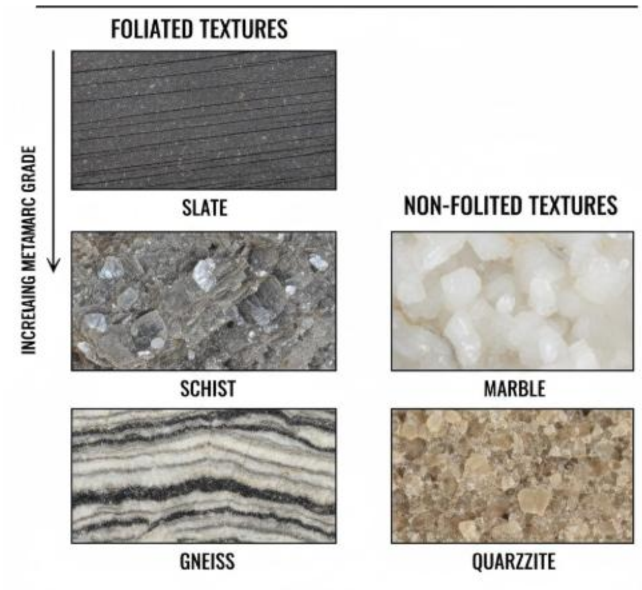

Figure 2.6: Foliated and non-foliated textures in metamorphic rocks

2.3.3 Microstructures in metamorphic rocks

Microstructures are small-scale features observed in thin sections of metamorphic rocks under a microscope. They provide detailed evidence of deformation and recrystallisation. Common microstructures include granoblastic texture, where equidimensional grains form due to recrystallisation, and porphyroblasts, which are large crystals that grow within a finer matrix. Studying microstructures helps geologists interpret the pressure-temperature history and deformation processes that affected the rock.

Fill in the blank: Large crystals that grow within a finer matrix during metamorphism are called _______.

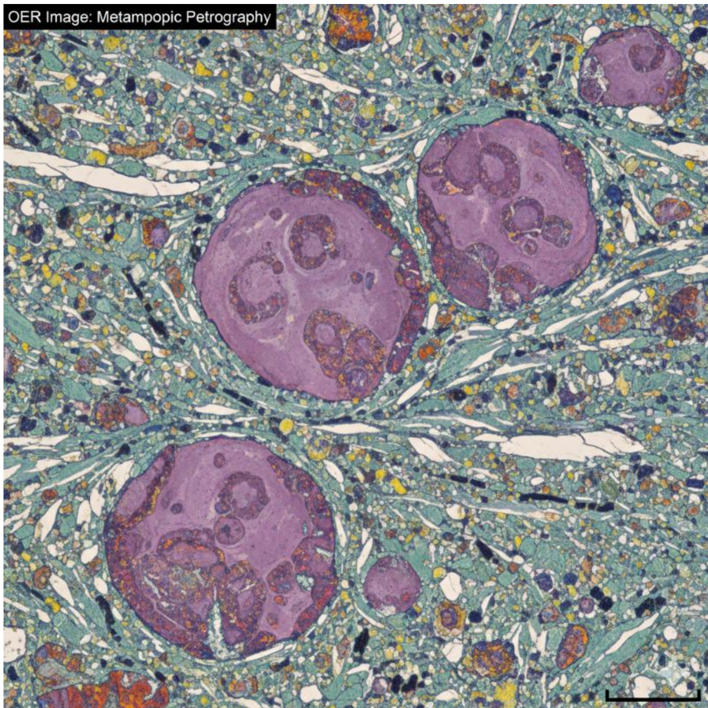

Plate 2.2: Porphyroblasts in a thin section of metamorphic rock

Pilot questions 2.3

1. What are index minerals and why are they important in metamorphic petrology?
2. Which index mineral is associated with high-grade metamorphism?
3. What is the main difference between foliated and non-foliated textures?
4. Give one example of a foliated metamorphic rock.
5. What are porphyroblasts and how do they form?

2.4 Classification of Metamorphic Rocks

2.4.1 Basis of classification (texture and mineralogy)

Metamorphic rocks are classified mainly on the basis of texture and mineralogy. Texture refers to the arrangement and appearance of minerals, which may be foliated (layered) or non-foliated (massive). Mineralogy refers to the specific minerals present, which reflect the chemical composition of the parent rock and the conditions of metamorphism. Together, these two features provide a systematic way of grouping metamorphic rocks into categories that are meaningful for geological study.

Fill in the blank: Metamorphic rocks are classified primarily on the basis of texture and ___.

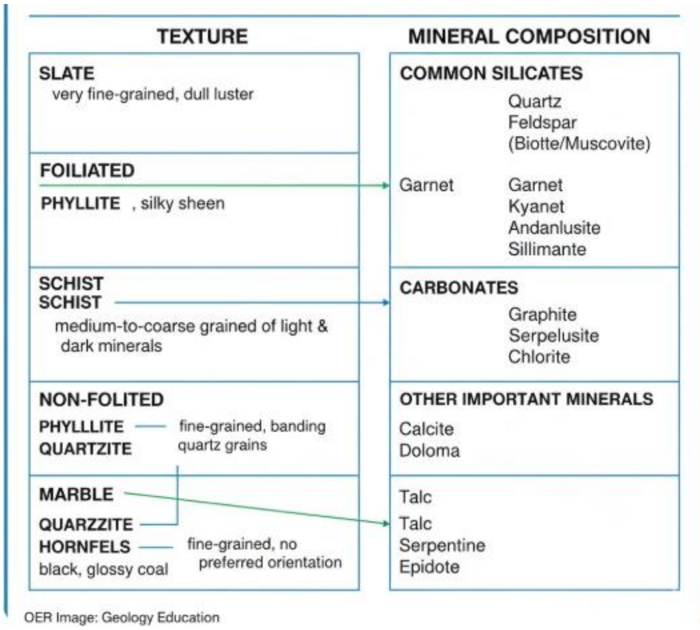

Figure 2.7: Basis of metamorphic rock classification

2.4.2 Foliated versus non-foliated categories

Metamorphic rocks are broadly divided into two categories:

- Foliated rocks: These display a layered or banded structure due to the alignment of minerals under direct pressure. Examples include slate, schist, and gneiss.

- Non-foliated rocks: These lack mineral alignment and appear massive or granular. Examples include marble and quartzite.

This distinction is important because it reflects the conditions under which the rocks formed. Foliated textures usually indicate strong directional pressure, while non-foliated textures suggest uniform pressure or mineral compositions that resist alignment.

Fill in the blank: Slate, schist, and gneiss are examples of ______ metamorphic rocks.

Rock Type	**Description**	**Key Characteristics**	**Common Examples**	**Parent Rock (Protolith)**
Foliated	Formed under **directed pressure** (stress from one direction). Minerals	Layered or "striped" appearance; often	**Slate, Phyllite, Schist, Gneiss**	Shale, Mudstone, Siltstone, or Granite

Rock Type	Description	Key Characteristics	Common Examples	Parent Rock (Protolith)
	align in parallel layers or bands.	splits into thin sheets.		
Non-Foliated	Formed under **uniform pressure** or high heat with little pressure (contact metamorphism).	Massive, crystalline appearance; no visible layers or bands.	**Marble, Quartzite, Hornfels, Anthracite**	Limestone, Sandstone, or Coal

Table 2.2: Categories of metamorphic rocks

2.4.3 Common classification schemes

Several schemes are used to classify metamorphic rocks systematically. One widely used approach is based on metamorphic grade, which refers to the intensity of metamorphism. Low-grade rocks such as slate form under relatively mild conditions, while high-grade rocks such as gneiss form under intense heat and pressure. Another scheme is based on parent rock composition, where metamorphic rocks are named according to the rock from which they were derived (e.g., limestone to marble, sandstone to quartzite). These schemes provide geologists with standardized methods to compare and describe metamorphic rocks across different regions.

Fill in the blank: A metamorphic rock formed from sandstone is called ________.

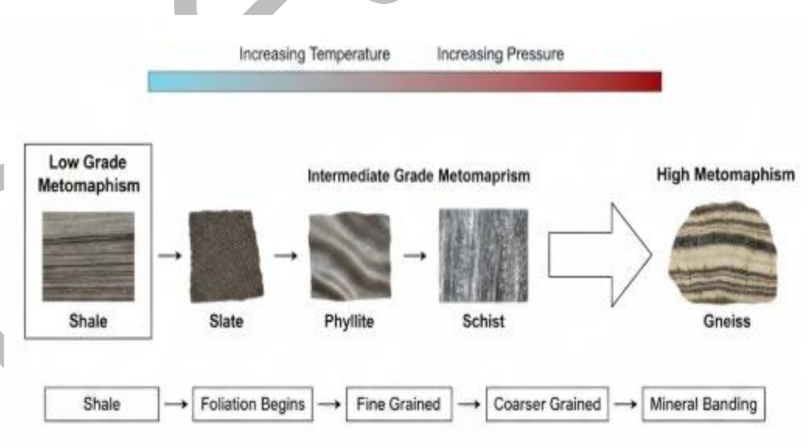

Figure 2.8: Metamorphic grade classification scheme

Pilot questions 2.4

1. What two features form the basis of metamorphic rock classification?

2. Give one example of a foliated metamorphic rock.

3. Name one non-foliated metamorphic rock.

4. What does the term metamorphic grade refer to?

5. Which metamorphic rock is formed from sandstone?

Series Summary

This Series has guided you through the systematic study of metamorphic rocks, emphasizing their importance in revealing Earth's dynamic processes and tectonic history. We began by examining metamorphism and its processes, considering the causes, types, and controlling factors. We then moved on to the description of metamorphic rocks, focusing on their field characteristics, common types, and methods of identification. Following that, we explored metamorphic minerals and textures, highlighting the role of index minerals, foliated and non-foliated structures, and microstructures. Finally, we concluded with the classification of metamorphic rocks, looking at the basis of classification, the distinction between foliated and non-foliated categories, and common schemes such as metamorphic grade and parent rock composition.

By completing this Series, you should now be able to define metamorphism and explain its processes (SLO 2.1), describe the features and types of metamorphic rocks (SLO 2.2), analyze the significance of index minerals and textures (SLO 2.3), and classify metamorphic rocks systematically using recognized schemes (SLO 2.4). These outcomes provide you with a strong foundation for interpreting metamorphic rocks and understanding their role in Earth's geological evolution.

Glossary of Terms

Banding: A texture in metamorphic rocks where light and dark minerals are segregated into distinct layers.

Chlorite: A green mineral that commonly forms during low-grade metamorphism and serves as an index mineral.

Foliation: The alignment of minerals in metamorphic rocks caused by direct pressure, giving the rock a layered appearance.

Garnet: A medium-grade index mineral that forms under moderate temperature and pressure conditions during metamorphism.

Gneiss: A coarse-grained foliated metamorphic rock characterized by alternating bands of light and dark minerals.

Hornfels: A fine-grained metamorphic rock formed by contact metamorphism, typically near magma intrusions.

Index minerals: Minerals that form under specific ranges of temperature and pressure, used to determine metamorphic grade.

Marble: A non-foliated metamorphic rock formed from limestone, composed mainly of calcite.

Metamorphic grade: A measure of the intensity of metamorphism, ranging from low-grade (mild conditions) to high-grade (intense heat and pressure).

Metamorphism: The process by which existing rocks are transformed in a solid state due to heat, pressure, and fluids, resulting in new textures and minerals.

Mylonite: A fine-grained metamorphic rock formed in fault zones due to dynamic metamorphism and intense shearing.

Porphyroblasts: Large crystals that grow within a finer-grained matrix during metamorphism.

Quartzite: A non-foliated metamorphic rock formed from sandstone, composed mainly of quartz.

Regional metamorphism: Metamorphism that occurs over large areas under high pressure and temperature, often associated with mountain building.

Schist: A medium- to coarse-grained foliated metamorphic rock with visible minerals such as mica.

Schistosity: A type of foliation in schist where platy minerals such as mica are aligned, giving the rock a shiny appearance.

Sillimanite: A high-grade index mineral that forms under intense metamorphic conditions.

Slate: A fine-grained foliated metamorphic rock formed from shale, characterized by slaty cleavage.

Slaty cleavage: A type of foliation in slate where the rock splits easily into thin sheets.

Texture: The arrangement and appearance of minerals in a rock, including whether it is foliated or non-foliated.

Thin section petrography: A laboratory method where rocks are sliced into thin sections and examined under a microscope to identify minerals and textures.

Uniform pressure: Pressure applied equally in all directions during metamorphism, often producing non-foliated textures.

Concept Check Questions [Series 2]

Objective Questions

1. Metamorphism occurs in the state, meaning rocks recrystallize without melting. (Linked to SLO 2.1)

2. Which type of metamorphism is most commonly associated with mountain building? (Linked to SLO 2.1)

3. Marble is a non-foliated metamorphic rock formed from . (Linked to SLO 2.2)

4. Garnet is an index mineral that typically indicates -grade metamorphism. (Linked to SLO 2.3)

5. Slate, schist, and gneiss are examples of metamorphic rocks. (Linked to SLO 2.4)

Short-Answer Questions

6. Define metamorphism in your own words. (Linked to SLO 2.1)

7. Identify two field features that help distinguish metamorphic rocks from igneous and sedimentary rocks. (Linked to SLO 2.2)

8. Explain the difference between foliated and non-foliated textures in metamorphic rocks. (Linked to SLO 2.3)

9. Name one metamorphic rock formed from sandstone and one formed from limestone. (Linked to SLO 2.4)

Long-Answer Questions

10. Analyse the causes of metamorphism and explain how temperature, pressure, and fluids interact to produce new mineral assemblages. (Linked to SLO 2.1)

11. Describe the common types of metamorphic rocks, highlighting their parent rocks and key features. (Linked to SLO 2.2)

12. Evaluate the role of index minerals and microstructures in interpreting metamorphic conditions. (Linked to SLO 2.3)

13. Discuss the basis of metamorphic rock classification, explaining the distinction between foliated and non-foliated categories and the use of metamorphic grade. (Linked to SLO 2.4)

Answers to Concept Check Questions [Series 2]

Objective Questions

1. Solid state.

2. Regional metamorphism.

3. Limestone.

4. Medium-grade.

5. Foliated.

Short-Answer Questions

6. Metamorphism is the process by which existing rocks are transformed in the solid state due to heat, pressure, and fluids, resulting in new textures and minerals.

7. Foliation and banding.

8. Foliated textures show mineral alignment and layering, while non-foliated textures are massive or granular without alignment.

9. Sandstone → Quartzite; Limestone → Marble.

Long-Answer Questions

10. Basic response: Metamorphism is caused by heat, pressure, and fluids. Heat promotes recrystallisation, pressure aligns minerals and produces foliation, and fluids accelerate chemical reactions. Together, these factors transform existing rocks into new metamorphic rocks.

Value-added response: The interaction of these factors also determines metamorphic facies, which are sets of mineral assemblages that reflect specific pressure-temperature conditions. For example, greenschist facies form under low-grade conditions, while granulite facies form under high-grade conditions.

11. Basic response: Common metamorphic rocks include slate (from shale), schist (from shale or basalt), gneiss (from granite or schist), marble (from limestone), and quartzite (from sandstone). Each has distinctive textures and mineral compositions.

Value-added response: These rocks also have practical uses. Slate is used for roofing, marble for sculpture and construction, quartzite for decorative stone, and gneiss for building materials. Their properties reflect their metamorphic history.

12. Basic response: Index minerals such as chlorite, garnet, and sillimanite indicate metamorphic grade. Microstructures like porphyroblasts and granoblastic textures provide evidence of recrystallisation and deformation.

Value-added response: Detailed petrographic analysis of microstructures can reveal deformation mechanisms such as pressure solution or dynamic recrystallisation, offering insights into tectonic processes and crustal evolution.

13. Basic response: Metamorphic rocks are classified based on texture and mineralogy. Foliated rocks include slate, schist, and gneiss, while non-foliated rocks include marble and quartzite. Classification schemes also use metamorphic grade to indicate intensity.

Value-added response: Advanced classification incorporates parent rock composition and metamorphic facies, allowing geologists to reconstruct pressure-temperature paths and tectonic settings. This makes classification a powerful tool for interpreting Earth's geological history.

Answers to Pilot Questions [Series 2]

Part 2.1: Metamorphism and its processes

1. Metamorphism is the transformation of existing rocks in the solid state without melting.

2. Heat, pressure, and fluids.

3. Regional metamorphism.

4. Hornfels.

5. Directed pressure.

Part 2.2: Description of metamorphic rocks

1. Foliation and banding.

2. Slate (foliated) and marble (non-foliated).

3. Marble.

4. Sandstone.

5. Thin section petrography.

Part 2.3: Metamorphic minerals and textures

1. Minerals that form under specific temperature and pressure conditions, used to determine metamorphic grade.

2. Sillimanite.

3. Foliated textures show mineral alignment, while non-foliated textures are massive or granular.

4. Schist.

5. Large crystals that grow within a finer matrix during metamorphism.

Part 2.4: Classification of metamorphic rocks

1. Texture and mineralogy.

2. Schist.

3. Quartzite.

4. The intensity of metamorphism.

5. Quartzite.

References and Attributions [Series 2]

All references and attributions listed below correspond to the instructional content, illustrations, and open educational resources (OERs) suggested in Series 2: Systematic Study of Metamorphic Rocks. The referencing style used here follows APA guidelines for clarity and consistency.

General References

- Yardley, B. W. D. (1989). An Introduction to Metamorphic Petrology. Longman Scientific & Technical.

- Winter, J. D. (2010). Principles of Igneous and Metamorphic Petrology (2nd ed.). Pearson Education.

- Marshak, S. (2019). Earth: Portrait of a Planet (6th ed.). W. W. Norton & Company.

- Open Educational Resources (OER) Commons. (n.d.). Retrieved from https://www.oercommons.org

Illustrations

Figure 2.1: The metamorphic process in the rock cycle

- AI-generated suggestion: “Generate a labelled diagram showing how igneous and sedimentary rocks transform into metamorphic rocks under heat and pressure.”

- Suggested OER search string: “OER diagram rock cycle metamorphism heat pressure.”

Figure 2.2: Types of metamorphism and their geological settings

- AI-generated suggestion: “Create a diagram illustrating contact, regional, and dynamic metamorphism with examples of rocks formed.”

- Suggested OER search string: “OER diagram types of metamorphism contact regional dynamic.”

Figure 2.3: Factors controlling metamorphism

- AI-generated suggestion: “Generate a diagram showing how temperature, pressure, and fluids influence metamorphic rock formation.”

- Suggested OER search string: “OER diagram factors controlling metamorphism temperature pressure fluids.”

Figure 2.4: Field characteristics of metamorphic rocks

- AI-generated suggestion: “Generate a labelled diagram showing foliated and non-foliated metamorphic rocks with field features.”

- Suggested OER search string: “OER diagram field characteristics metamorphic rocks foliated non-foliated.”

Table 2.1: Common metamorphic rock types and their parent rocks

- AI-generated suggestion: "Create a table showing common metamorphic rocks, their parent rocks, and key features."

- Suggested OER search string: "OER table metamorphic rocks parent rocks features."

Plate 2.1: Thin section view of foliated metamorphic rock

- AI-generated suggestion: "Generate an image of a thin section of schist under a microscope with labelled minerals."

- Suggested OER search string: "OER image thin section schist petrography microscope."

Figure 2.5: Index minerals as indicators of metamorphic grade

- AI-generated suggestion: "Generate a labelled diagram showing index minerals (chlorite, garnet, sillimanite) and their metamorphic grade ranges."

- Suggested OER search string: "OER diagram index minerals metamorphic grade chlorite garnet sillimanite."

Figure 2.6: Foliated and non-foliated textures in metamorphic rocks

- AI-generated suggestion: "Create a diagram comparing foliated textures (slate, schist, gneiss) and non-foliated textures (marble, quartzite)."

- Suggested OER search string: "OER diagram foliated non-foliated metamorphic textures."

Plate 2.2: Porphyroblasts in a thin section of metamorphic rock

- AI-generated suggestion: "Generate an image of a thin section of metamorphic rock showing porphyroblasts within a fine-grained matrix."

- Suggested OER search string: "OER image thin section porphyroblasts metamorphic rock petrography."

Figure 2.7: Basis of metamorphic rock classification

- AI-generated suggestion: "Generate a labelled diagram showing metamorphic rock classification based on texture and mineral composition."

- Suggested OER search string: "OER diagram metamorphic rock classification texture mineral composition."

Table 2.2: Categories of metamorphic rocks

- AI-generated suggestion: “Create a table showing foliated and non-foliated metamorphic rocks with examples.”

- Suggested OER search string: “OER table foliated non-foliated metamorphic rocks examples.”

Figure 2.8: Metamorphic grade classification scheme

- AI-generated suggestion: “Generate a diagram showing metamorphic grade progression from shale to slate, schist, and gneiss.”

- Suggested OER search string: “OER diagram metamorphic grade classification shale slate schist gneiss.”

Course Code: GEY 203

Course title: Introduction to Petrology

Units: 2 Units

List of Series

Series 1: Foundations of Igneous Petrology

Series 2: Systematic Study of Metamorphic Rocks

Series 3: Textures and Minerals in Metamorphism

Series 4: Introduction to Sedimentary Petrology

Series 5: Classification of Igneous, Metamorphic, and Sedimentary Rocks

3.1 Textural features of metamorphic rocks

- 3.1.1 Definition of texture in metamorphic rocks

- 3.1.2 Foliated textures (slaty cleavage, schistosity, gneissic banding)

- 3.1.3 Non-foliated textures (granoblastic, massive, crystalline)

3.2 Index minerals and metamorphic grade

- 3.2.1 Definition and role of index minerals

- 3.2.2 Common index minerals (chlorite, garnet, kyanite, sillimanite)

- 3.2.3 Metamorphic grade progression and facies interpretation

3.3 Microstructures in metamorphic rocks

- 3.3.1 Porphyroblasts and their significance

- 3.3.2 Granoblastic texture and recrystallisation features

- 3.3.3 Deformation microstructures (strain shadows, pressure solution, dynamic recrystallisation)

3.4 Applications of textures and minerals in geological interpretation

- 3.4.1 Using textures to infer pressure-temperature conditions

- 3.4.2 Using index minerals to reconstruct metamorphic history

- 3.4.3 Case studies linking textures and minerals to tectonic settings

Introduction

In the last Series, we examined the systematic study of metamorphic rocks, focusing on their processes, description, minerals, textures, and classification. Building on that foundation, this Series turns to the detailed study of metamorphic textures and minerals, which are essential for interpreting the conditions under which these rocks formed. Textures reveal the physical arrangement of minerals, while index minerals act as natural markers of metamorphic grade. Together, they provide powerful insights into the geological history recorded in metamorphic rocks.

The aim of this Series is to equip you with the ability to describe metamorphic textures, identify and interpret index minerals, analyze microstructures, and apply these features to reconstruct metamorphic conditions and tectonic settings.

We shall commence this Series by exploring the textural features of metamorphic rocks, beginning with the definition of texture and distinguishing between foliated and non-foliated types. Next, we will move on to index minerals and metamorphic grade, considering their role as indicators of pressure and temperature conditions. Following that, we will study microstructures such as porphyroblasts, granoblastic textures, and deformation features, which provide further evidence of metamorphic processes. Finally, we will wrap up by examining how textures and minerals are applied in geological interpretation, including case studies that link them to tectonic environments.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- SLO 3.1 define texture in metamorphic rocks and distinguish between foliated and non-foliated types,

- SLO 3.2 describe common foliated textures such as slaty cleavage, schistosity, and gneissic banding,

- SLO 3.3 explain non-foliated textures including granoblastic, massive, and crystalline forms,

- SLO 3.4 define index minerals and explain their role in determining metamorphic grade,

- SLO 3.5 identify common index minerals such as chlorite, garnet, kyanite, and sillimanite,

- SLO 3.6 analyze metamorphic grade progression and interpret facies using mineral assemblages,

- SLO 3.7 describes microstructures such as porphyroblasts, granoblastic textures, and deformation features,

- SLO 3.8 apply knowledge of textures and minerals to infer pressure–temperature conditions in metamorphic rocks, and

- SLO 3.9 evaluate case studies that link metamorphic textures and minerals to tectonic settings.

3.1 Textural Features of Metamorphic Rocks

3.1.1 Definition of texture in metamorphic rocks

Texture in metamorphic rocks refers to the size, shape, arrangement, and relationship of mineral grains within the rock. It provides important clues about the conditions under which the rock formed, including the pressure, temperature, and deformation history. Textures are often the first feature geologists examine when identifying metamorphic rocks in the field or laboratory.

Fill in the blank: The arrangement and relationship of mineral grains in a metamorphic rock is called its _______.

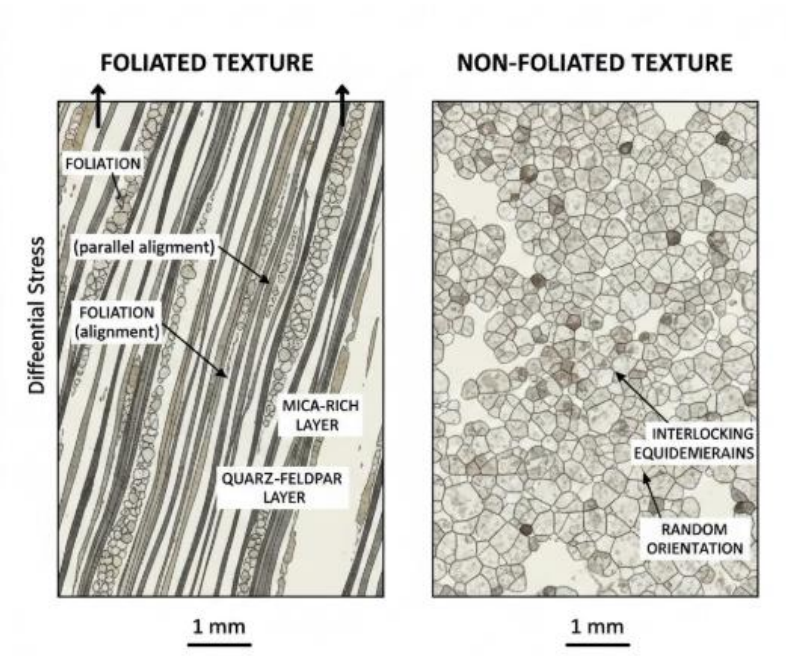

Figure 3.1: Basic textural features in metamorphic rocks

3.1.2 Foliated textures (slaty cleavage, schistosity, gneissic banding)

Foliated textures are characterized by the parallel alignment of minerals, giving the rock a layered or banded appearance. They form under directed pressure, which causes platy or elongated minerals to align.

- Slaty cleavage: Found in slate, this texture allows the rock to split easily into thin sheets.

- Schistosity: Found in schist, where larger platy minerals such as mica are aligned, giving the rock a shiny appearance.

- Gneissic banding: Found in gneiss, where light and dark minerals are segregated into distinct bands.

These textures are important because they reveal the intensity and direction of pressure during metamorphism.

Fill in the blank: The texture that allows slate to split into thin sheets is called ______ cleavage.

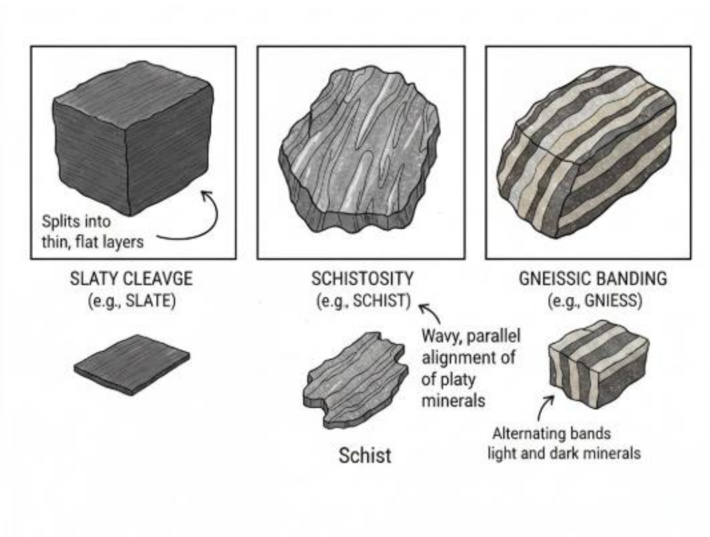

Figure 3.2: Types of foliated textures in metamorphic rocks

3.1.3 Non-foliated textures (granoblastic, massive, crystalline)

Non-foliated textures lack mineral alignment and appear massive or granular. They form under conditions where pressure is uniform or where the mineral composition prevents foliation.

- Granoblastic texture: Equidimensional grains formed by recrystallisation, common in quartzite and marble.

- Massive texture: Rocks appear homogeneous without visible layering, often seen in marble.

- Crystalline texture: Interlocking crystals that give the rock a dense and solid appearance.

Non-foliated textures are significant because they indicate uniform pressure or specific mineral compositions, such as calcite in marble or quartz in quartzite.

Fill in the blank: Quartzite and marble commonly display a _______ texture formed by equidimensional grains.

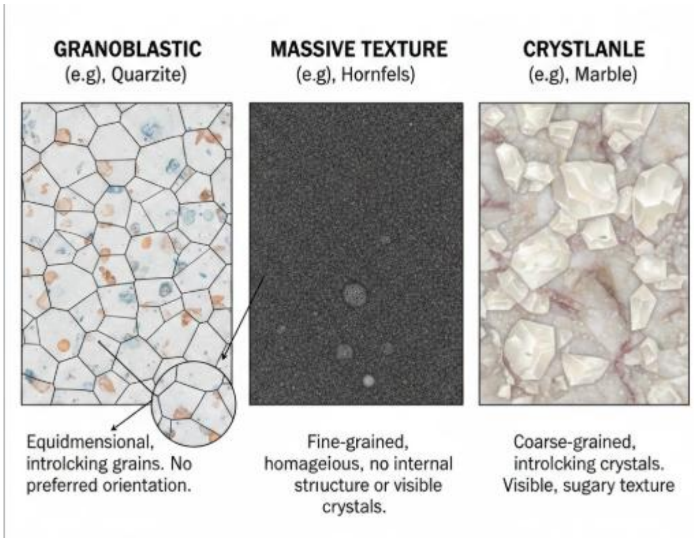

Figure 3.3: Types of non-foliated textures in metamorphic rocks

Pilot Questions 3.1

1. What does texture in metamorphic rocks refer to?
2. Name the three main types of foliated textures.
3. Which texture allows slate to split into thin sheets?
4. Give one example of a rock with granoblastic texture.
5. What conditions typically produce non-foliated textures?

3.2 Index Minerals and Metamorphic Grade

3.2.1 Definition and role of index minerals

Index minerals are minerals that form only under specific ranges of temperature and pressure during metamorphism. They are used by geologists to determine the metamorphic grade, which refers to the intensity of metamorphism experienced by a rock. Because each index mineral is stable only within a certain pressure–temperature window, their presence provides valuable clues about the conditions under which the rock formed.

Fill in the blank: Minerals that form under specific ranges of temperature and pressure during metamorphism are called _______ minerals.

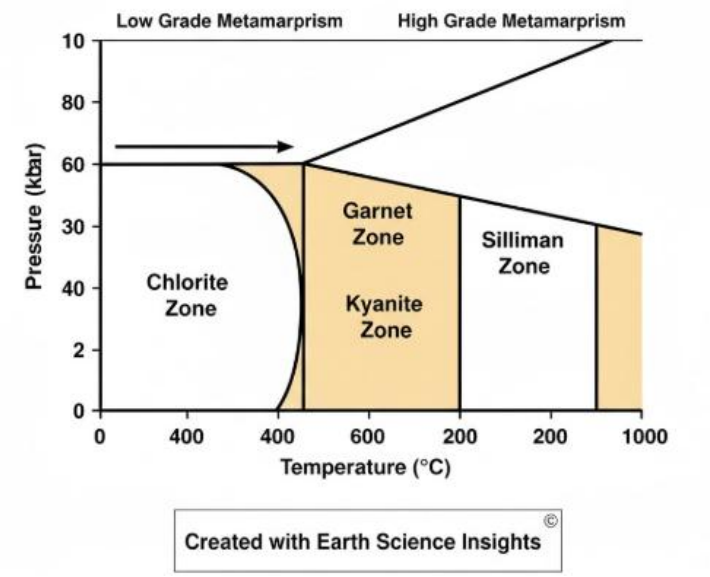

Figure 3.4: Stability ranges of index minerals in metamorphism

3.2.2 Common index minerals (chlorite, garnet, kyanite, sillimanite)

Several index minerals are widely recognized in metamorphic petrology:

- Chlorite: A green mineral that forms under low-grade metamorphism, typically in slates and phyllites.

- Garnet: A red to brown mineral that appears under medium-grade conditions, often in schists.

- Kyanite: A blue mineral stable under high-pressure conditions, commonly found in schists and gneisses.

- Sillimanite: A fibrous mineral that forms under high-grade metamorphism, marking intense heat and pressure.

These minerals act as natural markers of metamorphic grade and help geologists reconstruct the metamorphic history of rocks.

Fill in the blank: The blue mineral that indicates high-pressure metamorphic conditions is called _________.

Index Mineral	Metamorphic Grade	Temperature/Pressure Conditions	Geological Significance
Chlorite	Low Grade	Low (~200-400°C)	Marks the beginning of metamorphism (Greenschist facies). Common in slates.
Biotite	Low to Medium	Moderate (~300 -500°C)	Indicates increasing temperature; often found in phyllites and schists.
Garnet	Medium Grade	Moderate to High	Represents the transition to significant recrystallization. Key marker for schists.
Staurolite	Medium Grade	Moderate High	Often forms distinct "cross" crystals; indicates narrow, specific P-T ranges.
Kyanite	Medium to High	High Pressure, Moderate Temp	Indicates tectonic environments involving crustal thickening (e.g., mountain building).
Sillimanite	High Grade	High (>600°C)	Marks the upper limit of metamorphism before a rock begins to melt into magma.

Table 3.1: Common index minerals and their metamorphic significance

3.2.3 Metamorphic grade progression and facies interpretation

Metamorphic grade refers to the relative intensity of metamorphism, ranging from low-grade (mild conditions) to high-grade (intense heat and pressure). Rocks progress through grades as temperature and pressure increase, with characteristic index minerals marking each stage.

Closely related to grade is the concept of metamorphic facies, which are groups of mineral assemblages that form under specific pressure–temperature conditions. For example, the greenschist facies is characterized by chlorite and actinolite, while the amphibolite facies is marked by hornblende and plagioclase. Facies interpretation allows geologists to reconstruct the pressure–temperature path of a rock and understand the tectonic environment in which it formed.

Fill in the blank: The facies characterized by chlorite and actinolite is known as the _______ facies.

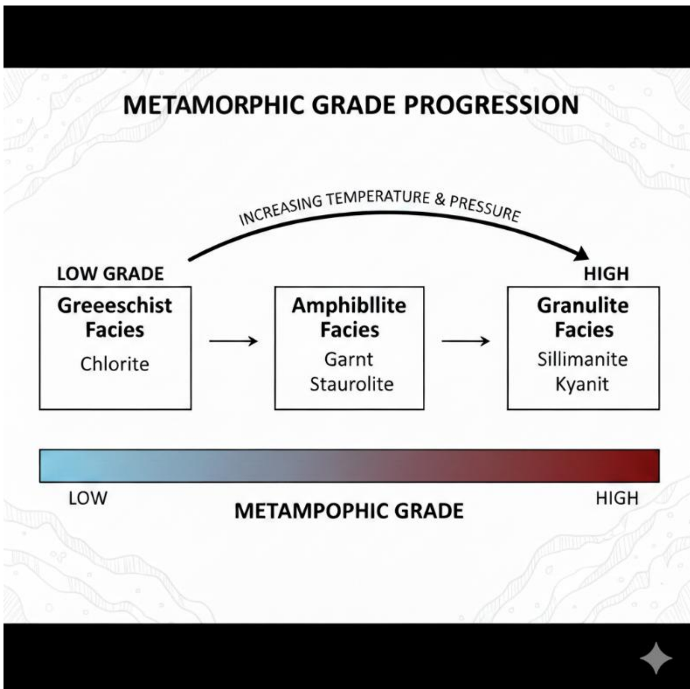

Figure 3.5: Metamorphic grade progression and facies interpretation

Pilot questions 3.2

1. What are index minerals and why are they important in metamorphic petrology?
2. Name two common index minerals and the metamorphic grade they represent.
3. Which mineral indicates high-pressure metamorphic conditions?
4. What does metamorphic grade refer to?
5. What is a metamorphic facies and how is it useful in geological interpretation?

3.3 Microstructures in Metamorphic Rocks

3.3.1 Porphyroblasts and their significance

Porphyroblasts are large crystals that grow within a finer-grained matrix during metamorphism. They often form later than the surrounding minerals and can contain inclusions that record earlier stages of the rock's history. Common porphyroblasts include garnet, staurolite, and kyanite. Their presence is significant because they provide clues about the pressure–temperature conditions and the sequence of mineral growth during metamorphism.

Fill in the blank: Large crystals that grow within a finer-grained matrix during metamorphism are called __________.

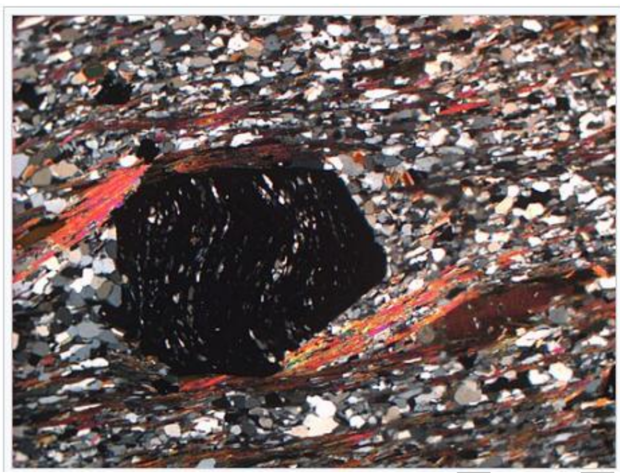

Plate 3.1: Garnet porphyroblast in a metamorphic rock thin section

3.3.2 Granoblastic texture and recrystallisation features

Granoblastic texture refers to an equidimensional arrangement of mineral grains formed by recrystallisation under uniform pressure. It is typical of non-foliated metamorphic rocks such as marble and quartzite. Recrystallisation eliminates pre-existing structures and produces interlocking grains that enhance the strength and durability of the rock.

Fill in the blank: The equidimensional arrangement of mineral grains formed by recrystallisation is called ________ texture.

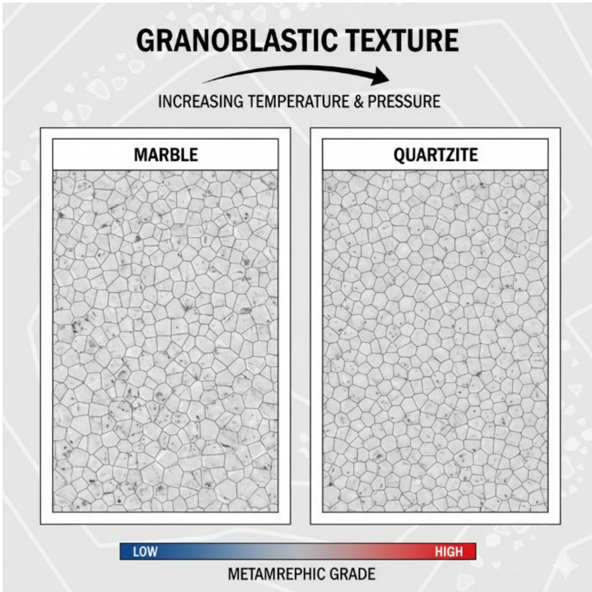

Figure 3.6: Granoblastic texture in metamorphic rocks

3.3.3 Deformation microstructures (strain shadows, pressure solution, dynamic recrystallisation)

Metamorphic rocks often display deformation microstructures, which are small-scale features formed under stress.

- Strain shadows: Areas around porphyroblasts where minerals grow in response to stress, forming distinctive patterns.

- Pressure solution: A process where minerals dissolve at points of high stress and reprecipitate in areas of lower stress, leading to elongated grains.

- Dynamic recrystallisation: The formation of new grains during deformation, often producing fine-grained textures in rocks such as mylonite.

These microstructures are important because they record the deformation history of rocks and help geologists interpret tectonic processes.

Fill in the blank: The process where minerals dissolve at points of high stress and reprecipitate elsewhere is called________.

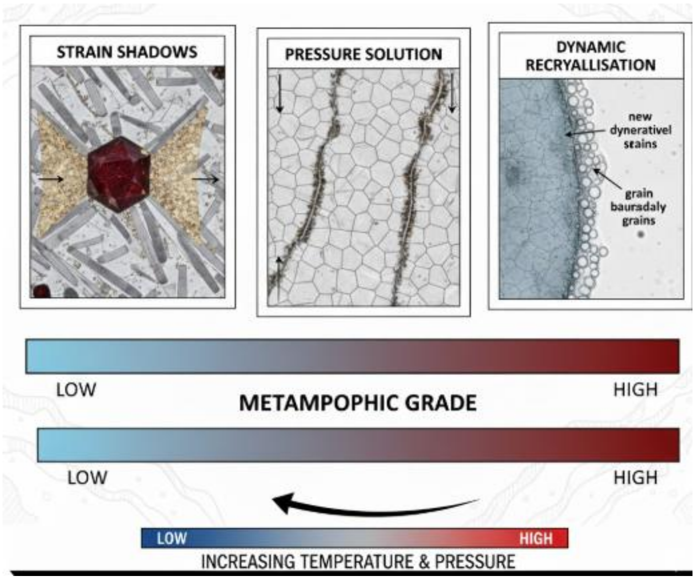

Figure 3.7: Common deformation microstructures in metamorphic rocks

Pilot questions 3.3

1. What are porphyroblasts and why are they significant in metamorphic rocks?
2. Which texture is typical of marble and quartzite?
3. What does granoblastic texture indicate about pressure conditions?
4. Name two common deformation microstructures in metamorphic rocks.
5. What process involves minerals dissolving under stress and reprecipitating elsewhere?

3.4 Applications of Textures and Minerals in Geological Interpretation

3.4.1 Using textures to infer pressure–temperature conditions

Metamorphic textures provide important evidence about the conditions under which rocks formed. Foliated textures such as schistosity and gneissic banding indicate directed pressure, while non-foliated textures such as granoblastic structures suggest uniform pressure. By studying these textures, geologists can reconstruct the pressure–temperature environment of metamorphism.

Fill in the blank: Foliated textures such as schistosity usually indicate the presence of ______ pressure during metamorphism.

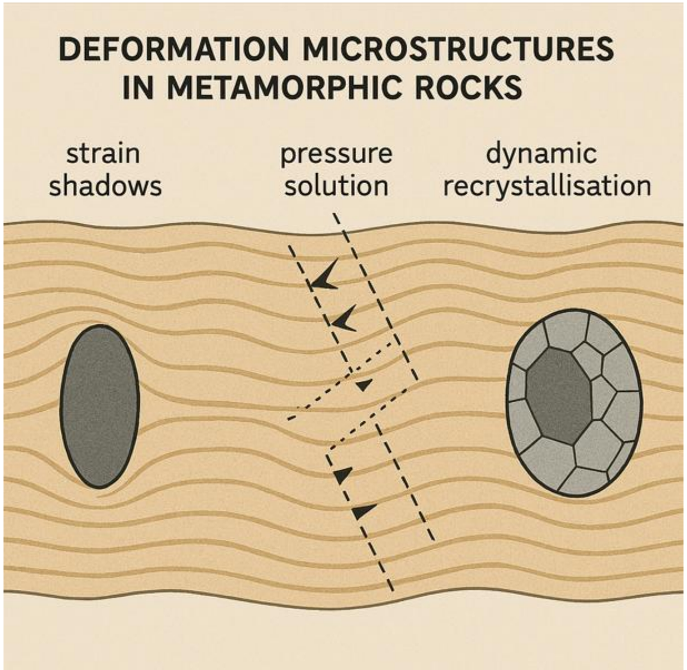

Figure 3.8: Textural evidence of metamorphic conditions

3.4.2 Using index minerals to reconstruct metamorphic history

Index minerals such as chlorite, garnet, kyanite, and sillimanite act as natural markers of metamorphic grade. Their presence allows geologists to determine the sequence of metamorphic events and the intensity of metamorphism. For example, garnet-bearing schists indicate medium-grade conditions, while sillimanite-bearing gneisses point to high-grade metamorphism. By mapping the distribution of index minerals across a region, geologists can reconstruct the metamorphic history and understand the tectonic processes involved.

Fill in the blank: The presence of sillimanite in a rock indicates -grade metamorphism.

Index Mineral	**Metamorphic Grade**	**Temperature/Pressure Context**	**Geological Application**
Chlorite	Low (Greenschist)	~200–400°C	Identifying the onset of metamorphism in pelitic (shale-derived) rocks.

Index Mineral	Metamorphic Grade	Temperature/Pressure Context	Geological Application
Biotite	Low to Medium	~300–450°C	Marking the transition from low-grade slate to more crystalline phyllite/schist.
Garnet (Almandine)	Medium	~450–600°C	Defining the "Garnet Zone"; used in geothermobarometry to calculate specific $P-T$ conditions.
Staurolite	Medium-High	~550–650°C	Key indicator of intermediate-pressure metamorphism in mountain-building (orogenic) belts.
Kyanite	High	High Pressure (P), Moderate Temp (T)	Indicating deep crustal thickening and subduction-related environments.
Sillimanite	Very High	>600°C, High Temp	Marking the highest grade of regional metamorphism before the rock begins to melt (migmatite).

Table 3.2: Index minerals and their geological applications

3.4.3 Case studies linking textures and minerals to tectonic settings

Textures and minerals are not only useful for identifying metamorphic grade but also for interpreting tectonic settings. Regional metamorphism with foliated textures is often associated with mountain-building events, while high-pressure minerals such as kyanite may indicate subduction zones. Non-foliated rocks such as marble and quartzite often form in stable continental interiors where uniform pressure dominates. Case studies from mountain belts, subduction zones, and continental shields demonstrate how textures and minerals provide insights into Earth's tectonic evolution.

Fill in the blank: High-pressure minerals such as kyanite are commonly associated with _______ zones.

Case Study: Metamorphic minerals in the Himalayas

The Himalayan Orogeny provides a world-class laboratory for observing how minerals and textures record the collision between the Indian and Eurasian plates. By analyzing **index minerals** and **deformation microstructures**, geologists have reconstructed the "P-T-t" (Pressure-Temperature-time) paths of rocks buried 50+ km deep.

1. Inverted Metamorphism

In a standard geological setting, metamorphic grade increases with depth. However, in the **Main Central Thrust (MCT)** zone of the Himalayas, the sequence is "inverted."

- **The Observation:** Lower-grade rocks (Chlorite/Biotite) are found at the bottom, while higher-grade rocks (Kyanite/Sillimanite) sit on top.
- **The Tectonic Reveal:** This proves massive **tectonic placing**, where hot, deep-crustal slabs were thrust over cooler, shallower rocks, transferring heat downward.

2. Pressure-Sensitive Index Minerals

The presence of specific aluminosilicates (Al_2SiO5 polymorphs) reveals the depth of the collision:

- **Kyanite:** Indicates the high-pressure conditions of initial crustal thickening.
- **Sillimanite:** Found in the **Greater Himalayan Sequence**, indicating subsequent extreme heating (>700°C) and the beginning of partial melting (**anatexis**), which formed the region's famous leucogranites.

3. Microstructures & Exhumation

The textures within these rocks act as a "flight recorder" for their journey back to the surface:

- **Garnet Porphyroblasts:** Often show "snowball" textures (rotated inclusions), recording the shear sense of the thrusting as the mountains rose.
- **Strain Shadows:** Developed around rigid garnets, these provide the direction of stretching during the mountain-building process.
- **Reaction Rims:** You might see **Kyanite** being replaced by **Sillimanite**, a clear sign of "decompression", the rock moving rapidly from high pressure (deep) to lower pressure (shallow).

Box 3.1: Case study – Metamorphic minerals in the Himalayas

The Himalayas provide an excellent example of how index minerals and textures reveal tectonic processes. Garnet-bearing schists indicate medium-grade metamorphism during mountain building, while sillimanite-bearing gneisses mark high-grade conditions at deeper crustal levels. Together, these features record the intense pressure–temperature history of continental collision.

Pilot questions 3.4

1. What do foliated textures reveal about pressure conditions during metamorphism?

2. Which index mineral indicates high-grade metamorphism?

3. How can mapping index minerals help reconstruct metamorphic history?

4. Name one tectonic setting where high-pressure minerals such as kyanite are found.

5. Give an example of a non-foliated metamorphic rock and the tectonic environment where it commonly forms.

Series Summary

This Series has focused on the study of metamorphic textures and index minerals, highlighting their importance in interpreting the conditions under which rocks form and evolve. Textures reveal the arrangement of minerals and the influence of pressure and temperature, while index minerals act as natural markers of metamorphic grade. Together, they provide geologists with powerful tools to reconstruct the metamorphic history of rocks and understand their tectonic significance.

We began by examining textural features, distinguishing between foliated and non-foliated types. Then we explored index minerals such as chlorite, garnet, kyanite, and sillimanite, linking them to metamorphic grade and facies. Following that, we studied microstructures including porphyroblasts, granoblastic textures, and deformation features, which record the pressure–temperature path and stress history of rocks. Finally, we considered how porphyroblasts, granoblastic textures, and deformation features, which record the pressure–temperature path and stress history of rocks. Finally, we considered how textures and minerals are applied in geological interpretation, including case studies that connect them to tectonic settings. By completing this Series, you should now be able to describe metamorphic textures (SLO 3.1–3.3), explain the role of index minerals (SLO 3.4–3.6), analyse microstructures (SLO 3.7), and apply these features to infer metamorphic conditions and tectonic environments (SLO 3.8–3.9).

Glossary of Terms

Chlorite: A green mineral that forms under low-grade metamorphism and serves as an index mineral.

Crystalline texture: A non-foliated texture where mineral crystals interlock, giving the rock a dense and solid appearance.

Dynamic recrystallisation: The process whereby new mineral grains form during deformation, often producing fine-grained textures.

Foliation: The alignment of minerals in metamorphic rocks caused by direct pressure, giving the rock a layered appearance.

Garnet: A red to brown mineral that appears under medium-grade metamorphism and is commonly found in schists.

Gneissic banding: A foliated texture where light and dark minerals are segregated into distinct bands.

Granoblastic texture: An equidimensional arrangement of mineral grains formed by recrystallisation under uniform pressure.

Index minerals: Minerals that form under specific ranges of temperature and pressure, used to determine metamorphic grade.

Kyanite: A blue mineral stable under high-pressure conditions, often found in schists and gneisses.

Massive texture: A non-foliated texture where the rock appears homogeneous without visible layering.

Metamorphic facies: Groups of mineral assemblages that form under specific pressure–temperature conditions, used to interpret metamorphic environments.

Metamorphic grade: A measure of the intensity of metamorphism, ranging from low-grade to high-grade conditions.

Porphyroblasts: Large crystals that grow within a finer-grained matrix during metamorphism, often recording earlier stages of mineral growth.

Pressure solution: A process where minerals dissolve at points of high stress and reprecipitate in areas of lower stress.

Schistosity: A foliated texture in schist where platy minerals such as mica are aligned, giving the rock a shiny appearance.

Sillimanite: A fibrous mineral that forms under high-grade metamorphism, marking intense heat and pressure.

Slaty cleavage: A foliated texture in slate that allows the rock to split easily into thin sheets.

Strain shadows: Areas around porphyroblasts where minerals grow in response to stress, forming distinctive patterns.

Texture: The arrangement, size, and relationship of mineral grains in a metamorphic rock, reflecting its formation conditions.

Concept Check Questions [Series 3]

Objective Questions

1. The arrangement and relationship of mineral grains in a metamorphic rock is called its . (Linked to SLO 3.1)

2. Which foliated texture allows slate to split into thin sheets? (Linked to SLO 3.2)

3. Garnet is an index mineral that typically indicates -grade metamorphism. (Linked to SLO 3.5)

4. The fibrous mineral that marks high-grade metamorphism is . (Linked to SLO 3.5)

5. High-pressure minerals such as kyanite are commonly associated with zones. (Linked to SLO 3.9)

Short-Answer Questions

6. Define metamorphic texture and explain its significance. (Linked to SLO 3.1)

7. Distinguish between schistosity and gneissic banding. (Linked to SLO 3.2)

8. Identify two non-foliated textures and the rocks in which they are commonly found. (Linked to SLO 3.3)

9. Explain the role of index minerals in determining metamorphic grade. (Linked to SLO 3.4)

10. What is a metamorphic facies and why is it important in geological interpretation? (Linked to SLO 3.6)

11. Describe porphyroblasts and their geological significance. (Linked to SLO 3.7)

Long-Answer Questions

12. Analyse how textures can be used to infer pressure–temperature conditions during metamorphism. (Linked to SLO 3.8)

13. Evaluate the progression of metamorphic grade using index minerals, providing examples of minerals at different grades. (Linked to SLO 3.6)

14. Discuss the importance of deformation microstructures in reconstructing tectonic processes. (Linked to SLO 3.7, 3.9)

15. Apply knowledge of textures and minerals to interpret a tectonic setting, using a case study such as the Himalayas. (Linked to SLO 3.9)

Answers to Concept Check Questions [Series 3]

Objective Questions

1. Texture.

2. Slaty cleavage.

3. Medium-grade.

4. Sillimanite.

5. Subduction zones.

Short-Answer Questions

6. Metamorphic texture refers to the size, shape, arrangement, and relationship of mineral grains. It is significant because it reveals the conditions under which the rock formed.

7. Schistosity is the alignment of platy minerals such as mica, giving schist a shiny appearance, while gneissic banding is the segregation of light and dark minerals into distinct bands.

8. Granoblastic texture in quartzite and marble; massive texture in marble.

9. Index minerals form under specific ranges of temperature and pressure, allowing geologists to determine metamorphic grades.

10. A metamorphic facies is a group of mineral assemblages that form under specific pressure–temperature conditions. It is important because it helps reconstruct metamorphic environments.

11. Porphyroblasts are large crystals that grow within a finer-grained matrix, recording earlier stages of mineral growth and providing clues about metamorphic conditions.

Long-Answer Questions

12. Basic response: Textures such as foliation indicate directed pressure, while non-foliated textures suggest uniform pressure. These features help geologists infer the pressure–temperature conditions during metamorphism.

Value-added response: Detailed analysis of textures, combined with microstructural evidence, allows reconstruction of pressure–temperature paths and deformation histories, linking rocks to specific tectonic environments.

13. Basic response: Index minerals mark different grades of metamorphism. Chlorite indicates low-grade, garnet medium-grade, and sillimanite high-grade conditions.

Value-added response: By mapping index minerals across regions, geologists can reconstruct metamorphic facies and pressure–temperature paths, providing insights into tectonic evolution.

14. Basic response: Deformation microstructures such as strain shadows, pressure solution, and dynamic recrystallisation record stress conditions and deformation history.

Value-added response: These microstructures reveal mechanisms of crustal deformation, such as subduction or continental collision, and help geologists interpret large-scale tectonic processes.

15. Basic response: In the Himalayas, garnet-bearing schists indicate medium-grade metamorphism, while sillimanite-bearing gneisses mark high-grade conditions. These features reflect continental collision.

Value-added response: Case studies show how textures and minerals can be integrated with structural geology and geochronology to reconstruct the tectonic evolution of mountain belts, providing a holistic view of Earth's dynamic processes.

Answers to Pilot Questions [Series 3]

Part 3.1: Textural features of metamorphic rocks

1. Texture.

2. Slaty cleavage, schistosity, and gneissic banding.

3. Slaty cleavage.

4. Quartzite.

5. Uniform pressure.

Part 3.2: Index minerals and metamorphic grade

1. Index minerals are minerals that form under specific ranges of temperature and pressure, used to determine metamorphic grade.

2. Chlorite (low-grade) and garnet (medium-grade).

3. Kyanite.

4. The intensity of metamorphism.

5. A metamorphic facies is a group of mineral assemblages that form under specific pressure–temperature conditions, useful for interpreting metamorphic environments.

Part 3.3: Microstructures in metamorphic rocks

1. Porphyroblasts are large crystals that grow within a finer-grained matrix, significant because they record metamorphic conditions and growth history.

2. Granoblastic texture.

3. Uniform pressure.

4. Strain shadows and pressure solution.

5. Pressure solution.

Part 3.4: Applications of textures and minerals in geological interpretation

1. Directed pressure.

2. Sillimanite.

3. By mapping index minerals, geologists can reconstruct the metamorphic history and intensity of metamorphism.

4. Subduction zones.

5. Marble, commonly formed in stable continental interiors.

References and Attributions [Series 3]

All references and attributions listed below correspond to the instructional content, illustrations, and open educational resources (OERs) suggested in Series 3: Metamorphic Textures and Index Minerals. The referencing style used here follows APA guidelines for clarity and consistency.

General References

- Yardley, B. W. D. (1989). An Introduction to Metamorphic Petrology. Longman Scientific & Technical.

- Winter, J. D. (2010). Principles of Igneous and Metamorphic Petrology (2nd ed.). Pearson Education.

- Marshak, S. (2019). Earth: Portrait of a Planet (6th ed.). W. W. Norton & Company.

- Open Educational Resources (OER) Commons. (n.d.). Retrieved from https://www.oercommons.org

Illustrations

Figure 3.1: Basic textural features in metamorphic rocks

- AI-generated suggestion: "Generate a labelled diagram showing mineral grains in foliated and non-foliated metamorphic textures."

- Suggested OER search string: "OER diagram metamorphic rock textures foliated non-foliated."

Figure 3.2: Types of foliated textures in metamorphic rocks

- AI-generated suggestion: "Create a diagram illustrating slaty cleavage, schistosity, and gneissic banding with labelled examples."

- Suggested OER search string: "OER diagram foliated textures slate schist gneiss."

Figure 3.3: Types of non-foliated textures in metamorphic rocks

- AI-generated suggestion: "Generate a diagram comparing granoblastic, massive, and crystalline textures in metamorphic rocks."

- Suggested OER search string: “OER diagram non-foliated metamorphic textures quartzite marble.”

Plate 3.1: Garnet porphyroblast in a metamorphic rock thin section

- AI-generated suggestion: “Generate an image of a thin section of schist showing a garnet porphyroblast with mineral inclusions.”

- Suggested OER search string: “OER image thin section garnet porphyroblast schist.”

Figure 3.6: Granoblastic texture in metamorphic rocks

- AI-generated suggestion: “Create a diagram illustrating granoblastic texture with equidimensional grains in marble and quartzite.”

- Suggested OER search string: “OER diagram granoblastic texture marble quartzite metamorphism.”

Figure 3.7: Common deformation microstructures in metamorphic rocks

- AI-generated suggestion: “Generate a diagram showing strain shadows, pressure solution, and dynamic recrystallisation in metamorphic rocks.”

- Suggested OER search string: “OER diagram deformation microstructures strain shadows pressure solution dynamic recrystallisation.”

Figure 3.4: Stability ranges of index minerals in metamorphism

- AI-generated suggestion: “Generate a labelled diagram showing index minerals (chlorite, garnet, kyanite, sillimanite) plotted against temperature and pressure conditions.”

- Suggested OER search string: “OER diagram index minerals metamorphism temperature pressure stability.”

Table 3.1: Common index minerals and their metamorphic significance

- AI-generated suggestion: “Create a table showing common index minerals, their metamorphic grade, and geological significance.”

- Suggested OER search string: “OER table index minerals metamorphic grade chlorite garnet kyanite sillimanite.”

Figure 3.5: Metamorphic grade progression and facies interpretation

- AI-generated suggestion: “Generate a diagram showing metamorphic grade progression from low-grade to high-grade with associated facies and index minerals.”

- Suggested OER search string: “OER diagram metamorphic grade progression facies chlorite garnet sillimanite.”

Figure 3.8: Textural evidence of metamorphic conditions

- AI-generated suggestion: “Generate a diagram showing foliated and non-foliated textures with their associated pressure–temperature conditions.”

- Suggested OER search string: “OER diagram metamorphic textures pressure temperature conditions.”

Table 3.2: Index minerals and their geological applications

- AI-generated suggestion: “Create a table showing index minerals, their metamorphic grade, and geological applications.”

- Suggested OER search string: “OER table index minerals metamorphic grade geological applications.”

Box 3.1: Case study – Metamorphic minerals in the Himalayas

- AI-generated suggestion: “Create a case study box summarising how index minerals and textures reveal tectonic processes in the Himalayas.”

- Suggested OER search string: “OER case study metamorphic minerals Himalayas tectonic processes.”

Course Code: GEY 203

Course title: Introduction to Petrology

Units: 2 Units

List of Series

Series 1: Foundations of Igneous Petrology

Series 2: Systematic Study of Metamorphic Rocks

Series 3: Textures and Minerals in Metamorphism

Series 4: Introduction to Sedimentary Petrology

Series 5: Classification of Igneous, Metamorphic, and Sedimentary Rocks

4.1 Sedimentary processes and environments

- 4.1.1 Definition of sedimentary processes
- 4.1.2 Weathering, erosion, transport, and deposition
- 4.1.3 Sedimentary environments (continental, transitional, marine)

4.2 Sedimentary textures and structures

- 4.2.1 Grain size, shape, and sorting
- 4.2.2 Porosity and permeability
- 4.2.3 Sedimentary structures (bedding, cross-bedding, ripple marks, graded bedding)

4.3 Sedimentary minerals and rock types

- 4.3.1 Common minerals in sedimentary rocks (quartz, feldspar, calcite, clay minerals)
- 4.3.2 Clastic rocks (sandstone, shale, conglomerate)
- 4.3.3 Chemical and biochemical rocks (limestone, dolomite, chert, coal)

4.4 Applications of sedimentary petrology

- 4.4.1 Sedimentary rocks as archives of Earth history
- 4.4.2 Economic importance (hydrocarbons, building materials, groundwater reservoirs)
- 4.4.3 Case studies linking sedimentary rocks to past environments

Introduction

Sedimentary rocks make up most of the Earth's surface and hold vital clues to its past environments, resources, and life. From the sand on a beach to the limestone used in construction, sedimentary materials are part of our everyday experience. In geology, they are especially important because they preserve evidence of weathering, transport, and deposition, as well as fossils that record the history of life. This Series introduces you to the foundations of sedimentary petrology, building on the knowledge gained in earlier studies of igneous and metamorphic rocks.

The aim of this Series is to provide you with a clear understanding of sedimentary processes, textures, minerals, and rock types, and to show how these features are applied in interpreting Earth's history and resources.

We shall commence this Series by exploring sedimentary processes and environments, considering how weathering, erosion, transport, and deposition shape rocks and landscapes. Next, we will examine sedimentary textures and structures, focusing on grain size, sorting, porosity, and features such as bedding and ripple marks. Following that, we will study sedimentary minerals and rock types, including clastic, chemical, and biochemical varieties. Finally, we will wrap up by looking at the applications of sedimentary petrology, highlighting how sedimentary rocks serve as archives of Earth history, as well as their economic importance and case studies linking them to past environments.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- SLO 4.1 define sedimentary processes and explain their role in shaping rocks and landscapes,

- SLO 4.2 describe the main sedimentary environments including continental, transitional, and marine settings,

- SLO 4.3 analyze sedimentary textures by assessing grain size, shape, and sorting,

- SLO 4.4 explain the concepts of porosity and permeability in relation to sedimentary rocks,

- SLO 4.5 identify and describe common sedimentary structures such as bedding, cross-bedding, ripple marks, and graded bedding,

- SLO 4.6 identify common minerals found in sedimentary rocks including quartz, feldspar, calcite, and clay minerals,

- SLO 4.7 classify clastic sedimentary rocks such as sandstone, shale, and conglomerate,

- SLO 4.8 distinguish chemical and biochemical sedimentary rocks including limestone, dolomite, chert, and coal,

- SLO 4.9 apply knowledge of sedimentary textures, minerals, and structures to interpret Earth's history,

- SLO 4.10 evaluate the economic importance of sedimentary rocks in relation to hydrocarbons, building materials, and groundwater reservoirs, and

- SLO 4.11 analyze case studies that link sedimentary rocks to past environments and tectonic settings.

4.1 Sedimentary Processes and Environments

4.1.1 Definition of sedimentary processes

Sedimentary processes are the natural mechanisms by which rocks are broken down, transported, deposited, and transformed into sedimentary rocks. These processes include weathering, erosion, transport, deposition, and lithification. They are fundamental to sedimentary petrology because they explain how sediments originate and how they record Earth's surface conditions.

Fill in the blank: The natural mechanisms that break down, transport, and deposit sediments are called ________ processes.

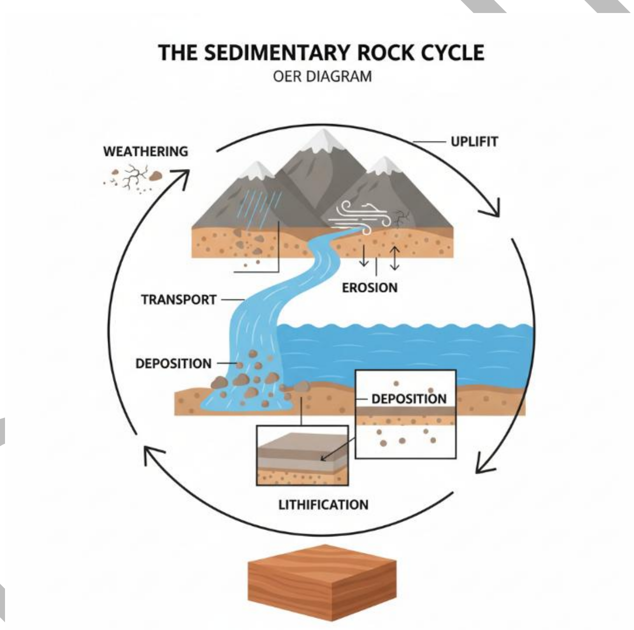

Figure 4.1: The sedimentary cycle of processes

4.1.2 Weathering, erosion, transport, and deposition

Weathering is the breakdown of rocks at Earth's surface through physical, chemical, or biological means. Erosion is the removal of weathered material by agents such as water, wind, or ice. Transport refers to the movement of sediments by these agents, while deposition occurs when sediments settle out of the transporting medium. Together, these processes determine the characteristics of sediments, including their size, shape, and sorting.

Fill in the blank: The removal of weathered material by water, wind, or ice is known as _____.

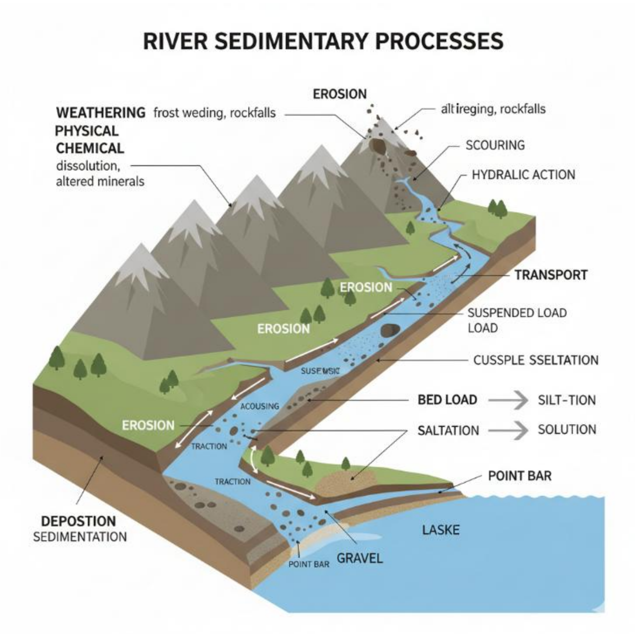

Figure 4.2: Sediment movement from source to basin

4.1.3 Sedimentary environments (continental, transitional, marine)

A sedimentary environment is a specific setting where sediments are deposited, characterized by physical, chemical, and biological conditions. These environments are broadly classified into:

- Continental environments: Include rivers, lakes, deserts, and glaciers. Sediments here are often coarse-grained and show features like cross-bedding or mud cracks.

- Transitional environments: Occur at the boundary between land and sea, such as deltas, beaches, and lagoons. Sediments here are influenced by both terrestrial and marine processes.

- Marine environments: Range from shallow continental shelves to deep ocean basins. Sediments include carbonates, muds, and turbidites, often preserving fossils.

Fill in the blank: Sediments deposited at the boundary between land and sea belong to_______ environments.

Category	Environment	Common Sediments	Distinguishing Features
Continental (Non-marine)	**Fluvial** (Rivers)	Sand, gravel, silt	Asymmetric ripples, cross-bedding, channel-shaped deposits, fining-upward sequences.
	Lacustrine (Lakes)	Fine silt, clay, mud	Thin laminations (varves), freshwater fossils, mudcracks at edges.
	Aeolian (Deserts)	Well-sorted sand, silt	Large-scale cross-bedding (dunes), frosted sand grains, very little organic matter.
	Glacial	"Till" (unsorted mix of clay to boulders)	Poorly sorted, non-stratified, striated (scratched) pebbles and bedrock.
	Alluvial Fan	Coarse gravel, sand, boulders	Wedge-shaped deposits at mountain bases, poorly sorted at the top, better sorted at the base.
Transitional (Marginal)	**Deltaic**	Silt, sand, clay, organic matter	Fan-shaped, "topset/foreset/bottomset" bedding, mix of terrestrial and marine fossils.
	Beach / Barrier Island	Well-sorted sand, gravel	Symmetrical wave ripples, cross-bedding, marine shells, high energy.

Category	Environment	Common Sediments	Distinguishing Features
	Lagoonal	Carbonate mud, silt, clay	Laminated fine sediments, brackish-water fossils, low energy.
	Tidal Flat	Mud, sand	Mudcracks, bidirectional (herringbone) cross-bedding, flaser bedding.
Marine (Oceanic)	**Shallow Marine** (Shelf)	Sand, silt, mud, carbonates	Extensive bioturbation (burrows), ripple marks, diverse marine fossils (corals, mollusks).
	Deep Marine (Abyssal)	Fine clay, volcanic ash, oozes	Very thin, uniform beds, manganese nodules, microscopic plankton fossils (chert/chalk).
	Submarine Fan (Slope/Rise)	Graded sand and mud	**Turbidites** (Bouma sequences), graded bedding (coarse at bottom, fine at top).
	Reef	Skeletal carbonate (coral/algae)	Massive limestone structures, "boundstone" textures, and high fossil density.

Table 4.1: Characteristics of major sedimentary environments

Pilot questions 4.1

1. What are sedimentary processes?

2. Name the four main processes that shape sediments before lithification.

3. What is the removal of weathered material by water, wind, or ice called?

4. Give two examples of continental sedimentary environments.

5. Which type of environment occurs at the boundary between land and sea?

4.2 Sedimentary Textures and Structures

4.2.1 Grain size, shape, and sorting

Grain size refers to the diameter of individual sediment particles, ranging from clay (very fine) to gravel (coarse). It is a key property used to classify clastic sedimentary rocks. Grain shapes describe whether particles are angular or rounded, reflecting the distance and intensity of transport. Sorting refers to the uniformity of grain sizes within a sediment, with well-sorted sediments having grains of similar size and poorly sorted sediments containing a wide range. These properties provide important clues about the energy and environment of deposition.

Fill in the blank: Sediments with grains of similar size are described as being _______.

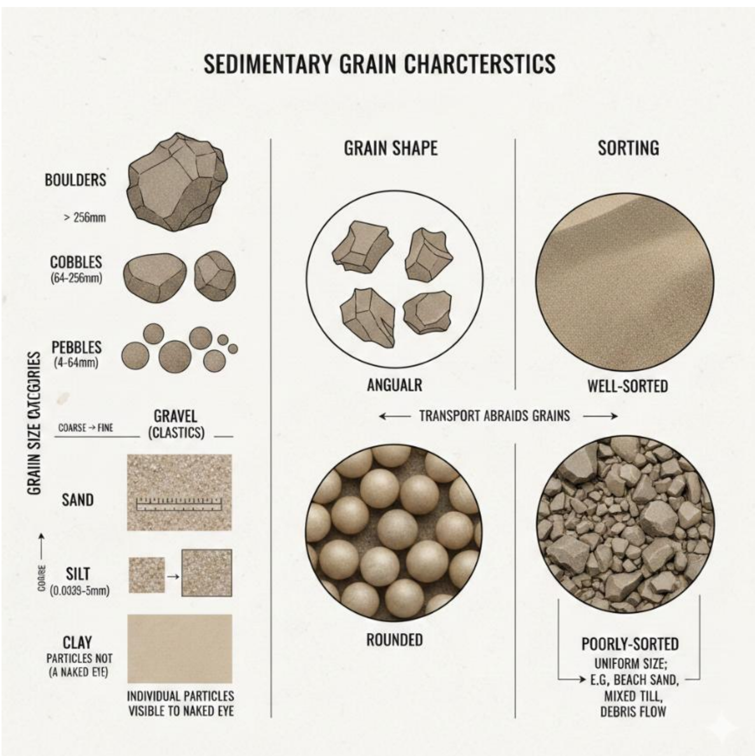

Figure 4.3: Grain size, shape, and sorting in sediments

4.2.2 Porosity and permeability

Porosity is the percentage of void spaces between grains in a sediment or rock. It determines how much fluid a rock can store. Permeability is the ability of a rock to transmit fluids through its pore spaces. Together, these properties are crucial for understanding groundwater reservoirs and hydrocarbon storage. Well-sorted, rounded grains usually increase porosity and permeability, while poorly sorted sediments reduce them.

Fill in the blank: The ability of a rock to transmit fluids through its pore spaces is called ___.

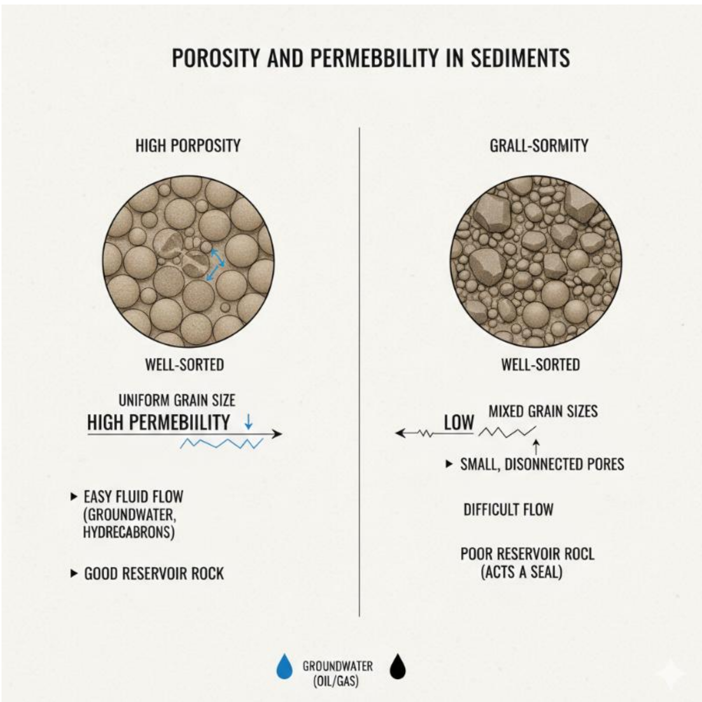

Figure 4.4: Porosity and permeability in sedimentary rocks

4.2.3 Sedimentary structures (bedding, cross-bedding, ripple marks, graded bedding)

Sedimentary structures are physical features formed during or shortly after deposition. They provide evidence of depositional processes and environments.

- Bedding: Layers of sediment that accumulate over time, forming stratification.

- Cross-bedding: Inclined layers within beds, formed by currents or wind, indicating flow direction.

- Ripple marks: Small ridges formed by water or wind movement, useful for interpreting shallow environments.

- Graded bedding: Layers where grain size decreases from bottom to top, often formed by turbidity currents.

These structures are essential for interpreting past environments and reconstructing depositional histories.

Fill in the blank: Layers where grain size decreases from bottom to top are known as _______ bedding.

Category	Environment	Common Sediments	Distinguishing Features
Continental (Non-marine)	**Fluvial** (Rivers)	Sand, gravel, silt	Asymmetric ripples, cross-bedding, channel-shaped deposits, fining-upward sequences.
	Lacustrine (Lakes)	Fine silt, clay, mud	Thin laminations (varves), freshwater fossils, mudcracks at edges.
	Aeolian (Deserts)	Well-sorted sand, silt	Large-scale cross-bedding (dunes), frosted sand grains, very little organic matter.
	Glacial	"Till" (unsorted mix of clay to boulders)	Poorly sorted, non-stratified, striated (scratched) pebbles and bedrock.
	Alluvial Fan	Coarse gravel, sand, boulders	Wedge-shaped deposits at mountain bases, poorly sorted at the top, better sorted at the base.
Transitional (Marginal)	**Deltaic**	Silt, sand, clay, organic matter	Fan-shaped, "topset/foreset/bottomset" bedding, mix of terrestrial and marine fossils.
	Beach / Barrier Island	Well-sorted sand, gravel	Symmetrical wave ripples, cross-bedding, marine shells, high energy.

Category	Environment	Common Sediments	Distinguishing Features
	Lagoonal	Carbonate mud, silt, clay	Laminated fine sediments, brackish-water fossils, low energy.
	Tidal Flat	Mud, sand	Mudcracks, bidirectional (herringbone) cross-bedding, flaser bedding.
Marine (Oceanic)	**Shallow Marine** (Shelf)	Sand, silt, mud, carbonates	Extensive bioturbation (burrows), ripple marks, diverse marine fossils (corals, mollusks).
	Deep Marine (Abyssal)	Fine clay, volcanic ash, oozes	Very thin, uniform beds, manganese nodules, microscopic plankton fossils (chert/chalk).
	Submarine Fan (Slope/Rise)	Graded sand and mud	**Turbidites** (Bouma sequences), graded bedding (coarse at bottom, fine at top).
	Reef	Skeletal carbonate (coral/algae)	Massive limestone structures, "boundstone" textures, high fossil density.

Figure 4.5: Common sedimentary structures

Pilot questions 4.2

1. What three properties are used to describe sedimentary texture?

2. What term describes sediments with grains of similar size?

3. What is the difference between porosity and permeability?

4. Name two common sedimentary structures formed by currents or water movement.

5. Which sedimentary structure shows a decrease in grain size from bottom to top?

4.3 Sedimentary Minerals and Rock Types

4.3.1 Common minerals in sedimentary rocks

Sedimentary rocks are composed of a variety of minerals, many of which are stable at Earth's surface conditions. The most common include:

- Quartz: A hard, chemically resistant mineral that dominates many sandstones.
- Feldspar: Less stable than quartz, but present in arkosic sandstones.
- Calcite: A carbonate mineral that forms limestones and reacts readily with dilute acid.
- Clay minerals: Fine-grained minerals such as kaolinite and illite, which form shales and mudstones.

These minerals are important because they reflect the source rocks and the chemical environment of deposition.

Fill in the blank: The mineral that dominates many sandstones due to its hardness and chemical resistance is ________.

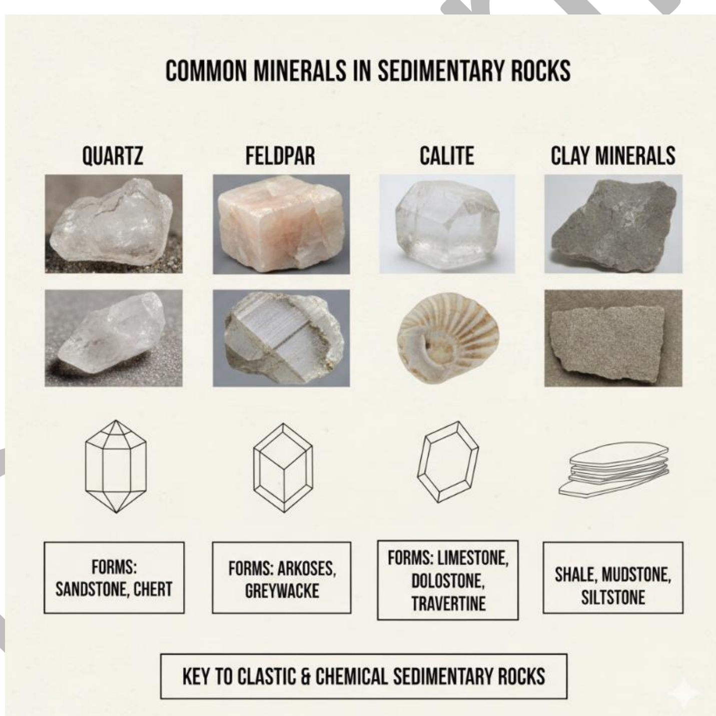

Figure 4.6: Common minerals in sedimentary rocks

4.3.2 Clastic rocks (sandstone, shale, conglomerate)

Clastic rocks are formed from fragments of pre-existing rocks that have been weathered, transported, and deposited. Their classification is based on grain size and composition.

- Sandstone: Composed mainly of sand-sized particles, often quartz-rich.

- Shale: Fine-grained rock formed from clay and silt particles, typically splitting into thin layers.

- Conglomerate: Coarse-grained rock containing rounded pebbles and cobbles cemented together.

Clastic rocks are significant because they record the mechanical processes of erosion and transport, as well as depositional environments.

Fill in the blank: A coarse-grained clastic rock containing rounded pebbles and cobbles is called a ______.

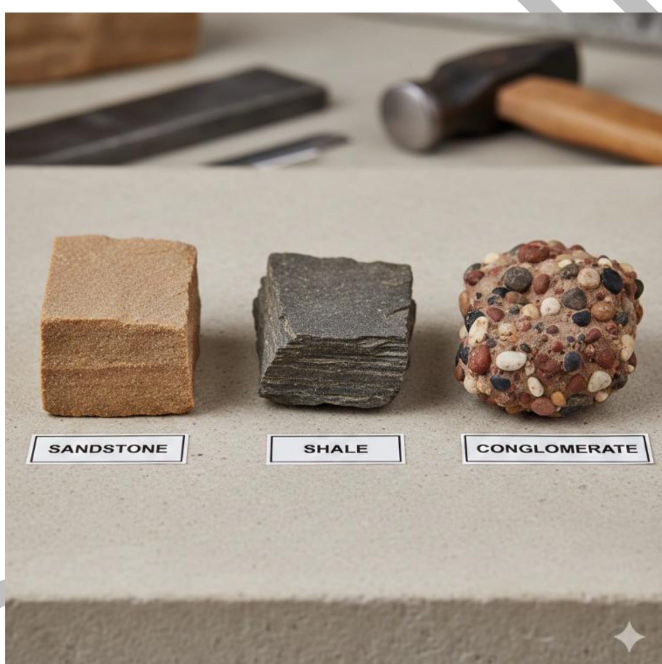

Plate 4.1: Examples of clastic sedimentary rocks

4.3.3 Chemical and biochemical rocks (limestone, dolomite, chert, coal)

Chemical sedimentary rocks form from the precipitation of minerals from solution, while biochemical rocks form from the accumulation of biological material.

- Limestone: Composed mainly of calcite, often formed from shells and skeletal fragments.

- Dolomite: Similar to limestone but contains the mineral dolomite, often formed by chemical alteration.

- Chert: Hard, silica-rich rock formed from the accumulation of microscopic organisms or chemical precipitation.

- Coal: Organic rock formed from the compaction of plant material in swampy environments.

These rocks are important because they record chemical conditions and biological activity in past environments.

Fill in the blank: The organic sedimentary rock formed from compacted plant material is called _______.

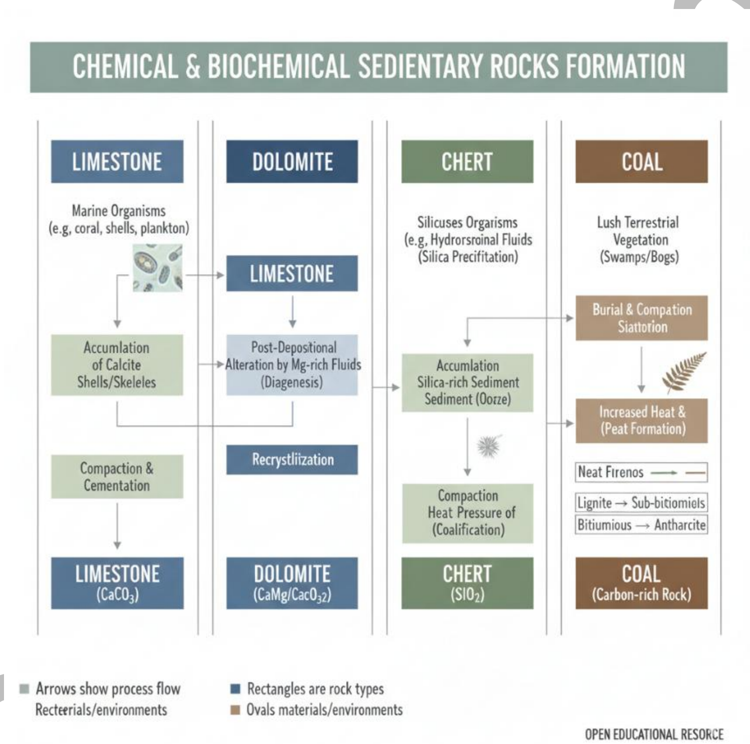

Figure 4.7: Formation of chemical and biochemical sedimentary rocks

Pilot questions 4.3

1. Name four common minerals found in sedimentary rocks.

2. Which mineral dominates many sandstones due to its resistance to weathering?

3. Give two examples of clastic sedimentary rocks.

4. What type of rock is formed from compacted clay and silt particles?

5. Which organic sedimentary rock is formed from plant material?

4.4 Applications of Sedimentary Petrology

4.4.1 Sedimentary rocks as archives of Earth history

Sedimentary rocks act as archives of Earth history, meaning they preserve evidence of past environments, climates, and biological activity. Fossils within sedimentary rocks record the evolution of life, while sedimentary structures such as ripple marks and mud cracks reveal ancient depositional settings. Chemical signatures, including isotopes, can provide information about past climates and ocean chemistry. By studying these features, geologists reconstruct the dynamic history of Earth's surface.

Fill in the blank: Sedimentary rocks preserve evidence of past environments and biological activity, making them archives of _______ history.

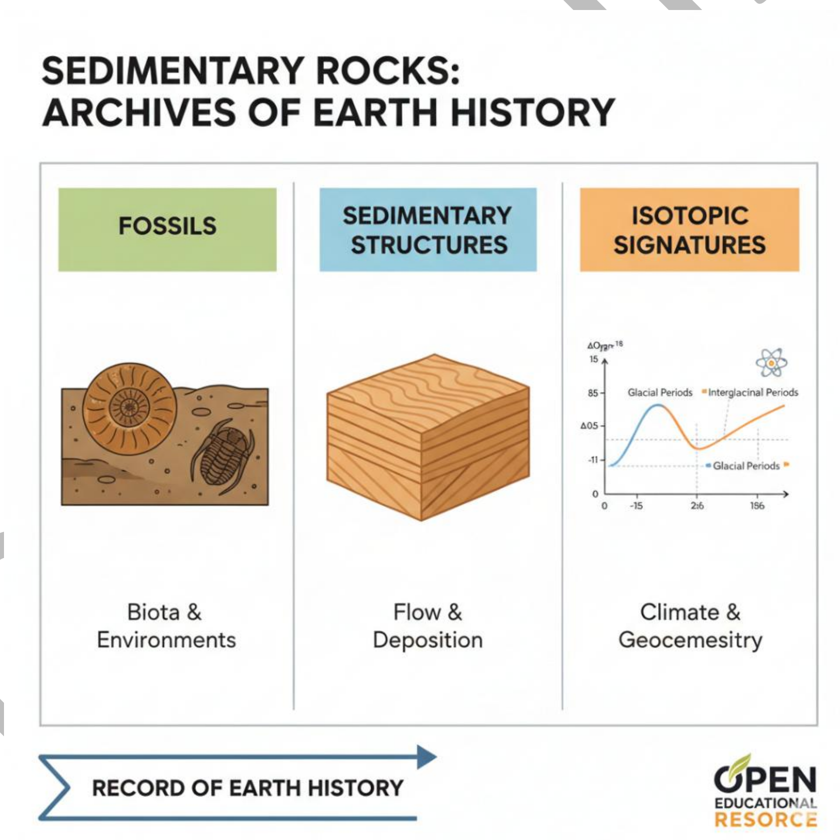

Figure 4.8: Sedimentary rocks as archives of Earth history

4.4.2 Economic importance (hydrocarbons, building materials, groundwater reservoirs)

Sedimentary rocks have significant economic importance. Hydrocarbons such as oil and natural gas accumulate in porous and permeable sedimentary rocks, making them vital energy resources. Building materials such as limestone and sandstone are widely used in construction. Sedimentary aquifers, composed of porous rocks like sandstone, store and transmit groundwater, providing essential water supplies. Understanding sedimentary petrology is therefore crucial for resource exploration and sustainable management.

Fill in the blank: Oil and natural gas accumulate in porous and permeable ______ rocks.

Economic Category	**Primary Rock Examples**	**Specific Applications & Uses**
Energy & Hydrocarbons	Coal, Shale, Sandstone, Limestone	**Coal** is a primary fuel for electricity. **Sandstone** and **Limestone** act as "reservoir rocks" that trap oil and natural gas due to their high porosity.
Construction Materials	Limestone, Sandstone, Shale, Gypsum	**Limestone** is the main ingredient in cement/concrete. **Sandstone** is used as building stone. **Shale** is used to make bricks and tiles. **Gypsum** is used for plaster and drywall.
Water Resources	Sandstone, Limestone (Karst)	These rocks form **aquifers**. Their porous nature allows them to store and transmit huge volumes of **groundwater** for drinking and irrigation.
Industrial Minerals	Rock Salt (Halite), Potash, Phosphate Rock	**Rock salt** is used for de-icing roads and chemical manufacturing. **Potash** and **Phosphate** are critical for agricultural fertilizers.

Economic Category	Primary Rock Examples	Specific Applications & Uses
Metallic Ores	Banded Iron Formations (BIF), Bauxite	Sedimentary processes concentrate metals. **BIFs** are the world's primary source of iron ore; **Bauxite** is the main ore for aluminum.
Glass & Manufacturing	Quartz Sandstone, Diatomite	Pure **Quartz sand** is melted to produce glass. **Diatomite** (made of fossilized algae) is used in filtration and mild abrasives (like toothpaste).

Table 4.2: Economic importance of sedimentary rocks

4.4.3 Case studies linking sedimentary rocks to past environments

Case studies demonstrate how sedimentary rocks provide insights into past environments and tectonic settings. For example, limestones in shallow marine settings record warm, clear seas, while coal deposits indicate ancient swampy environments rich in vegetation. Turbidites in deep marine basins reveal submarine landslides and tectonic activity. These examples highlight how sedimentary petrology connects rock features to broader geological processes.

Fill in the blank: Coal deposits indicate ancient _________ environments rich in vegetation.

Case Study: The Tertiary Niger Delta Petroleum System

Overview: The Niger Delta is one of the world's most prolific hydrocarbon provinces, holding over **34 billion barrels of oil** and **93 trillion cubic feet of natural gas**. Its economic success is entirely dependent on the specific arrangement of three sedimentary rock formations.

1. The Stratigraphic "Engine"

The basin is composed of three main diachronous (time-transgressive) layers that act as a complete "petroleum factory":

Formation	Rock Type	Economic/Environmental Role
Benin Formation	Continental Sands	**Aquifers & Construction:** The youngest layer; contains fresh groundwater and vast reserves of sand for building.

Formation	Rock Type	Economic/Environmental Role
Agbada Formation	Alternating Sand & Shale	**The Reservoir:** This is where the oil is stored. The sands are highly porous, while the shales act as seals to trap the fluids.
Akata Formation	Marine Shales	**The Source:** The deepest layer; contains high concentrations of organic matter that "cooked" into oil and gas over time.

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2. Geological Significance

- **Structural Traps:** The weight of rapidly depositing sediments caused the underlying Akata shales to deform, creating **growth faults** and **rollover anticlines**. These structures act as "bowls" that catch migrating oil.
- **Environmental Markers:** Sedimentary structures like **cross-bedding** and **herringbone stratigraphy** found in core samples tell geologists that the area was once a high-energy tidal environment.
- **Fossil Record:** The presence of **palynomorphs** (fossil pollen and spores) and **foraminifera** (tiny marine shells) allows scientists to date the rocks and reconstruct ancient shorelines.

3. Economic Impact

The sedimentary record of the Niger Delta hasn't just provided energy; it has shaped the regional economy through:

- **Oil and Gas Exports:** Accounting for a massive portion of Nigeria's foreign exchange.
- **Industrial Mining:** Extraction of glass sands and lignite (brown coal) from upper sedimentary layers.
- **Agriculture:** The fertile deltaic soils (alluvium) deposited by the Niger River support vast agricultural ecosystems.

Box 4.1: Case study – Sedimentary rocks in the Niger Delta

The Niger Delta illustrates how sedimentary rocks record both environmental and economic significance. Deltaic sandstones act as major hydrocarbon reservoirs, while associated shales preserve fossils and depositional structures that reveal the history of river and marine interactions. This case study shows how sedimentary petrology links rock features to tectonic settings and resource exploration.

Pilot questions 4.4

1. Why are sedimentary rocks described as archives of Earth history?

2. Which sedimentary rocks are important for hydrocarbon reservoirs?

3. Name two building materials derived from sedimentary rocks.

4. What type of sedimentary rocks form aquifers for groundwater storage?

5. What do coal deposits indicate about past environments?

Series Summary

This Series has introduced you to the fundamentals of sedimentary petrology, emphasising the importance of sedimentary rocks in recording Earth's history, environments, and resources. Sedimentary processes such as weathering, erosion, transport, and deposition were explored first, showing how they shape sediments and control their eventual lithification. We then examined sedimentary textures and structures, including grain size, sorting, porosity, permeability, and features such as bedding and ripple marks, which provide valuable clues about depositional conditions.

Following that, we studied the minerals and rock types that make up sedimentary formations, from quartz and clay minerals to clastic rocks like sandstone and shale, as well as chemical and biochemical rocks such as limestone, dolomite, chert, and coal. Finally, we considered the applications of sedimentary petrology, highlighting how sedimentary rocks serve as archives of Earth history, their economic importance in hydrocarbons, building materials, and groundwater, and case studies linking them to past environments. By completing this Series, you should now be able to describe sedimentary processes (SLO 4.1–4.2), analyze textures and structures (SLO 4.3–4.5), identify minerals and classify rock types (SLO 4.6–4.8), and apply this knowledge to interpret Earth's history and evaluate the economic and environmental significance of sedimentary rocks (SLO 4.9–4.11).

Glossary of Terms

Bedding: Layers of sediment that accumulate over time, forming visible stratification in sedimentary rocks.

Calcite: A carbonate mineral that forms limestones and reacts readily with dilute acid.

Chert: A hard, silica-rich sedimentary rock formed either by chemical precipitation or from microscopic organisms.

Clay minerals: Fine-grained minerals such as kaolinite and illite that commonly form shales and mudstones.

Clastic rocks: Sedimentary rocks composed of fragments of pre-existing rocks, such as sandstone, shale, and conglomerate.

Coal: An organic sedimentary rock formed from compacted plant material in swampy environments.

Conglomerate: A coarse-grained clastic rock containing rounded pebbles and cobbles cemented together.

Cross-bedding: Inclined layers within sedimentary beds, formed by currents or wind, indicating flow direction.

Deposition: The process by which sediments settle out of the transporting medium such as water, wind, or ice.

Dolomite: A carbonate rock similar to limestone but containing the mineral dolomite, often formed by chemical alteration.

Erosion: The removal of weathered material by agents such as water, wind, or ice.

Feldspar: A mineral less stable than quartz but present in arkosic sandstones.

Graded bedding: A sedimentary structure where grain size decreases from bottom to top, often formed by turbidity currents.

Grain shape: The description of sediment particles as angular or rounded, reflecting transport distance and intensity.

Grain size: The diameter of individual sediment particles, ranging from clay to gravel.

Groundwater reservoir (aquifer): A porous and permeable sedimentary rock, such as sandstone, that stores and transmits water.

Limestone: A sedimentary rock composed mainly of calcite, often formed from shells and skeletal fragments.

Mud cracks: Polygonal cracks formed when muddy sediments dry and shrink, indicating exposure to air.

Porosity: The percentage of void spaces between grains in a sediment or rock, determining fluid storage capacity.

Permeability: The ability of a rock to transmit fluids through its pore spaces.

Quartz: A hard, chemically resistant mineral that dominates many sandstones.

Ripple marks: Small ridges formed on sediment surfaces by water or wind movement, indicating shallow depositional environments.

Sandstone: A clastic sedimentary rock composed mainly of sand-sized particles, often quartz-rich.

Sedimentary environment: A specific setting where sediments are deposited, such as continental, transitional, or marine.

Sedimentary processes: Natural mechanisms including weathering, erosion, transport, deposition, and lithification that form sedimentary rocks.

Sedimentary structures: Physical features formed during or shortly after deposition, such as bedding, ripple marks, and cross-bedding.

Shale: A fine-grained clastic sedimentary rock formed from clay and silt particles, splitting easily into thin layers.

Sorting: The uniformity of grain sizes within a sediment, with well-sorted sediments having grains of similar size.

Weathering: The breakdown of rocks at Earth's surface through physical, chemical, or biological means.

Concept Check Questions [Series 4]

Objective Questions

1. The breakdown of rocks at Earth's surface through physical, chemical, or biological means is called . (Linked to SLO 4.1)

2. Sediments deposited at the boundary between land and sea belong to environments. (Linked to SLO 4.2)

3. Sediments with grains of similar size are described as being . (Linked to SLO 4.3)

4. The ability of a rock to transmit fluids through its pore spaces is called . (Linked to SLO 4.4)

5. Layers where grain size decreases from bottom to top are known as bedding. (Linked to SLO 4.5)

6. The mineral that dominates many sandstones due to its hardness and chemical resistance is . (Linked to SLO 4.6)

7. A coarse-grained clastic rock containing rounded pebbles and cobbles is called a . (Linked to SLO 4.7)

8. The organic sedimentary rock formed from compacted plant material is called . (Linked to SLO 4.8)

Short-Answer Questions

9. Define sedimentary processes and explain their role in shaping rocks. (Linked to SLO 4.1)

10. Describe the main differences between continental, transitional, and marine sedimentary environments. (Linked to SLO 4.2)

11. Explain how grain shape reflects the distance and intensity of transport. (Linked to SLO 4.3)

12. Distinguish between porosity and permeability in sedimentary rocks. (Linked to SLO 4.4)

13. Identify two common sedimentary structures and explain what they reveal about depositional conditions. (Linked to SLO 4.5)

14. List four common minerals found in sedimentary rocks and state their significance. (Linked to SLO 4.6)

15. Classify sandstone, shale, and conglomerate as clastic rocks and describe their key features. (Linked to SLO 4.7)

16. Distinguish between chemical and biochemical sedimentary rocks, giving one example of each. (Linked to SLO 4.8)

17. Explain why sedimentary rocks are described as archives of Earth history. (Linked to SLO 4.9)

18. State two economic uses of sedimentary rocks. (Linked to SLO 4.10)

Long-Answer Questions

19. Analyse how sedimentary textures and structures can be used to interpret depositional environments. (Linked to SLO 4.3–4.5)

20. Evaluate the progression from clastic to chemical and biochemical sedimentary rocks, highlighting their formation processes. (Linked to SLO 4.6–4.8)

21. Discuss the importance of sedimentary rocks in resource exploration, focusing on hydrocarbons and groundwater reservoirs. (Linked to SLO 4.10)

22. Apply knowledge of sedimentary rocks to interpret a case study such as the Niger Delta, linking rock features to past environments and economic significance. (Linked to SLO 4.11)

Answers to Concept Check Questions [Series 4]

Objective Questions

1. Weathering

2. Transitional environments

3. Well-sorted

4. Permeability

5. Graded bedding

6. Quartz

7. Conglomerate

8. Coal

Short-Answer Questions

9. Sedimentary processes are natural mechanisms including weathering, erosion, transport, deposition, and lithification. They shape sediments and control rock formation.

10. Continental environments include rivers, lakes, deserts, and glaciers; transitional environments occur at land–sea boundaries such as deltas and beaches; marine environments range from shallow shelves to deep basins.

11. Angular grains indicate short transport distances, while rounded grains reflect longer transport and abrasion.

12. Porosity is the percentage of void spaces in a rock, while permeability is the ability to transmit fluids through those spaces.

13. Bedding shows successive layers of deposition, while ripple marks indicate shallow water or wind activity. Both reveal depositional conditions.

14. Quartz (resistant to weathering), feldspar (source rock indicator), calcite (forms limestones), clay minerals (form shales).

15. Sandstone: sand-sized particles, often quartz-rich; shale: fine-grained, splits into thin layers; conglomerate: coarse-grained with rounded pebbles.

16. Chemical rocks form from precipitation (e.g., dolomite), while biochemical rocks form from biological material (e.g., limestone).

17. Sedimentary rocks preserve fossils, structures, and chemical signatures, making them records of past environments and life.

18. Hydrocarbons in sandstones and shales; building materials such as limestone and sandstone.

Long-Answer Questions

19. Basic response: Textures such as grain size and sorting reveal energy conditions, while structures like ripple marks and cross-bedding indicate depositional processes.

Value-added response: Integrating textures and structures allows geologists to reconstruct palaeoenvironmental conditions, flow directions, and depositional histories across different settings.

20. Basic response: Clastic rocks form from fragments of pre-existing rocks, while chemical and biochemical rocks form from precipitation or biological accumulation.

Value-added response: Understanding the transition highlights how physical, chemical, and biological processes interact, linking sedimentary rocks to broader Earth system cycles.

21. Basic response: Sedimentary rocks store hydrocarbons in porous reservoirs and groundwater in aquifers, making them vital resources.

Value-added response: Evaluating these roles involves considering porosity, permeability, and structural traps, which are critical for exploration and sustainable management.

22. Basic response: In the Niger Delta, sandstones act as hydrocarbon reservoirs, while shales preserve fossils and depositional structures.

Value-added response: Case studies demonstrate how sedimentary petrology integrates environmental interpretation with economic geology, linking depositional features to tectonic settings and resource exploitation.

Answers to Pilot Questions [Series 4]

Part 4.1: Sedimentary processes and environments

1. Sedimentary processes.

2. Weathering, erosion, transport, and deposition.

3. Erosion.

4. Rivers and deserts (also lakes and glaciers).

5. Transitional environments.

Part 4.2: Sedimentary textures and structures

1. Grain size, grain shape, and sorting.

2. Well-sorted.

3. Porosity is the percentage of void spaces, while permeability is the ability to transmit fluids.

4. Ripple marks and cross-bedding.

5. Graded bedding.

Part 4.3: Sedimentary minerals and rock types

1. Quartz, feldspar, calcite, and clay minerals.

2. Quartz.

3. Sandstone and shale (also conglomerate).

4. Shale.

5. Coal.

Part 4.4: Applications of sedimentary petrology

1. Because they preserve fossils, structures, and chemical signatures that record past environments and life.

2. Sandstone and shale.

3. Limestone and sandstone.

4. Sandstone aquifers.

5. Ancient swampy environments.

References and Attributions [Series 4]

All references and attributions listed below correspond to the instructional content, illustrations, and open educational resources (OERs) suggested in Series 4: Fundamentals of Sedimentary Petrology. The referencing style used here follows APA guidelines for clarity and consistency.

General References

- Boggs, S. (2012). Principles of Sedimentology and Stratigraphy (5th ed.). Pearson Education.

- Nichols, G. (2009). Sedimentology and Stratigraphy (2nd ed.). Wiley-Blackwell.

- Tucker, M. E. (2001). Sedimentary Petrology: An Introduction to the Origin of Sedimentary Rocks (3rd ed.). Wiley-Blackwell.

- Open Educational Resources (OER) Commons. (n.d.). Retrieved from https://www.oercommons.org

Illustrations

Figure 4.1: The sedimentary cycle of processes

- AI-generated suggestion: “Generate a labelled diagram showing sedimentary processes: weathering, erosion, transport, deposition, and lithification.”

- Suggested OER search string: “OER diagram sedimentary cycle processes weathering erosion deposition lithification.”

Figure 4.2: Sediment movement from source to basin

- AI-generated suggestion: “Create a diagram showing weathering, erosion, transport, and deposition in a river system.”

- Suggested OER search string: “OER diagram sediment transport river weathering erosion deposition.”

Table 4.1: Characteristics of major sedimentary environments

- AI-generated suggestion: “Create a table showing continental, transitional, and marine sedimentary environments with examples and features.”

- Suggested OER search string: “OER table sedimentary environments continental transitional marine features.”

Figure 4.3: Grain size, shape, and sorting in sediments

- AI-generated suggestion: “Generate a diagram showing grain size categories, angular vs rounded grains, and examples of well-sorted and poorly sorted sediments.”

- Suggested OER search string: “OER diagram sedimentary grain size shape sorting.”

Figure 4.4: Porosity and permeability in sedimentary rocks

- AI-generated suggestion: “Create a diagram comparing porosity and permeability in well-sorted and poorly sorted sediments.”

- Suggested OER search string: “OER diagram porosity permeability sedimentary rocks groundwater hydrocarbons.”

Figure 4.5: Common sedimentary structures

- AI-generated suggestion: “Generate a diagram illustrating bedding, cross-bedding, ripple marks, and graded bedding with labelled examples.”

- Suggested OER search string: “OER diagram sedimentary structures bedding cross-bedding ripple marks graded bedding.”

Figure 4.6: Common minerals in sedimentary rocks

- AI-generated suggestion: “Generate a labelled diagram showing quartz, feldspar, calcite, and clay minerals with examples of sedimentary rocks they form.”

- Suggested OER search string: “OER diagram common minerals sedimentary rocks quartz feldspar calcite clay.”

Plate 4.1: Examples of clastic sedimentary rocks

- AI-generated suggestion: “Generate an image showing hand specimens of sandstone, shale, and conglomerate with labels.”

- Suggested OER search string: “OER image clastic sedimentary rocks sandstone shale conglomerate.”

Figure 4.7: Formation of chemical and biochemical sedimentary rocks

- AI-generated suggestion: “Create a diagram showing formation pathways of limestone, dolomite, chert, and coal.”

- Suggested OER search string: “OER diagram chemical biochemical sedimentary rocks limestone dolomite chert coal.”

Figure 4.8: Sedimentary rocks as archives of Earth history

- AI-generated suggestion: “Generate a diagram showing fossils, ripple marks, and isotopic signatures preserved in sedimentary rocks as records of Earth history.”

- Suggested OER search string: “OER diagram sedimentary rocks archives fossils structures isotopes.”

Table 4.2: Economic importance of sedimentary rocks

- AI-generated suggestion: “Create a table showing the economic importance of sedimentary rocks, with examples and applications.”

- Suggested OER search string: “OER table economic importance sedimentary rocks hydrocarbons building materials groundwater.”

Box 4.1: Case study – Sedimentary rocks in the Niger Delta

- AI-generated suggestion: “Create a case study box summarising how sedimentary rocks in the Niger Delta record environmental and economic significance.”

- Suggested OER search string: “OER case study sedimentary rocks Niger Delta hydrocarbons fossils depositional structures.”

Course Code: GEY 203

Course title: Introduction to Petrology

Units: 2 Units

List of Series

Series 1: Foundations of Igneous Petrology

Series 2: Systematic Study of Metamorphic Rocks

Series 3: Textures and Minerals in Metamorphism

Series 4: Introduction to Sedimentary Petrology

Series 5: Classification of Igneous, Metamorphic, and Sedimentary Rocks

5.1 Classification of igneous rocks

- 5.1.1 Basis of classification (texture and mineral composition)
- 5.1.2 Intrusive igneous rocks (granite, diorite, gabbro)
- 5.1.3 Extrusive igneous rocks (rhyolite, andesite, basalt)
- 5.1.4 Special categories (pegmatites, pyroclastic rocks)

5.2 Classification of metamorphic rocks

- 5.2.1 Basis of classification (texture and mineral assemblage)
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- 5.2.3 Non-foliated metamorphic rocks (marble, quartzite, hornfels)
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5.3 Classification of sedimentary rocks

- 5.3.1 Basis of classification (clastic, chemical, biochemical, organic)
- 5.3.2 Clastic sedimentary rocks (conglomerate, sandstone, shale)
- 5.3.3 Chemical and biochemical sedimentary rocks (limestone, dolomite, chert)
- 5.3.4 Organic sedimentary rocks (coal and related deposits)

Introduction

In the last Series, we explored the fundamentals of sedimentary petrology, focusing on the processes, textures, minerals, and applications of sedimentary rocks. Having now studied igneous, metamorphic, and sedimentary rocks individually, it is important to bring these strands together through a systematic approach to their classification. Classification provides a framework for identifying rocks, understanding their origins, and comparing them across different geological settings. This Series will therefore help you consolidate your knowledge and apply it in a structured way.

The aim of this Series is to equip you with the skills to classify igneous, metamorphic, and sedimentary rocks based on their textures, mineral composition, and formation processes. By the end, you should be able to confidently distinguish between major rock types and explain the criteria used in their classification.

We shall commence this Series by examining the classification of igneous rocks, beginning with the basis of classification and moving on to intrusive and extrusive types, as well as special categories such as pegmatites and pyroclastic rocks. Next, we will continue with the classification of metamorphic rocks, considering both foliated and non-foliated varieties, and the role of index minerals in determining metamorphic grade. Finally, we will wrap up by studying the classification of sedimentary rocks, exploring clastic, chemical, biochemical, and organic categories. In conclusion, this Series will round off your study of petrology by providing a comprehensive framework for recognizing and classifying the three major rock groups.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- SLO 5.1 define the basis of igneous rock classification in terms of texture and mineral composition,
- SLO 5.2 distinguish between intrusive igneous rocks such as granite, diorite, and gabbro,
- SLO 5.3 classify extrusive igneous rocks including rhyolite, andesite, and basalt,

- SLO 5.4 describe special categories of igneous rocks such as pegmatites and pyroclastic rocks,

- SLO 5.5 explain the basis of metamorphic rock classification using texture and mineral assemblage,

- SLO 5.6 identify foliated metamorphic rocks such as slate, schist, and gneiss,

- SLO 5.7 classify non-foliated metamorphic rocks including marble, quartzite, and hornfels,

- SLO 5.8 analyze the role of index minerals in determining metamorphic grade,

- SLO 5.9 describe the basis of sedimentary rock classification into clastic, chemical, biochemical, and organic categories,

- SLO 5.10 classify clastic sedimentary rocks such as conglomerate, sandstone, and shale,

- SLO 5.11 distinguish chemical and biochemical sedimentary rocks including limestone, dolomite, and chert, and

- SLO 5.12 identify organic sedimentary rocks such as coal and explain their formation.

5.1 Classification of Igneous Rocks

5.1.1 Basis of classification (texture and mineral composition)

Igneous rocks are classified primarily on the basis of texture and mineral composition. Texture refers to the size, shape, and arrangement of crystals within the rock, which reflects the cooling history of the magma. Coarse-grained textures indicate slow cooling beneath the Earth's surface, while fine-grained textures suggest rapid cooling at or near the surface. Mineral composition refers to the types and proportions of minerals present, which depend on the chemical makeup of the magma. Rocks rich in silica are termed felsic, while those with more iron and magnesium are mafic.

Fill in the blank: Igneous rocks that cool slowly beneath the Earth's surface typically develop a -grained texture.

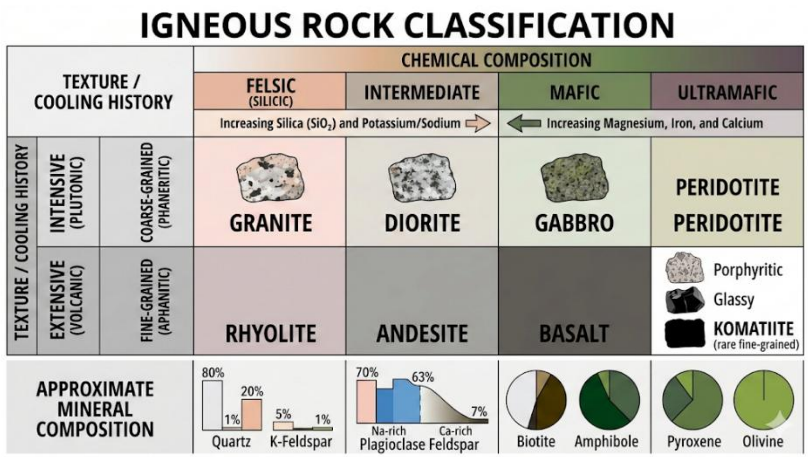

Figure 5.1: Basis of igneous rock classification

5.1.2 Intrusive igneous rocks (granite, diorite, gabbro)

Intrusive igneous rocks form when magma cools slowly beneath the Earth’s surface, producing large crystals. Examples include:

- Granite: A felsic rock composed mainly of quartz and feldspar, often light-colored.

- Diorite: Intermediate in composition, containing plagioclase feldspar and amphibole.

- Gabbro: A mafic rock rich in pyroxene and calcium-rich plagioclase, usually dark-colored.

These rocks are important for understanding continental crust composition and are widely used as building materials.

Fill in the blank: A coarse-grained felsic intrusive rock composed mainly of quartz and feldspar is called ______.

Plate 5.1: Examples of intrusive igneous rocks

5.1.3 Extrusive igneous rocks (rhyolite, andesite, basalt)

Extrusive igneous rocks form when lava cools quickly at or near the Earth's surface, producing fine-grained textures. Examples include:

- Rhyolite: A felsic rock, fine-grained equivalent of granite, often light-colored.

- Andesite: Intermediate composition, fine-grained equivalent of diorite, commonly grey.

- Basalt: A mafic rock, fine-grained equivalent of gabbro, typically dark-colored and widespread in oceanic crust.

These rocks are significant in volcanic studies and provide insights into tectonic settings such as mid-ocean ridges and subduction zones.

Fill in the blank: The fine-grained mafic rock that forms the bulk of oceanic crust is called

_________.

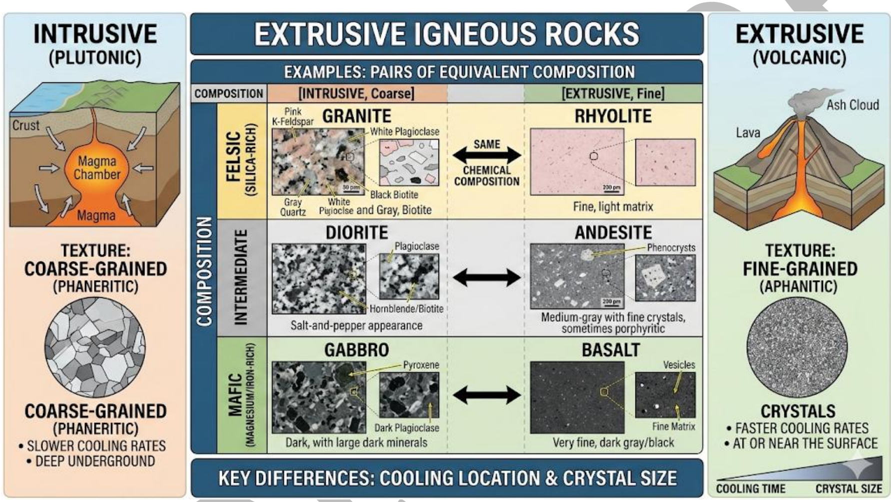

Figure 5.2: Comparison of intrusive and extrusive igneous rocks

5.1.4 Special categories (pegmatites, pyroclastic rocks)

Some igneous rocks fall into special categories:

- Pegmatites: Extremely coarse-grained intrusive rocks, often containing rare minerals such as tourmaline or beryl. They form from late-stage crystallization of magma.

- Pyroclastic rocks: Formed from volcanic fragments ejected during explosive eruptions. Examples include tuff and volcanic breccia. These rocks are classified based on fragment size and composition.

These categories highlight the diversity of igneous rocks and their varied formation processes.

Fill in the blank: Igneous rocks composed of volcanic fragments ejected during explosive eruptions are called ______ rocks.

Pegmatites are unique **intrusive igneous rocks** characterized by exceptionally large crystals (often >2.5 cm). While they share a chemical composition similar to granite, their value lies in their role as a primary source of rare elements and gemstones.

Why Pegmatites are Geologically Significant:

- **Extreme Crystal Growth:** They form during the final stages of magma crystallization. As the magma cools, water and volatiles become concentrated, allowing ions to move rapidly and grow massive crystal sometimes several meters long.
- **Incompatible Elements:** Elements that don't "fit" into the crystal structures of common rock-forming minerals (like quartz or feldspar) get squeezed into the remaining fluid. This concentrates rare elements like **Lithium (Li)**, **Beryllium (Be)**, and **Tantalum (Ta)**.
- **Economic Hubs:** They are the primary global source of lithium, which is critical for modern battery technology and the green energy transition.

Box 5.1: Special feature – Pegmatites as sources of rare minerals

Pegmatites are important not only for their unique textures but also for their economic value. They often host rare minerals used in electronics, jewelry, and industry. For example, lithium-bearing minerals in pegmatites are critical for battery production.

Pilot questions 5.1

1. What two main criteria are used to classify igneous rocks?

2. Which intrusive igneous rock is felsic and composed mainly of quartz and feldspar?

3. Name the fine-grained mafic rock that forms the bulk of oceanic crust.

4. What type of igneous rock is formed from volcanic fragments during explosive eruptions?

5. Give one example of a rare mineral commonly found in pegmatites.

5.2 Classification of Metamorphic Rocks

5.2.1 Basis of classification (texture and mineral assemblage)

Metamorphic rocks are classified mainly on the basis of texture and mineral assemblage. Texture refers to the arrangement of minerals within the rock, which may be foliated (layered) or non-foliated (massive). Mineral assemblage describes the specific set of minerals present, which reflects the pressure, temperature, and chemical conditions during metamorphism. Together, these criteria help geologists identify metamorphic rocks and interpret the conditions under which they formed.

Fill in the blank: Metamorphic rocks that show a layered arrangement of minerals are described as ________.

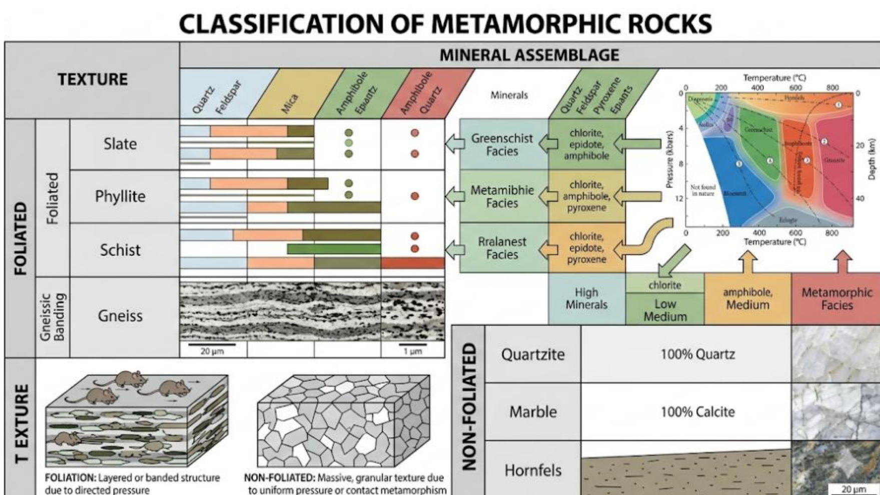

Figure 5.3: Basis of metamorphic rock classification

5.2.2 Foliated metamorphic rocks (slate, schist, gneiss)

Foliated metamorphic rocks display a layered or banded texture due to the alignment of platy minerals under directed pressure. Examples include:

- Slate: Fine-grained rock formed from shale, splits easily into thin sheets.

- Schist: Medium- to coarse-grained rock with visible platy minerals such as mica.

- Gneiss: Coarse-grained rock with alternating light and dark mineral bands, often derived from granite.

These rocks are important indicators of regional metamorphism and provide clues about tectonic forces.

Fill in the blank: A coarse-grained foliated metamorphic rock with alternating light and dark mineral bands is called ______.

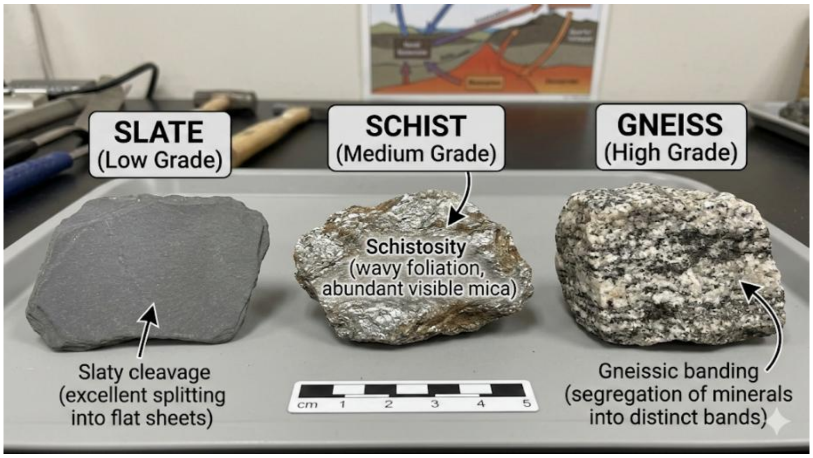

Plate 5.2: Examples of foliated metamorphic rocks

5.2.3 Non-foliated metamorphic rocks (marble, quartzite, hornfels)

Non-foliated metamorphic rocks lack a layered texture and are typically formed under conditions of uniform pressure or from rocks composed of minerals that do not align easily. Examples include:

- Marble: Formed from limestone, composed mainly of calcite, often used in sculpture and construction.

- Quartzite: Formed from sandstone, composed mainly of quartz, very hard and resistant.

- Hornfels: Fine-grained rock formed by contact metamorphism, often dark and tough.

These rocks are significant in contact metamorphism and are widely used as building and decorative materials.

Fill in the blank: The non-foliated metamorphic rock formed from limestone and composed mainly of calcite is called _______.

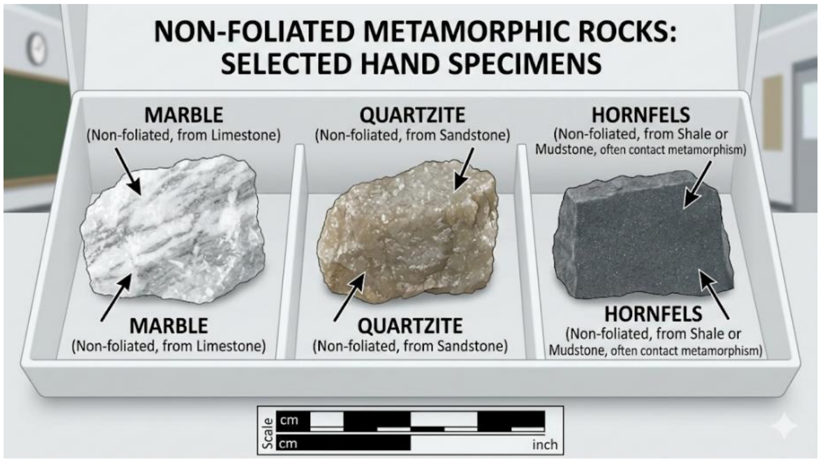

Plate 5.3: Examples of non-foliated metamorphic rocks

5.2.4 Index minerals and metamorphic grade in classification

Index minerals are minerals that form only under specific ranges of pressure and temperature, making them useful indicators of metamorphic grade. Examples include chlorite (low grade), garnet (medium grade), and sillimanite (high grade). Metamorphic grade refers to the intensity of metamorphism, ranging from low grade (slight changes) to high grade (extensive recrystallisation). By identifying index minerals, geologists can classify metamorphic rocks and reconstruct the metamorphic conditions they experienced.

Fill in the blank: The mineral garnet is typically associated with _____ grade metamorphism.

Metamorphic Grade	**Index Mineral**	**Common Rock Examples**	**Characteristic Features**
Low Grade	**Chlorite**	Slate	Very fine-grained; excellent slaty cleavage; dull surface.
Low Grade	**Muscovite / Biotite**	Phyllite	Fine-grained; satiny or shiny sheen; wavy foliation.
Intermediate	**Garnet**	Schist	Visible crystals (porphyroblasts); "sparkly" appearance.

Metamorphic Grade	Index Mineral	Common Rock Examples	Characteristic Features
Intermediate	**Staurolite**	Schist	Larger, often cross-shaped crystals; high-mica content.
High Grade	**Kyanite**	Schist / Gneiss	Bladed blue crystals; indicates high-pressure conditions.
High Grade	**Sillimanite**	Gneiss	Coarse-grained; distinct light and dark mineral banding.

Table 5.1: Common index minerals and metamorphic grades

Pilot questions 5.2

1. What two main criteria are used to classify metamorphic rocks?

2. Which foliated metamorphic rock has alternating light and dark mineral bands?

3. Name the non-foliated metamorphic rock formed from limestone.

4. What are index minerals used for in metamorphic classification?

5. Which mineral is typically associated with medium-grade metamorphism?

5.3 Classification of Sedimentary Rocks

5.3.1 Basis of classification (clastic, chemical, biochemical, organic)

Sedimentary rocks are classified according to their origin and composition. The four main categories are:

- Clastic rocks: Formed from fragments of pre-existing rocks that have been weathered, transported, and deposited.

- Chemical rocks: Formed by the precipitation of minerals from solution.

- Biochemical rocks: Formed from the accumulation of biological material such as shells or skeletal fragments.

- Organic rocks: Formed from the compaction of plant material, such as coal.

This classification helps geologists understand depositional environments and the processes that created the rocks.

Fill in the blank: Sedimentary rocks formed from fragments of pre-existing rocks are classified as ______ rocks.

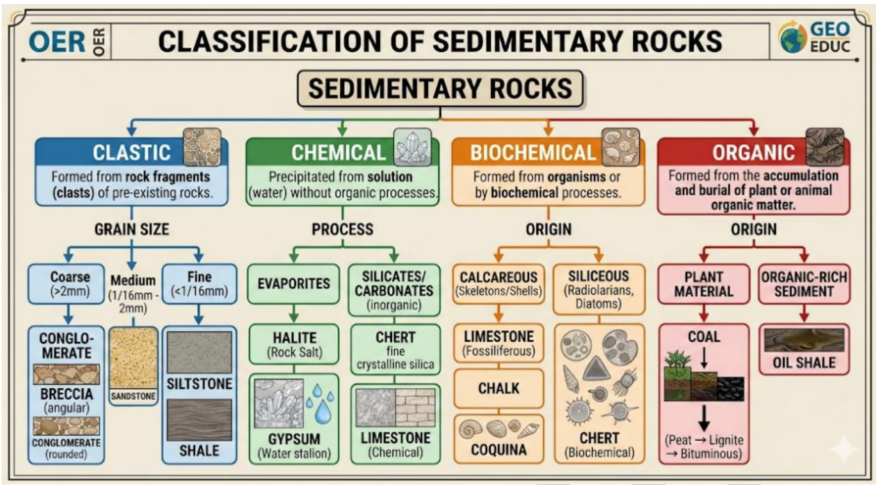

Figure 5.4: Basis of sedimentary rock classification

5.3.2 Clastic sedimentary rocks (conglomerate, sandstone, shale)

Clastic sedimentary rocks are classified mainly by grain size and composition.

- Conglomerate: Coarse-grained rock with rounded pebbles and cobbles cemented together.

- Sandstone: Medium-grained rock composed mostly of sand-sized particles, often quartz-rich.

- Shale: Fine-grained rock formed from clay and silt particles, splitting easily into thin layers.

These rocks record mechanical processes of erosion and transport, making them useful indicators of depositional energy and environment.

Fill in the blank: A fine-grained clastic rock formed from clay and silt particles that splits into thin layers is called _______.

Plate 5.4: Examples of clastic sedimentary rocks

5.3.3 Chemical and biochemical sedimentary rocks (limestone, dolomite, chert)

Chemical sedimentary rocks form when minerals precipitate directly from solution, while biochemical rocks form from biological activity.

- Limestone: Composed mainly of calcite, often formed from shells and skeletal fragments.

- Dolomite: Similar to limestone but containing the mineral dolomite, often formed by chemical alteration.

- Chert: Hard, silica-rich rock formed either chemically or from microscopic organisms.

These rocks are important for interpreting past chemical conditions and biological activity in depositional environments.

Fill in the blank: The sedimentary rock composed mainly of calcite and often formed from shells is called ________.

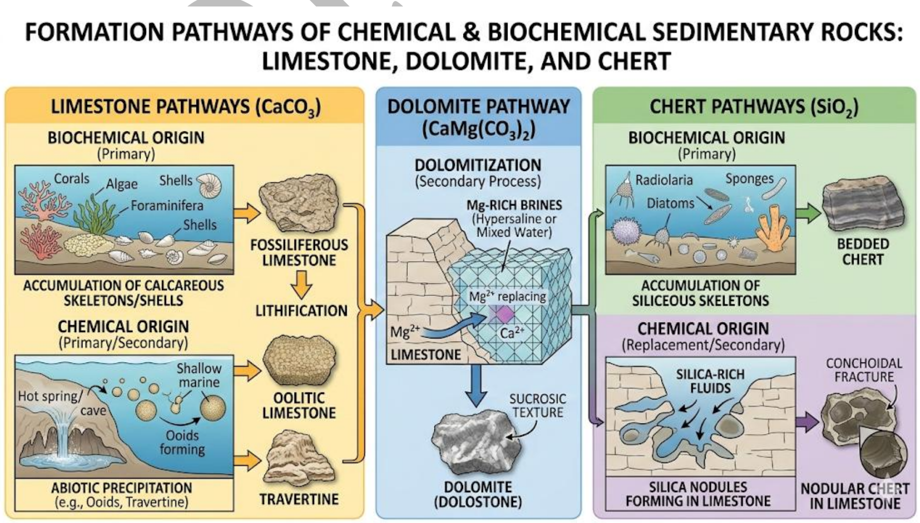

Figure 5.5: Formation of chemical and biochemical sedimentary rocks

5.3.4 Organic sedimentary rocks (coal and related deposits)

Organic sedimentary rocks are formed from the accumulation and compaction of plant material. The most common example is coal, which develops in swampy environments rich in vegetation. Coal is classified into types such as lignite, bituminous, and anthracite, depending on the degree of carbon concentration and metamorphism. These rocks are economically important as energy resources and environmentally significant as indicators of ancient ecosystems.

Fill in the blank: The organic sedimentary rock formed from compacted plant material in swampy environments is called ________.

Coal is a non-renewable fossil fuel formed from remains of ancient vegetation subjected to millions of years of heat and pressure (a process called **coalification**). It is classified into four primary "ranks" based on its degree of transformation, which determines its carbon content and energy density.

Classification of Coal Types

The following table summarizes the key characteristics and applications of the primary coal ranks:

Coal Type	Rank	Carbon Content	Energy Content (Btu/lb)	Typical Uses
Lignite	Lowest	**25% – 35%**	4,000 – 8,300	Primarily used for electricity generation; often burned near mines due to high moisture.
Sub-bituminous	Low-Mid	**35% – 45%**	8,300 – 13,000	Power plants; preferred in some regions for lower sulfur content compared to higher ranks.
Bituminous	Middle	**45% – 86%**	10,500 – 15,500	Most abundant rank; used for electricity and to produce **coke** for steel manufacturing.
Anthracite	Highest	**86% – 97%**	~15,000	Residential/commercial heating and specialized metallurgical processes; burns very cleanly.

Key Properties & Considerations

- **Energy Density:** As coal rank increases from lignite to anthracite, the moisture content decreases and the **fixed carbon** increases, resulting in a higher heating value.
- **Environmental Impact:** Lower-rank coals (lignite) generally produce more CO_{2} and particulate emissions per unit of energy produced because they contain more impurities and moisture.
- **Formation:** The quality of coal is a direct result of the **geological time** and the **intensity of heat and pressure** applied. Anthracite is the oldest and most compressed, while lignite is geologically "young."

Box 5.2: Special feature – Coal as an energy resource

Coal is one of the most widely used fossil fuels. Its classification into lignite, bituminous, and anthracite reflects increasing carbon content and energy potential. While economically valuable, coal also raises environmental concerns due to greenhouse gas emissions.

Pilot questions 5.3

1. What are the four main categories of sedimentary rocks?

2. Which clastic sedimentary rock is fine-grained and splits into thin layers?

3. Name the sedimentary rock composed mainly of calcite and often formed from shells.

4. What type of sedimentary rock is coal classified as?

5. How does coal classification reflects its carbon content and energy potential?

Series Summary

This Series has focused on the classification of igneous, metamorphic, and sedimentary rocks, providing you with a structured framework for identifying and distinguishing between the three major rock groups. Classification is central to petrology because it allows geologists to interpret rock origins, depositional or metamorphic conditions, and tectonic settings. By working through this Series, you have seen how texture, mineral composition, and formation processes serve as the basis for systematic classification.

We began with igneous rocks, examining how texture and mineral composition determine whether a rock is intrusive or extrusive, and considering special categories such as pegmatites and pyroclastic rocks. We then moved on to metamorphic rocks, where classification was guided by texture and mineral assemblage, distinguishing foliated types such as slate, schist, and gneiss from non-foliated rocks like marble, quartzite, and hornfels, and exploring the role of index minerals in defining metamorphic grade. Finally, we studied sedimentary rocks, classifying them into clastic, chemical, biochemical, and organic categories, with examples ranging from sandstone and shale to limestone, chert, and coal. In line with the Series Learning Outcomes, you should now be able to define the criteria for classification (SLOs 5.1, 5.5, 5.9), identify and distinguish specific rock types across all three groups (SLOs 5.2–5.4, 5.6–5.8, 5.10–5.12), and apply this knowledge to interpret geological processes and environments.

Glossary of Terms

Andesite: A fine-grained extrusive igneous rock of intermediate composition, commonly grey in colour.

Basalt: A fine-grained mafic extrusive igneous rock that forms the bulk of oceanic crust.

Biochemical sedimentary rocks: Rocks formed from the accumulation of biological material such as shells or skeletal fragments.

Calcite: A carbonate mineral that forms limestones and reacts readily with dilute acid.

Chert: A hard, silica-rich sedimentary rock formed either chemically or from microscopic organisms.

Clastic sedimentary rocks: Rocks formed from fragments of pre-existing rocks, classified mainly by grain size and composition.

Coal: An organic sedimentary rock formed from compacted plant material in swampy environments.

Conglomerate: A coarse-grained clastic sedimentary rock containing rounded pebbles and cobbles cemented together.

Diorite: An intrusive igneous rock of intermediate composition, containing plagioclase feldspar and amphibole.

Dolomite: A carbonate sedimentary rock similar to limestone but containing the mineral dolomite, often formed by chemical alteration.

Extrusive igneous rocks: Igneous rocks that form when lava cools quickly at or near the Earth's surface, producing fine-grained textures.

Foliated metamorphic rocks: Metamorphic rocks that display a layered or banded texture due to the alignment of minerals under pressure.

Gabbro: A coarse-grained mafic intrusive igneous rock rich in pyroxene and calcium-rich plagioclase.

Gneiss: A coarse-grained foliated metamorphic rock with alternating light and dark mineral bands.

Granite: A coarse-grained felsic intrusive igneous rock composed mainly of quartz and feldspar.

Hornfels: A fine-grained non-foliated metamorphic rock formed by contact metamorphism, often dark and tough.

Index minerals: Minerals that form only under specific ranges of pressure and temperature, used to indicate metamorphic grade.

Intrusive igneous rocks: Igneous rocks that form when magma cools slowly beneath the Earth's surface, producing large crystals.

Limestone: A sedimentary rock composed mainly of calcite, often formed from shells and skeletal fragments.

Marble: A non-foliated metamorphic rock formed from limestone, composed mainly of calcite.

Metamorphic grade: The intensity of metamorphism, ranging from low grade (slight changes) to high grade (extensive recrystallisation).

Mineral assemblage: The specific set of minerals present in a metamorphic rock, reflecting the conditions of formation.

Organic sedimentary rocks: Rocks formed from the compaction of plant material, such as coal.

Pegmatite: An extremely coarse-grained intrusive igneous rock, often containing rare minerals such as tourmaline or beryl.

Porphyritic texture: An igneous texture characterised by larger crystals set in a finer-grained matrix, indicating two stages of cooling.

Pyroclastic rocks: Igneous rocks formed from volcanic fragments ejected during explosive eruptions, such as tuff and volcanic breccia.

Quartzite: A non-foliated metamorphic rock formed from sandstone, composed mainly of quartz.

Rhyolite: A fine-grained felsic extrusive igneous rock, the volcanic equivalent of granite.

Sandstone: A clastic sedimentary rock composed mainly of sand-sized particles, often quartz-rich.

Schist: A medium- to coarse-grained foliated metamorphic rock with visible platy minerals such as mica.

Sedimentary rock categories: The four main groups of sedimentary rocks: clastic, chemical, biochemical, and organic.

Shale: A fine-grained clastic sedimentary rock formed from clay and silt particles, splitting easily into thin layers.

Slate: A fine-grained foliated metamorphic rock formed from shale, splitting into thin sheets.

Texture (igneous rocks): The size, shape, and arrangement of crystals in an igneous rock, reflecting its cooling history.

Texture (metamorphic rocks): The arrangement of minerals in a metamorphic rock, which may be foliated or non-foliated.

Concept Check Questions [Series 5]

Objective Questions

1. Igneous rocks are classified mainly on the basis of and mineral composition. (Linked to SLO 5.1)

2. A coarse-grained felsic intrusive igneous rock composed mainly of quartz and feldspar is called . (Linked to SLO 5.2)

3. The fine-grained mafic extrusive rock that forms the bulk of oceanic crust is . (Linked to SLO 5.3)

4. Igneous rocks composed of volcanic fragments ejected during explosive eruptions are called rocks. (Linked to SLO 5.4)

5. Metamorphic rocks that display a layered or banded texture are described as . (Linked to SLO 5.5)

6. A coarse-grained foliated metamorphic rock with alternating light and dark mineral bands is . (Linked to SLO 5.6)

7. The non-foliated metamorphic rock formed from limestone and composed mainly of calcite is . (Linked to SLO 5.7)

8. Garnet is typically associated with grade metamorphism. (Linked to SLO 5.8)

9. Sedimentary rocks formed from fragments of pre-existing rocks are classified as . (Linked to SLO 5.9)

10. A fine-grained clastic sedimentary rock formed from clay and silt particles that splits into thin layers is . (Linked to SLO 5.10)

11. The sedimentary rock composed mainly of calcite and often formed from shells is . (Linked to SLO 5.11)

12. The organic sedimentary rock formed from compacted plant material in swampy environments is . (Linked to SLO 5.12)

Short-Answer Questions

13. Define texture in igneous rocks and explain its significance in classification. (Linked to SLO 5.1)

14. Distinguish between intrusive and extrusive igneous rocks, giving one example of each. (Linked to SLO 5.2–5.3)

15. Describe pegmatites and explain why they are economically important. (Linked to SLO 5.4)

16. Explain the difference between foliated and non-foliated metamorphic rocks, with examples. (Linked to SLO 5.5–5.7)

17. What are index minerals, and how are they used to determine metamorphic grade? (Linked to SLO 5.8)

18. List the four main categories of sedimentary rocks and give one example of each. (Linked to SLO 5.9–5.12)

Long-Answer Questions

19. Analyse how texture and mineral composition are used together to classify igneous rocks. (Linked to SLO 5.1–5.4)

20. Evaluate the role of texture and mineral assemblage in classifying metamorphic rocks, highlighting the importance of index minerals. (Linked to SLO 5.5–5.8)

21. Discuss the classification of sedimentary rocks into clastic, chemical, biochemical, and organic categories, explaining how each reflects depositional processes. (Linked to SLO 5.9–5.12)

22. Apply your knowledge of rock classification to explain how geologists use igneous, metamorphic, and sedimentary rocks to interpret Earth's history and resources. (Linked to SLOs across Series 5)

Answers to Concept Check Questions [Series 5]

Objective Questions

1. Texture

2. Granite

3. Basalt

4. Pyroclastic

5. Foliated

6. Gneiss

7. Marble

8. Medium

9. Clastic

10. Shale

11. Limestone

12. Coal

Short-Answer Questions

13. Texture in igneous rocks refers to the size, shape, and arrangement of crystals, indicating cooling history.

14. Intrusive rocks form beneath the surface with coarse grains (e.g., granite), while extrusive rocks form at the surface with fine grains (e.g., basalt).

15. Pegmatites are extremely coarse-grained igneous rocks that often contain rare minerals such as tourmaline or lithium, making them economically valuable.

16. Foliated rocks show mineral alignment (e.g., schist, gneiss), while non-foliated rocks lack layering (e.g., marble, quartzite).

17. Index minerals form under specific pressure and temperature ranges, helping geologists determine metamorphic grade.

18. Clastic (sandstone), chemical (dolomite), biochemical (limestone), organic (coal).

Long-Answer Questions

19. Basic response: Igneous rocks are classified by texture (coarse vs fine-grained) and mineral composition (felsic vs mafic).

Value-added response: Combining these criteria allows geologists to link rocks to tectonic settings, such as continental crust (granite) or oceanic crust (basalt).

20. Basic response: Metamorphic rocks are classified by texture (foliated vs non-foliated) and mineral assemblage. Index minerals indicate metamorphic grade.

Value-added response: This classification helps reconstruct pressure–temperature conditions, linking rocks to regional or contact metamorphism and tectonic processes.

21. Basic response: Sedimentary rocks are classified into clastic, chemical, biochemical, and organic categories, each reflecting depositional processes.

Value-added response: This classification provides insights into past environments, from river systems (sandstone) to shallow seas (limestone) and swampy ecosystems (coal).

22. Basic response: Geologists use rock classification to identify igneous, metamorphic, and sedimentary rocks and interpret their formation.

Value-added response: Rock classification supports broader geological interpretations, including tectonic history, resource exploration (hydrocarbons, minerals), and environmental reconstruction.

Answers to Pilot Questions [Series 5]

Part 5.1: Classification of igneous rocks

1. Texture and mineral composition
2. Granite
3. Basalt
4. Pyroclastic
5. Tourmaline (also beryl or lithium-bearing minerals)

Part 5.2: Classification of metamorphic rocks

1. Texture and mineral assemblage
2. Gneiss
3. Marble
4. To indicate metamorphic grade (pressure–temperature conditions)
5. Garnet

Part 5.3: Classification of sedimentary rocks

1. Clastic, chemical, biochemical, and organic
2. Shale
3. Limestone
4. Organic sedimentary rock
5. By increasing carbon content and energy potential (lignite, bituminous, anthracite)

References and Attributions [Series 5]

All references and attributions listed below correspond to the instructional content, illustrations, and open educational resources (OERs) suggested in Series 5: Rock

Classification: Igneous, Metamorphic, and Sedimentary. The referencing style used here follows APA guidelines for clarity and consistency.

General References

- Boggs, S. (2012). Principles of Sedimentology and Stratigraphy (5th ed.). Pearson Education.

- Best, M. G. (2003). Igneous and Metamorphic Petrology (2nd ed.). Wiley-Blackwell.

- Nichols, G. (2009). Sedimentology and Stratigraphy (2nd ed.). Wiley-Blackwell.

- Tucker, M. E. (2001). Sedimentary Petrology: An Introduction to the Origin of Sedimentary Rocks (3rd ed.). Wiley-Blackwell.

- Winter, J. D. (2010). Principles of Igneous and Metamorphic Petrology (2nd ed.). Pearson Education.

- Open Educational Resources (OER) Commons. (n.d.). Retrieved from https://www.oercommons.org

Illustrations for Part 5.1: Classification of igneous rocks

Figure 5.1: Basis of igneous rock classification

- AI-generated suggestion: "Generate a diagram showing igneous rock classification by texture (coarse vs fine-grained) and composition (felsic vs mafic)."

- Suggested OER search string: "OER diagram igneous rock classification texture composition felsic mafic."

Plate 5.1: Examples of intrusive igneous rocks

- AI-generated suggestion: "Generate an image showing labelled hand specimens of granite, diorite, and gabbro."

- Suggested OER search string: "OER image intrusive igneous rocks granite diorite gabbro."

Figure 5.2: Comparison of intrusive and extrusive igneous rocks

- AI-generated suggestion: "Create a diagram comparing intrusive and extrusive igneous rocks with examples (granite vs rhyolite, diorite vs andesite, gabbro vs basalt)."

- Suggested OER search string: "OER diagram intrusive extrusive igneous rocks comparison."

Box 5.1: Special feature – Pegmatites as sources of rare minerals

- AI-generated suggestion: "Create a box summarising the importance of pegmatites as sources of rare minerals."

- Suggested OER search string: "OER case study pegmatite rare minerals lithium tourmaline beryl."

Illustrations for Part 5.2: Classification of metamorphic rocks

Figure 5.3: Basis of metamorphic rock classification

- AI-generated suggestion: "Generate a diagram showing metamorphic rock classification by texture (foliated vs non-foliated) and mineral assemblage."

- Suggested OER search string: "OER diagram metamorphic rock classification texture mineral assemblage."

Plate 5.2: Examples of foliated metamorphic rocks

- AI-generated suggestion: "Generate an image showing labelled hand specimens of slate, schist, and gneiss."

- Suggested OER search string: "OER image foliated metamorphic rocks slate schist gneiss."

Plate 5.3: Examples of non-foliated metamorphic rocks

- AI-generated suggestion: "Generate an image showing labelled hand specimens of marble, quartzite, and hornfels."

- Suggested OER search string: "OER image non-foliated metamorphic rocks marble quartzite hornfels."

Table 5.1: Common index minerals and metamorphic grades

- AI-generated suggestion: "Create a table showing index minerals, their metamorphic grades, and example rocks."

- Suggested OER search string: "OER table index minerals metamorphic grade classification."

Illustrations for Part 5.3: Classification of sedimentary rocks

Figure 5.4: Basis of sedimentary rock classification

- AI-generated suggestion: "Generate a diagram showing classification of sedimentary rocks into clastic, chemical, biochemical, and organic categories with examples."

- Suggested OER search string: “OER diagram sedimentary rock classification clastic chemical biochemical organic.”

Plate 5.4: Examples of clastic sedimentary rocks

- AI-generated suggestion: “Generate an image showing labelled hand specimens of conglomerate, sandstone, and shale.”

- Suggested OER search string: “OER image clastic sedimentary rocks conglomerate sandstone shale.”

Figure 5.5: Formation of chemical and biochemical sedimentary rocks

- AI-generated suggestion: “Create a diagram showing formation pathways of limestone, dolomite, and chert.”

- Suggested OER search string: “OER diagram chemical biochemical sedimentary rocks limestone dolomite chert.”

Box 5.2: Special feature – Coal as an energy resource

- AI-generated suggestion: “Create a box summarizing coal as an energy resource, including lignite, bituminous, and anthracite types.”

- Suggested OER search string: “OER case study coal classification lignite bituminous anthracite energy resource.”