SEDIMENTOLOGY AND STRATIGRAPHY

SECOND EDITION

GARY NICHOLS

Sedimentology and Stratigraphy

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Second Edition

Gary Nichols

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Preface

There is pleasing symmetry about the fact that the backbone of the first edition of this book was written within the Antarctic Circle in gaps between fieldwork with the British Antarctic Survey, while the bulk of this second edition has been written from within the Arctic Circle during my tenure of a 2-year position as Professor of Geology at the University Centre on Svalbard. It is not that I have any great affinity for the polar regions, it just seems that I have almost literally gone to the ends of the Earth to find the peace and quiet that I need to write a book. Between my sojourns in these polar regions 10 years have passed, and both sedimentology and stratigraphy have moved on enough for a thorough update of the material to be required. Just as importantly, technology has moved on, and I can provide a much more satisfying range of illustrative material in digital form on a CD included with the text. Geology is a wonderfully visual science, and it is best appreciated at first hand in the field, but photographs of examples can also aid understanding. I am an unashamed geo-tourist, always looking for yet another example of a geological phenomenon, whether on fieldwork or on holiday. The photographs used in this book and accompanying CD-ROM were taken over a period of 20 years and include examples from many 'corners' of the globe.

AN UNDERGRADUATE TEXT

This book has been written for students who are studying geology at university and it is intended to provide them with an introduction to sedimentology and stratigraphy. It is hoped that the text is accessible to those who are completely new to the subject and that it will also provide a background in concepts and terminology used in more advanced work. The approach is largely descriptive and is intended to complement the more numerical treatment of the topics provided by books such as Leeder (1999). Sedimentary processes are covered in more detail in texts such as Allen (1997) and a much more detailed analysis of sedimentary environments and facies is provided by Reading (1996). For a more comprehensive treatment of some aspects of stratigraphy books such as Coe (2003) are recommended.

DEFINITIONS OF TERMS

This book does not include a glossary, but instead it is intended that terminology is explained and, where necessary, defined in context within the text. The first occurrence of a technical term is usually cast in ***bold italics***, and it is at this point that an explanation is provided. To find the meaning of a term, the reader should consult the index and go to its first listed occurrence. There are differences of opinion about some terminology, but it is beyond the scope of this text to provide discussion of the issues: in most cases the most broadly accepted view has been adopted; in others simplicity and consistency within the book have taken precedence.

REFERENCES

The references chosen are not intended to be comprehensive for a topic, but merely a selection of a few relatively recent publications that can be used as a starting point for further information. Older sources are cited where these provide important primary accounts of a topic. At the end of each chapter there is a list of suggested further reading materials: these are mainly recent textbooks, compilations of papers in special publications and key review papers and are intended as a starting point for further general information about the topics covered in the chapter.

CROSS-REFERENCING AND THE CD-ROM

To reduce duplication of material, there is quite extensive cross-referencing within the text, indicated by the section number italicised in parentheses, for example (*2.3.4*). Relevant figures are indicated by, for example, 'Fig. 2.34'. The accompanying CD-ROM contains more illustrative material, principally photographs, than is provided within the book: specific reference to this material has not been made in the text, as the book is intended to be 'stand-alone'. In contrast, the CD-ROM is intended for use in conjunction with the book, and so the diagrams and photographs on it are not fully captioned or explained. An index on the CD-ROM contains information about each slide. All photographs used in the book and CD-ROM were taken by the author and all diagrams drafted by the author. A list of the locations of each of the photographs in the text is provided in an appendix on the CD-ROM.

Acknowledgements

Thanks to Phil Chapman for casually suggesting to the teenage younger brother of his friend Roger Nichols that he might like to study geology at 'A' level: this turned out to be the best piece of advice I ever received. The late Doug Shearman was an inspirational lecturer in sedimentology when I was a student at Imperial College, London, and he unwittingly made me committed to the idea of being an academic sedimentologist. (The greatest professional compliment ever paid to me was by Rick Sibson, a former colleague of Doug, who, after I had given a presentation at a conference nearly 20 years later, said 'there were shades of Doug Shearman in the talk you gave today'.) Peter Friend provided understated guidance to me as PhD project supervisor: I could not have a better academic pedigree than as a former research student of Peter. It has been a great pleasure to work with many different people in many different countries, all of whom have in some way provided me with some inspiration. Most importantly, they have made my whole experience of 25 years in geology a lot of fun. Thanks also to Davina for just about everything else.

1

Introduction: Sedimentology and Stratigraphy

Sedimentology is the study of the processes of formation, transport and deposition of material that accumulates as sediment in continental and marine environments and eventually forms sedimentary rocks. Stratigraphy is the study of rocks to determine the order and timing of events in Earth history: it provides the time frame that allows us to interpret sedimentary rocks in terms of dynamic evolving environments. The stratigraphic record of sedimentary rocks is the fundamental database for understanding the evolution of life, plate tectonics through time and global climate change.

1.1 SEDIMENTARY PROCESSES

The concept of interpreting rocks in terms of modern processes dates back to the 18th and 19th centuries ('the present is the key to the past'). 'Sedimentology' has existed as a distinct branch of the geological sciences for only a few decades. It developed as the observational elements of physical stratigraphy became more quantitative and the layers of strata were considered in terms of the physical, chemical and biological processes that formed them.

The nature of sedimentary material is very varied in origin, size, shape and composition. Particles such as grains and pebbles may be derived from the erosion of older rocks or directly ejected from volcanoes. Organisms form a very important source of material, ranging from microbial filaments encrusted with calcium carbonate to whole or broken shells, coral reefs, bones and plant debris. Direct precipitation of minerals from solution in water also contributes to sediments in some situations.

Formation of a body of sediment involves either the transport of particles to the site of deposition by gravity, water, air, ice or mass flows or the chemical or biological growth of the material in place. Accumulation of sediments in place is largely influenced by the chemistry, temperature and biological character of the setting. The processes of transport and deposition can be determined by looking at individual layers of sediment. The size, shape and distribution of particles all provide clues to the way in which the material was carried and deposited. Sedimentary structures such as ripples can be seen in sedimentary rocks and can be compared to ripples forming today, either in natural environments or in a laboratory tank.

Assuming that the laws that govern physical and chemical processes have not changed through time, detailed measurements of sedimentary rocks can be used to make estimates (to varying degrees of accuracy) of the physical, chemical and biological conditions that existed at the time of sedimentation. These conditions may include the salinity, depth and flow velocity in lake or seawater, the strength and direction of the wind in a desert and the tidal range in a shallow marine setting.

1.2 SEDIMENTARY ENVIRONMENTS AND FACIES

The environment at any point on the land or under the sea can be characterised by the physical and chemical processes that are active there and the organisms that live under those conditions at that time. As an example, a fluvial (river) environment includes a channel confining the flow of fresh water that carries and deposits gravelly or sandy material on bars in the channel (Fig. 1.1). When the river floods, water spreads relatively fine sediment over the floodplain where it is deposited in thin layers. Soils form and vegetation grows on the floodplain area. In a succession of sedimentary rocks (Fig. 1.2) the channel may be represented by a lens of sandstone or conglomerate that shows internal structures formed by deposition on the channel bars. The floodplain setting will be represented by thinly bedded mudrock and sandstone with roots and other evidence of soil formation.

In the description of sedimentary rocks in terms of depositional environments, the term 'facies' is often used. A rock ***facies*** is a body of rock with specified characteristics that reflect the conditions under which it was formed (Reading & Levell 1996). Describing the facies of a body of sediment involves documenting all the characteristics of its lithology, texture, sedimentary structures and fossil content that can aid in determining the processes of formation. By recognising associations of facies it is possible to establish the combinations of processes that were dominant; the characteristics of a depositional environment are determined by the processes that are present, and hence there is a link between facies associations and environments of deposition. The lens of sandstone in Fig. 1.2 may be shown to be a river channel if the floodplain deposits are found associated with it. However, recognition of a channel form on its own is not a sufficient basis to determine the depositional environment because channels filled with sand exist in other settings, including deltas,

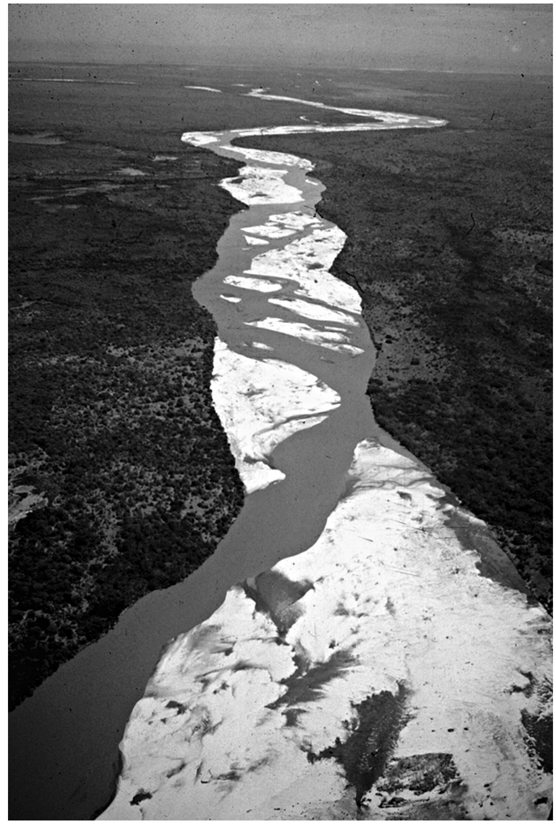

Fig. 1.1 A modern depositional environment: a sandy river channel and vegetated floodplain.

Fig. 1.2 Sedimentary rocks interpreted as the deposits of a river channel (the lens of sandstones in the centre right of the view) scoured into mudstone deposited on a floodplain (the darker, thinly bedded strata below and to the side of the sandstone lens).

tidal environments and the deep sea floor: it is the association of different processes that provides the full picture of a depositional environment.

1.3 THE SPECTRUM OF ENVIRONMENTS AND FACIES

Every depositional environment has a unique combination of processes, and the products of these processes, the sedimentary rocks, will be a similarly unique assemblage. For convenience of description and interpretation, depositional environments are classified as, for example, a delta, an estuary or a shoreline, and subcategories of each are established, such as wave-dominated, tide-dominated and river-dominated deltas. This approach is in general use by sedimentary geologists and is followed in this book. It is, however, important to recognise that these environments of deposition are convenient categories or 'pigeonholes', and that the description of them tends to be of 'typical' examples. The reality is that every delta, for example, is different from its neighbour in space or time, that every deltaic deposit will also be unique, and although we categorise deltas into a number of types, our deposit is likely to fall somewhere in between these 'pigeonholes'. Sometimes it may not even be possible to conclusively distinguish between the deposits of a delta and an estuary, especially if the data set is incomplete, which it inevitably is when dealing with events of the past. However, by objectively considering each bed in terms of physical, chemical and biological processes, it is always possible to provide some indication of where and how a sedimentary rock was formed.

1.4 STRATIGRAPHY

Use of the term 'stratigraphy' dates back to d'Orbingy in 1852, but the concept of layers of rocks, or strata, representing a sequence of events in the past is much older. In 1667 Steno developed the principle of superposition: 'in a sequence of layered rocks, any layer is older than the layer next above it'. Stratigraphy can be considered as the relationship between rocks and time and the stratigrapher is concerned with the observation, description and interpretation of direct and tangible evidence in rocks to determine the history of the Earth. We all recognise that our planet is a dynamic place, where plate tectonics creates mountains and oceans and where changes in the atmosphere affect the climate, perhaps even on a human time scale. To understand how these global systems work, we need a record of their past behaviour to analyse, and this is provided by the study of stratigraphy.

Stratigraphy provides the temporal framework for geological sciences. The relative ages of rocks, and hence the events that are recorded in those rocks, can be determined by simple stratigraphic relationships (younger rocks generally lie on top of older, as Steno recognised), the fossils that are preserved in strata and by measurements of processes such as the radioactive decay of elements that allow us to date some rock units. At one level, stratigraphy is about establishing a nomenclature for rock units of all ages and correlating them all over the world, but at another level it is about finding the evidence for climate change in the past or the movements of tectonic plates. One of the powerful tools we have for predicting future climate change is the record in the rock strata of local and global changes over periods of thousands to millions of years. Furthermore our understanding of evolutionary processes is in part derived from the study of fossils found in rocks of different ages that tell us about how forms of life have changed through time. Other aspects of stratigraphy provide the tools for finding new resources: for example, 'sequence stratigraphy' is a predictive technique, widely used in the hydrocarbon industry, that can be used to help to find new reserves of oil and gas.

The combination of sedimentology and stratigraphy allows us to build up pictures of the Earth's surface at different times in different places and relate them to each other. The character of the sedimentary rocks deposited might, for example, indicate that at one time a certain area was an arid landscape, with desert dunes and with washes of gravel coming from a nearby mountain range. In that same place, but at a later time, conditions allowed the formation of coral reefs in a shallow sea far away from any landmass, and we can find the record of this change by interpreting the rocks in terms of their processes and environments of deposition. Furthermore, we might establish that at the same time as there were shallow tropical seas in one place, there lay a deep ocean a few tens of kilometres away where fine sediment was deposited by ocean currents. We can thus build up pictures of the ***palaeogeography***, the appearance of an area during some time in the past, and establish changes in palaeogeography through Earth history. To complete the picture, the distribution of different environments and their changes through time can be related to plate tectonics, because mountain building provides the source for much of the sediment, and plate movements also create the sedimentary basins where sediment accumulates.

1.5 THE STRUCTURE OF THIS BOOK

Sedimentology and stratigraphy can be considered together as a continuum of processes and products, both in space and time. Sedimentology is concerned primarily with the formation of sedimentary rocks but as soon as these beds of rock are looked at in terms of their temporal and spatial relationships the study has become stratigraphic. Similarly if the stratigrapher wishes to interpret layers of rock in terms of environments of the past the research is sedimentological. It is therefore appropriate to consider sedimentology and stratigraphy together at an introductory level.

The starting point taken in this book is the smallest elements, the particles of sand, pebbles, clay minerals, pieces of shell, algal filaments, chemical precipitates and other constituents that make up sediments (Chapters 2 and 3). An introduction to the petrographic analysis of sedimentary materials in hand specimen and under the microscope is included in these chapters. In Chapter 4 the processes of sediment transport and deposition are considered, followed by a section on the methodology of recording and analysing sedimentary data in the field in Chapter 5. Weathering and erosion is considered in Chapter 6 as an introduction to the processes which generate the clastic material that is deposited in many sedimentary environments. The following chapters (7 to 17) deal largely with different depositional environments, outlining the physical, chemical and biological processes that are active, the characteristics of the products of these processes and how they may be recognised in sedimentary rocks. Continental environments are covered in Chapters 8 to 10, followed by marine environments in Chapters 12 to 16 – the general theme being to start at the top, with the mountains, and end up in the deep oceans. Exceptions to this pattern are Chapter 7 on glacial environments and Chapter 17 on volcanic processes and products. Post-depositional processes, including lithification and the formation of hydrocarbons, are considered in Chapter 18. Chapters 19 to 23 are on different aspects of stratigraphy and are intended to provide an introduction to the principles of stratigraphic analysis using techniques such as lithostratigraphy, biostratigraphy and sequence stratigraphic correlation. The final chapters in the book provide a brief introduction to sedimentary basins and the large-scale tectonic and climatic controls on the sedimentary record.

Sedimentology and stratigraphy cannot be considered in isolation from other aspects of geology, and in particular, plate tectonics, petrology, palaeontology and geomorphology are complementary topics. Reference is made to these subjects in the text, but only a basic knowledge of these topics is assumed.

FURTHER READING

The following texts provide a general background to geology.

Chernicoff, S. & Whitney, D. (2007) *Geology: an Introduction to Physical Geology* (4th edition). Pearson/Prentice Hall, New Jersey.

Grotzinger, J., Jordan, T.H., Press, F. & Siever, R. (2007) *Understanding Earth* (5th edition). Freeman and Co., New York.

Lutgens, F.K. & Tarbuck, E.J. (2006) *Essentials of Geology* (9th edition). Pearson/Prentice Hall, New Jersey.

Smith, G.A. & Pun, A. (2006) *How Does the Earth Work? Physical Geology and the Process of Science*. Pearson/Prentice Hall, New Jersey.

Summerfield, M.A. (1991) *Global Geomorphology: an Introduction to the Study of Landforms*. Longman/Wiley, London/New York.

2

Terrigenous Clastic Sediments: Gravel, Sand and Mud

Terrigenous clastic sediments and sedimentary rocks are composed of fragments that result from the weathering and erosion of older rocks. They are classified according to the sizes of clasts present and the composition of the material. Analysis of gravels and conglomerates can be carried out in the field and can reveal where the material came from and how it was transported. Sands and sandstones can also be described in the field, but for a complete analysis examination under a petrographic microscope is required to reveal the composition of individual grains and their relationships to each other. The finest sediments, silt and clay, can only be fully analysed using scanning electron microscopes and X-ray diffractometers. The proportions of different clast sizes and the textures of terrigenous clastic sediments and sedimentary rocks can provide information about the history of transport of the material and the environment of deposition.

2.1 CLASSIFICATION OF SEDIMENTS AND SEDIMENTARY ROCKS

A convenient division of all sedimentary rocks is shown in Fig. 2.1. Like most classification schemes of natural processes and products it includes anomalies (a deposit of chemically precipitated calcium carbonate would be classified as a limestone, not an evaporite) and arbitrary divisions (the definition of a limestone as a rock having more than 50% calcium carbonate), but it serves as a general framework.

Terrigenous clastic material This is material that is made up of particles or ***clasts*** derived from pre-existing rocks. The clasts are principally detritus eroded from bedrock and are commonly made up largely of silicate minerals: the terms ***detrital sediments*** and ***siliciclastic sediments*** are also used for this material. Clasts range in size from clay particles measured in microns, to boulders metres across. Sandstones and conglomerates make up 20–25% of the sedimentary rocks in the stratigraphic record and mudrocks are 60% of the total.

Carbonates By definition, a limestone is any sedimentary rock containing over 50% calcium carbonate ($CaCO_3$). In the natural environment a principal source of calcium carbonate is from the hard parts of organisms, mainly invertebrates such

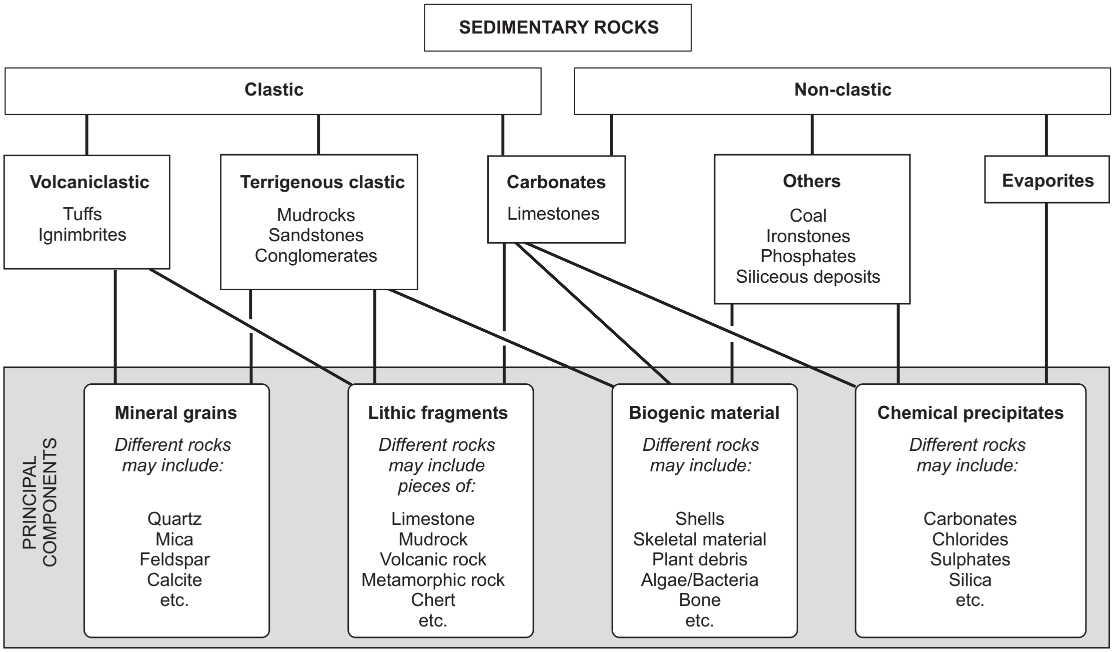

Fig. 2.1 A classification scheme for sediments and sedimentary rocks.

as molluscs. Limestones constitute 10–15% of the sedimentary rocks in the stratigraphic record.

Evaporites These are deposits formed by the precipitation of salts out of water due to evaporation.

Volcaniclastic sediments These are the products of volcanic eruptions or the result of the breakdown of volcanic rocks.

Others Other sediments and sedimentary rocks are sedimentary ironstone, phosphate sediments, organic deposits (coals and oil shales) and cherts (siliceous sedimentary rocks). These are volumetrically less common than the above, making up about 5% of the stratigraphic record, but some are of considerable economic importance.

In this chapter terrigenous clastic deposits are considered: the other types of sediment and sedimentary rock are covered in Chapter 3.

2.1.1 Terrigenous clastic sediments and sedimentary rocks

A distinction can be drawn between sediments (generally loose material) and sedimentary rocks which are lithified sediment: ***lithification*** is the process of 'turning into rock' (*18.2*). Mud, silt and sand are all loose ***aggregates***; the addition of the suffix '-stone' (mudstone, siltstone, sandstone) indicates that the material has been lithified and is now a solid rock. Coarser, loose gravel material is named according to its size as granule, pebble, cobble and boulder aggregates, which become lithified into conglomerate (sometimes with the size range added as a prefix, e.g. 'pebble conglomerate').

A threefold division on the basis of grain size is used as the starting point to classify and name terrigenous clastic sediments and sedimentary rocks: gravel and conglomerate consist of clasts greater than 2 mm in diameter; sand-sized grains are between 2 mm and 1/16 mm (63 microns) across; mud (including clay and silt) is made up of particles less than 63 μm in diameter. There are variants on this scheme and there are a number of ways of providing subdivisions within these categories, but sedimentologists generally use the Wentworth Scale (Fig. 2.2) to define and name terrigenous clastic deposits.

mm	phi	Name	
		Boulders	Gravel Conglomerate
256	–8		
128	–7		
64	–6	Cobbles	
32	–5		
16	–4		
8	–3	Pebbles	
4	–2		
		Granules	
2	–1		
		Very coarse sand	Sand Sandstone
1	0		
		Coarse sand	
0.5	1		
		Medium sand	
0.25	2		
		Fine sand	
0.125	3		
		Very fine sand	
0.063	4		
		Coarse silt	Mud Mudrock
0.031	5		
		Medium silt	
0.0156	6		
		Fine silt	
0.0078	7		
		Very fine silt	
0.0039	8		
		Clay	

Fig. 2.2 The Udden–Wentworth grain-size scale for clastic sediments: the clast diameter in millimetres is used to define the different sizes on the scale, and the phi values are $-\log_2$ of the grain diameter.

2.1.2 The Udden–Wentworth grain-size scale

Known generally as the ***Wentworth Scale***, this is the scheme in most widespread use for the classification of aggregates particulate matter (Udden 1914; Wentworth 1922). The divisions on the scale are made on the basis of factors of two: for example, medium sand grains are 0.25 to 0.5 mm in diameter, coarse sand grains are 0.5 to 1.0 mm, very coarse sand 1.0 to 2.0 mm, etc. It is therefore a logarithmic progression, but a logarithm to the 'base two', as opposed to the 'base ten' of the more common 'log' scales. This scale has been chosen because these divisions appear to reflect the natural distribution of sedimentary particles and in a simple way it can be related to starting with a large block and repeatedly breaking it into two pieces.

Four basic divisions are recognised:

clay (<4 μm)
silt (4 μm to 63 μm)
sand (63 μm or 0.063 mm to 2.0 mm)
gravel/aggregates (>2.0 mm)

The ***phi scale*** is a numerical representation of the Wentworth Scale. The Greek letter 'ϕ' (phi) is often used as the unit for this scale. Using the logarithm base two, the grain size can be denoted on the phi scale as

$$\phi = -\log_2 \text{(grain diameter in mm)}$$

The negative is used because it is conventional to represent grain sizes on a graph as decreasing from left to right (*2.5.1*). Using this formula, a grain diameter of 1 mm is 0ϕ: increasing the grain size, 2 mm is −1ϕ, 4 mm is −2ϕ, and so on; decreasing the grain size, 0.5 mm is +1ϕ, 0.25 mm is 2ϕ, etc.

2.2 GRAVEL AND CONGLOMERATE

Clasts over 2 mm in diameter are divided into granules, pebbles, cobbles and boulders (Fig. 2.2). Consolidated gravel is called ***conglomerate*** (Fig. 2.3) and when described will normally be named according to the dominant clast size: if most of the clasts are between 64 mm and 256 mm in diameter the rock would be called a cobble conglomerate. The term ***breccia*** is commonly used for conglomerate made up of clasts that are angular in shape (Fig. 2.4). In

Fig. 2.3 A conglomerate composed of well-rounded pebbles.

Fig. 2.4 A conglomerate (or breccia) made up of angular clasts.

some circumstances it is prudent to specify that a deposit is a 'sedimentary breccia' to distinguish it from a 'tectonic breccia' formed by the fragmentation of rock in fault zones. Mixtures of rounded and angular clasts are sometimes termed ***breccio-conglomerate***. Occasionally the noun ***rudite*** and the adjective ***rudaceous*** are used: these terms are synonymous with conglomerate and conglomeratic.

2.2.1 Composition of gravel and conglomerate

A more complete description of the nature of a gravel or conglomerate can be provided by considering the types of clast present. If all the clasts are of the same material (all of granite, for example), the conglomerate is considered to be ***monomict***. A ***polymict*** conglomerate is one that contains clasts of many different lithologies, and sometimes the term ***oligomict*** is used where there are just two or three clast types present.

Almost any lithology may be found as a clast in gravel and conglomerate. ***Resistant lithologies***, those which are less susceptible to physical and chemical breakdown, have a higher chance of being preserved as a clast in a conglomerate. Factors controlling the resistance of a rock type include the minerals present and the ease with which they are chemically or physically broken down in the environment. Some sandstones break up into sand-sized fragments when eroded because the grains are weakly cemented together. The most important factor controlling the varieties of clast found is the bedrock being eroded in the area. Gravel will be composed entirely of limestone clasts if the source area is made up only of limestone bedrock. Recognition of the variety of clasts can therefore be a means of determining the source of a conglomeratic sedimentary rock (*5.4.1*).

2.2.2 Texture of conglomerate

Conglomerate beds are rarely composed entirely of gravel-sized material. Between the granules, pebbles, cobbles and boulders, finer sand and/or mud will often be present: this finer material between the large clasts is referred to as the ***matrix*** of the deposit. If there is a high proportion (over 20%) of matrix, the rock may be referred to as a ***sandy conglomerate*** or ***muddy conglomerate***, depending on the grain size of the matrix present (Fig. 2.5). An ***intraformational conglomerate*** is composed of clasts of the same material as the matrix and is formed as a result of reworking of lithified sediment soon after deposition.

The proportion of matrix present is an important factor in the texture of conglomeratic sedimentary rock, that is, the arrangement of different grain sizes within it. A distinction is commonly made between conglomerates that are ***clast-supported*** (Fig. 2.6), that is, with clasts touching each other throughout the rock, and those which are ***matrix-supported*** (Fig. 2.7), in which most of the clasts are completely surrounded by matrix. The term ***orthoconglomerate*** is sometimes used to indicate that the rock is clast-supported, and ***paraconglomerate*** for a matrix-supported texture. These textures are significant when determining the mode of transport and deposition of a conglomerate (e.g. on alluvial fans: *9.5*).

The arrangement of the sizes of clasts in a conglomerate can also be important in interpretation of depositional processes. In a flow of water, pebbles are moved more easily than cobbles that in turn require less energy to move them than boulders. A deposit that is made up of boulders overlain by cobbles and then pebbles may be interpreted in some cases as having been formed from a flow that was decreasing in velocity. This sort of interpretation is one of the techniques used in determining the processes of transport and deposition of sedimentary rocks (*4.2*).

2.2.3 Shapes of clasts

The shapes of clasts in gravel and conglomerate are determined by the fracture properties of the bedrock they are derived from and the history of transport.

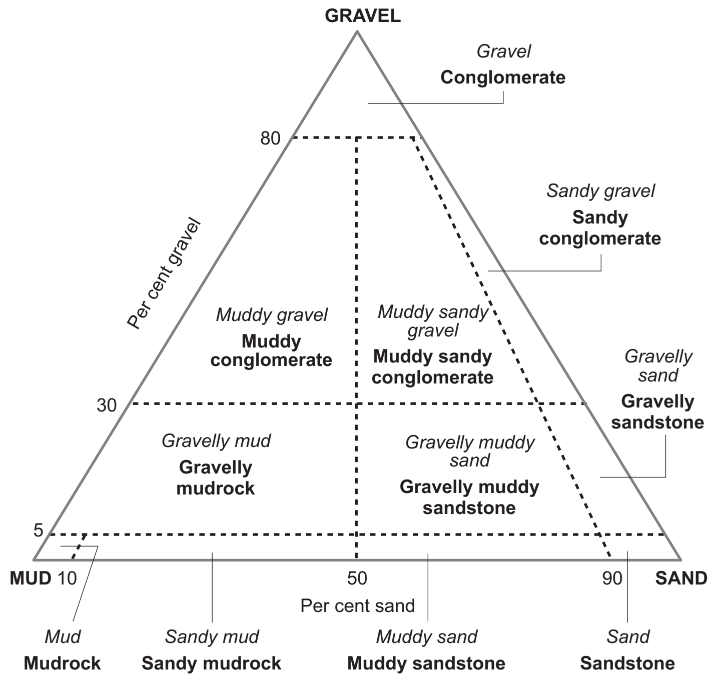

Fig. 2.5 Nomenclature used for mixtures of gravel, sand and mud in sediments and sedimentary rock.

Rocks with equally spaced fracture planes in all directions form cubic or ***equant*** blocks that form spherical clasts when the edges are rounded off (Fig. 2.8). Bedrock lithologies that break up into slabs, such as a well-bedded limestone or sandstone, form clasts with one axis shorter than the other two (Krumbein & Sloss 1951). This is termed an ***oblate*** or ***discoid*** form. Rod-shaped or ***prolate*** clasts are less common, forming mainly from metamorphic rocks with a strong linear fabric.

When discoid clasts are moved in a flow of water they are preferentially oriented and may stack up in a form known as ***imbrication*** (Figs 2.9 & 2.10). These stacks are arranged in positions that offer the least resistance to flow, which is with the discoid clasts dipping upstream. In this orientation, the water can flow most easily up the upstream side of the clast, whereas when clasts are oriented dipping down stream, flow at the edge of the clast causes it to be reoriented. The direction of imbrication of discoid

Fig. 2.6 A clast-supported conglomerate: the pebbles are all in contact with each other.

Fig. 2.7 A matrix-supported conglomerate: each pebble is surrounded by matrix.

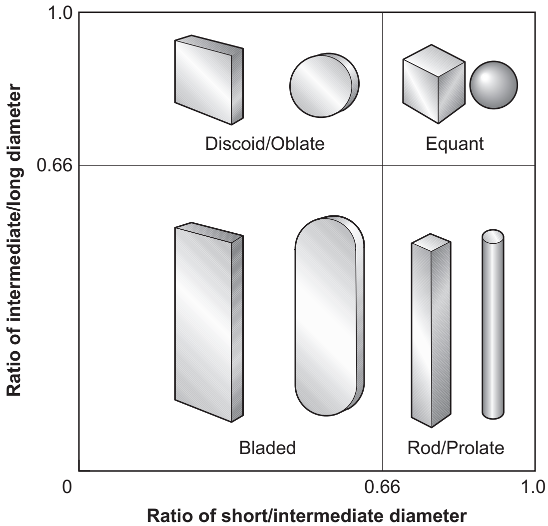

Fig. 2.8 The shape of clasts can be considered in terms of four end members, equant, rod, disc and blade. Equant and disc-shaped clasts are most common.

Fig. 2.9 A conglomerate bed showing imbrication of clasts due to deposition in a current flowing from left to right.

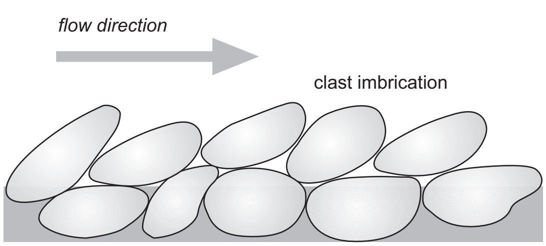

Fig. 2.10 The relationship between imbrication and flow direction as clasts settle in a stable orientation.

pebbles in a conglomerate can be used to indicate the direction of the flow that deposited the gravel. If a discoid clast is also elongate, the orientation of the longest axis can help to determine the mode of deposition: clasts deposited by a flow of water will tend to have their long axis oriented perpendicular to the flow, whereas glacially deposited clasts (*7.3.3*) will have the long axis oriented parallel to the ice flow.

2.3 SAND AND SANDSTONE

Sand grains are formed by the breakdown of pre-existing rocks by weathering and erosion (*6.4 & 6.5*), and from material that forms within the depositional environment. The breakdown products fall into two categories: ***detrital mineral grains***, eroded from pre-existing rocks, and sand-sized pieces of rock, or ***lithic fragments***. Grains that form within the depositional environment are principally biogenic in origin, that is, they are pieces of plant or animal, but there are some which are formed by chemical reactions.

Sand may be defined as a sediment consisting primarily of grains in the size range 63 μm to 2 mm and a ***sandstone*** is defined as a sedimentary rock with grains of these sizes. This size range is divided into five intervals: very fine, fine, medium, coarse and very coarse (Fig. 2.2). It should be noted that this nomenclature refers only to the size of the particles. Although many sandstones contain mainly quartz grains, the term sandstone carries no implication about the amount of quartz present in the rock and some sandstones contain no quartz at all. Similarly, the term ***arenite***, which is a sandstone with less than 15% matrix, does not imply any particular clast composition. Along with the adjective ***arenaceous*** to describe a rock as sandy, arenite has its etymological roots in the Latin word for sand, 'arena', also used to describe a stadium with a sandy floor.

2.3.1 Detrital mineral grains in sands and sandstones

A very large number of different minerals may occur in sands and in sandstones, and only the most common are described here.

Quartz

Quartz is the commonest mineral species found as grains in sandstone and siltstone. As a primary mineral it is a major constituent of granitic rocks, occurs in some igneous rocks of intermediate composition and is absent from basic igneous rock types. Metamorphic rocks such as gneisses formed from granitic material and many coarse-grained metasedimentary rocks contain a high proportion of quartz. Quartz also occurs in veins, precipitated by hot fluids associated with igneous and metamorphic processes. Quartz is a very stable mineral that is resistant to chemical breakdown at the Earth's surface. Grains of quartz may be broken or abraded during transport but with a hardness of 7 on ***Mohs' scale*** of hardness, quartz grains remain intact over long distances and long periods of transport. In hand specimen quartz grains show little variation: coloured varieties such as smoky or milky quartz and amethyst occur but mostly quartz is seen as clear grains.

Feldspar

Most igneous rocks contain feldspar as a major component. Feldspar is hence very common and is released in large quantities when granites, andesites, gabbros as well as some schists and gneisses break down. However, feldspar is susceptible to chemical alteration during weathering and, being softer than quartz, tends to be abraded and broken up during transport. Feldspars are only commonly found in circumstances where the chemical weathering of the bedrock has not been too intense and the transport pathway to the site of deposition is relatively short. Potassium feldspars are more common as detrital grains than sodium- and calcium-rich varieties, as they are chemically more stable when subjected to weathering (*6.4*).

Mica

The two commonest mica minerals, ***biotite*** and ***muscovite***, are relatively abundant as detrital grains in sandstone, although muscovite is more resistant to weathering. They are derived from granitic to intermediate composition igneous rocks and from schists and gneisses where they have formed as metamorphic minerals. The platy shape of mica grains makes them distinctive in hand specimen and under the microscope. Micas tend to be concentrated in bands on bedding planes and often have a larger surface area than the other detrital grains in the sediment; this is because a platy grain has a lower settling velocity than an equant mineral grain of the same mass and volume so micas stay in temporary suspension longer than quartz or feldspar grains of the same mass.

Heavy minerals

The common minerals found in sands have densities of around 2.6 or 2.7 g cm^{-3}: quartz has a density of 2.65 g cm^{-3}, for example. Most sandstones contain a small proportion, commonly less than 1%, of minerals that have a greater density. These ***heavy minerals*** have densities greater than 2.85 g cm^{-3} and are traditionally separated from the bulk of the lighter minerals by using a liquid of that density which the common minerals will float in but the small proportion of dense minerals will sink. These minerals are uncommon and study of them is only possible after concentrating them by dense liquid separation. They are valuable in provenance studies (*5.4.1*) because they can be characteristic of a particular source area and are therefore valuable for studies of the sources of detritus. Common heavy minerals include zircon, tourmaline, rutile, apatite, garnet and a range of other metamorphic and igneous accessory minerals.

Miscellaneous minerals

Other minerals rarely occur in large quantities in sandstone. Most of the common minerals in igneous silicate rocks (e.g. olivine, pyroxenes and amphiboles) are all too readily broken down by chemical weathering. Oxides of iron are relatively abundant. Local concentrations of a particular mineral may occur when there is a nearby source.

2.3.2 Other components of sands and sandstones

Lithic fragments

The breakdown of pre-existing, fine- to medium-grained igneous, metamorphic and sedimentary rocks results in sand-sized fragments. Sand-sized lithic fragments are only found of fine to medium-grained rocks because by definition the mineral crystal and grains of a coarser-grained rock type are the size of sand grains or larger. Determination of the lithology of these fragments of rock usually requires petrographic analysis by thin-section examination (*2.3.5*) to identify the mineralogy and fabric.

Grains of igneous rocks such as basalt and rhyolite are susceptible to chemical alteration at the Earth's surface and are only commonly found in sands formed close to the source of the volcanic material. Beaches around volcanic islands may be black because they are made up almost entirely of lithic grains of basalt. Sandstone of this sort of composition is rare in the stratigraphic record, but grains of volcanic rock types may be common in sediments deposited in basins related to volcanic arcs or rift volcanism (Chapter 17).

Fragments of schists and pelitic (fine-grained) metamorphic rocks can be recognised under the microscope by the strong aligned fabric that these lithologies possess: pressure during metamorphism results in mineral grains becoming reoriented or growing into an alignment perpendicular to the stress field. Micas most clearly show this fabric, but quartz crystals in a metamorphic rock may also display a strong alignment. Rocks formed by the metamorphism of quartz-rich lithologies break down to relatively resistant grains that can be incorporated into a sandstone.

Lithic fragments of sedimentary rocks are generated when pre-existing strata are uplifted, weathered and eroded. Sand grains can be reworked by this process and individual grains may go through a number of cycles of erosion and redeposition (*2.5.4*). Finer-grained mudrock lithologies may break up to form sand-sized grains although their resistance to further breakdown during transport is largely dependent on the degree of lithification of the mudrock (*18.2*). Pieces of limestone are commonly found as lithic fragments in sandstone although a rock made up largely of calcareous grains would be classified as a limestone (*3.1*). One of the most common lithologies seen as a sand grain is chert (*3.3*), which being silica is a resistant material.

Biogenic particles

Small pieces of calcium carbonate found in sandstone are commonly broken shells of molluscs and other organisms that have calcareous hard parts. These ***biogenic fragments*** are common in sandstone deposited in shallow marine environments where these organisms are most abundant. If these calcareous fragments make up over 50% of the bulk of the rock it would be considered to be a limestone (the nature and occurrence of calcareous biogenic fragments is described in the next chapter: *3.1.3*). Fragments of bone and teeth may be found in sandstones from a wide variety of environments but are rarely common. Wood, seeds and other parts of land plants may be preserved in sandstone deposited in continental and marine environments.

Authigenic minerals

Minerals that grow as crystals in a depositional environment are called ***authigenic*** minerals. They are distinct from all the detrital minerals that formed by igneous or metamorphic processes and were subsequently reworked into the sedimentary realm. Many carbonate minerals form authigenically and another important mineral formed in this way is glauconite/glaucony (*11.5.1*), a green iron silicate that forms in shallow marine environments.

Matrix

Fine-grained material occurring between the sand grains is referred to as matrix (*2.2.2*). In sands and sandstone the matrix is typically silt and clay-sized material, and it may wholly or partly fill the spaces between the grains. A distinction should be drawn between the matrix, which is material deposited along with the grains, and cement (*18.2.2*), which is chemically precipitated after deposition.

2.3.3 Sandstone nomenclature and classification

Full description of a sandstone usually includes some information concerning the types of grain present. Informal names such as ***micaceous sandstone*** are used when the rock clearly contains a significant amount of a distinctive mineral such as mica. Terms such as ***calcareous sandstone*** and ***ferruginous sandstone*** may also be used to indicate a particular chemical composition, in these cases a noticeable proportion of calcium carbonate and iron respectively. These names for a sandstone are useful and appropriate for field and hand-specimen descriptions, but when a full petrographic analysis is possible with a thin-section of the rock under a microscope, a more

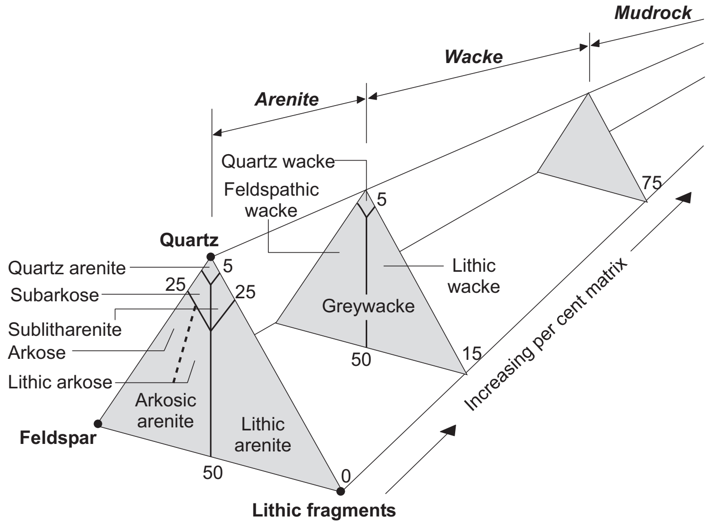

Fig. 2.11 The Pettijohn classification of sandstones, often referred to as a 'Toblerone plot' (Pettijohn 1975).

formal nomenclature is used. This is usually the Pettijohn et al. (1987) classification scheme (Fig. 2.11).

The Pettijohn sandstone classification combines textural criteria, the proportion of muddy matrix, with compositional criteria, the percentages of the three commonest components of sandstone: quartz, feldspar and lithic fragments. The triangular plot has these three components as the end members to form a '***Q, F, L***' triangle, which is commonly used in clastic sedimentology. To use this scheme for sandstone classification, the relative proportions of quartz, feldspar and lithic fragments must first be determined by visual estimation or by counting grains under a microscope: other components, such as mica or biogenic fragments, are disregarded. The third dimension of the classification diagram is used to display the texture of the rock, the relative proportions of clasts and matrix. In a sandstone the matrix is the silt and clay material that was deposited with the sand grains. The second stage is therefore to measure or estimate the amount of muddy matrix: if the amount of matrix present is less than 15% the rock is called an arenite, between 15% and 75% it is a ***wacke*** and if most of the volume of the rock is fine-grained matrix it is classified as a mudstone (*2.4.1*).

Quartz is the most common grain type present in most sandstones so this classification emphasises the presence of other grains. Only 25% feldspar need be present for the rock to be called a ***feldspathic arenite***, ***arkosic arenite*** or ***arkose*** (these three terms are interchangeable when referring to sandstone rich in feldspar grains). By the same token, 25% of lithic fragments in a sandstone make it a ***lithic arenite*** by this scheme. Over 95% of quartz must be present for a rock to be classified as a ***quartz arenite***; sandstone with intermediate percentages of feldspar or lithic grains is called subarkosic arenite and sublithic arenite. Wackes are similarly divided into ***quartz wacke***, ***feldspathic*** (***arkosic***) ***wacke*** and ***lithic wacke***, but without the subdivisions. If a grain type other than the three main components is present in significant quantities (at least 5% or 10%), a prefix may be used such as 'micaceous quartz arenite': note that such a rock would not necessarily contain 95% quartz as a proportion of all the grains present, but 95% of the quartz, feldspar and lithic fragments when they are added together.

The term ***greywacke*** has been used in the past for a sandstone that might also be called a feldspathic or lithic wacke. They are typically mixtures of rock fragments, quartz and feldspar grains with a matrix of clay and silt-sized particles.

2.3.4 Petrographic analysis of sands and sandstones

In sand-grade rocks, the nature of the individual grains and the relationship between these grains and the material between them is best seen in a ***thin-section***

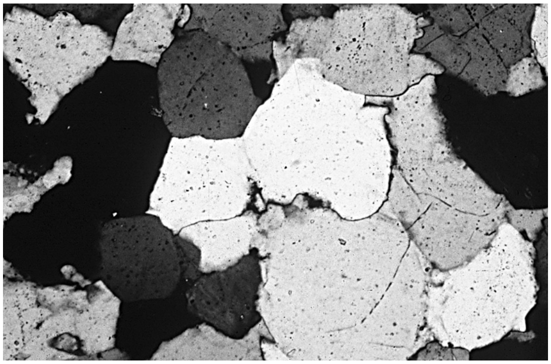

Fig. 2.12 A photomicrograph of a sandstone: the grains are all quartz but appear different shades of grey under crossed polars due to different orientations of the grains.

of the rock, a very thin (normally 30 microns) slice of the rock, which can be examined under a ***petrological/petrographic microscope*** (Fig. 2.12). Thin-section examination is a standard technique for the analysis of almost all types of rock, igneous and metamorphic as well as sedimentary, and the procedures form part of the training of most geologists.

The petrographic microscope

A thin-section of a rock is cemented onto a glass microscope slide and it is normal practice to cement a thin glass cover slip over the top of the rock slice to form a sandwich, but there are circumstances where the thin-section is left uncovered (*3.1.2*). The slide is placed on the microscope stage where a beam of white light is projected through the slide and up through the lenses to the eyepiece: this transmitted light microscopy is the normal technique for the examination of rocks, the main exceptions being ore minerals, which are examined using reflected light (this is because of the optical properties of the minerals concerned – see below). The majority of minerals are translucent when they are sliced to 30 microns thick, whatever their colour or appearance in hand specimen: this is particularly true of silicate and carbonate minerals, which are the groups of prime interest to the sedimentary geologist. It is therefore possible to view the ***optical properties*** of the minerals, the way they appear and interact with the light going through them, using a petrographic microscope.

Underneath the microscope stage the light beam passes through a ***polarising filter***, which only allows light waves vibrating in one plane to pass through it and hence through the thin-section. Toward the bottom of the eyepiece tube there is a second polarising filter that is retractable. This polarising filter is mounted perpendicular to the one below the stage, such that it only allows through light waves that are vibrating at ninety degrees to the lower one. If this second filter, known as the ***analysing filter***, is inserted across the lenses when there is no thin-section, or just plain glass, on the stage, then all the light from the beam will be cut out and it appears black. The same effect can be achieved with 'Polaroid' sunglasses: putting two Polaroid lenses at ninety degrees to each other should result in the blocking out of all light.

Other standard features on a petrographic microscope are a set of lenses at the end of the eyepiece tube that allow different magnifications of viewing to be achieved. The total magnification will be a multiple of one of these lenses and the eyepiece magnification. The eyepiece itself has a very fine cross-wire mounted in it: this acts as a frame of reference to be used when the orientation of the thin-section is changed by rotating the stage. The stage itself is graduated in degrees around the edge so that the amount of rotation can be measured. An optional feature within the eyepiece is a ***graticule***, a scale that allows measurements of features of the thin-section to be made if the magnification is known.

There are usually further tools for optical analyses on the microscope, such as additional lenses that can be inserted above and below the stage, and plates that can be introduced into the eyepiece tube. These are used when advanced petrographic techniques are employed to make more detailed analyses of minerals. However, at an introductory level of sedimentary petrography, such techniques are rarely used, and analysis can be carried out using only a limited range of the optical properties of minerals, which are described in the following sections.

2.3.5 Thin-section analysis of sandstones

Use of the following techniques will allow identification of the most frequently encountered minerals in sedimentary rocks. Only a very basic introduction to the principles and application of thin-section analysis is provided here. For more detailed and advanced petrographic analysis, reference should be made to an appropriate book on optical mineralogy (e.g. Gribble & Hall 1999; Nesse 2004), which should be used in conjunction with suitable reference books on sedimentary petrography, particularly colour guides such as Adams et al. (1984).

Grain shape

A distinctive shape can be a characterising feature of a mineral, for example members of the mica family, which usually appear long and thin if they have been cut perpendicular to their platy form. Minerals may also be elongate, needle-like or equant, but in all cases it must be remembered that the shape depends on the angle of the cut through the grain. Grain shape also provides information about the history of the sediment (*2.5.4*) so it is important to distinguish between grains that show crystal faces and those that show evidence of abrasion of the edges.

Relief

Relief is a measure of how strong the lines that mark the edges of the mineral, or minerals that comprise a grain, are and how clearly the grain stands out against the glass or the other grains around it. It is a visual appraisal of the refractive index of the mineral, which is in turn related to its density. A mineral such as quartz has a refractive index that is essentially the same as glass, so a grain of quartz 30 microns thick mounted on a microscope slide will only just be visible (the mounting medium – glue – normally has the same optical properties as the glass slide): it is therefore considered to have ‘low relief’. In contrast, a grain of calcite against glass will appear to have very distinct, dark edges, because it is a denser mineral with a higher refractive index and therefore has a ‘high relief’. Because a sedimentary grain will often be surrounded by a cement (*18.2.2*) the contrast with the cement is important, and a quartz grain will stand out very clearly if surrounded by a calcite cement. Certain ‘heavy minerals’, such as zircon, can readily be distinguished by their extremely high relief.

Cleavage

Not all minerals have a regular ***cleavage***, a preferred fracture orientation determined by the crystal lattice structure, so the presence or absence of a cleavage when the mineral is viewed in thin-section can be a useful distinguishing feature. Quartz, for example, lacks a cleavage, but feldspars, which otherwise have many optical properties that are similar to quartz, commonly show clear, parallel lines of cleavage planes. However, the orientation of the mineral in the thin-section will have an important effect because if the cut is parallel to the cleavage planes it will appear as if the mineral does not have a cleavage. The angle between pairs of cleavage planes can be important distinguishing features (e.g. between minerals of the pyroxene family and the amphibole group of minerals). The cleavage is usually best seen under plane-polarised light and often becomes clearer if the intensity of the light shining through is reduced.

Colour and opacity

This property is assessed using plane-polarised light (i.e. without the analysing filter inserted). Some minerals are completely clear while others appear slightly cloudy, but are essentially still colourless: minerals that display distinct colours in hand specimen do not necessarily show any colours in thin-section (e.g. purple quartz or pink feldspar). Colours may be faint tints or much stronger hues, the most common being shades of green and brown (some amphiboles and micas), with rarer yellows and blues. (A note of caution: if a rock is rather poorly lithified, part of the process of manufacture of the thin-section is to inject a resin into the pore spaces between the grains to consolidate it; this resin is commonly dyed bright blue so that it can easily be distinguished from the original components of the rock – it is not a blue mineral!)

Some grains may appear black or very dark brown. The black grains are opaque minerals that do not allow any light through them even when cut to a thin slice. Oxides and sulphides are the commonest opaque minerals in sedimentary rocks, particularly iron oxides (such as haematite) and iron sulphide (pyrite), although others may occur. Black grains that have a brown edge, or grains that are dark brown throughout, are likely to be fragments of organic material.

Pleochroism

A grain of hornblende, a relatively common member of the amphibole group, may appear green or brown when viewed under plane-polarised light, but what is distinctive is that it changes from one colour to the other when the grain is moved by rotating the microscope stage. This phenomenon is known as ***pleochroism*** and is also seen in biotite mica and a number of other minerals. It is caused by variations in the degree of absorption of different wavelengths of light when the crystal lattice is at different orientations.

Birefringence colours

When the analysing lens is inserted across the objective/eyepiece tube, the appearance of the minerals in the thin-section changes dramatically. Grains that had appeared colourless under plane-polarised light take on a range of colours, black, white or shades of grey, and this is a consequence of the way the polarised light has interacted with the minerals. Non-opaque minerals can be divided into two groups: ***isotropic minerals*** have crystal lattices that do not have any effect on the pathway of light passing through them, whatever orientation they are in (halite is an example of an isotropic mineral); when light passes through a crystal of an ***anisotropic mineral***, the pathway of the light is modified, and the degree to which it is affected depends on the orientation of the crystal. When a crystal of an isotropic mineral is viewed with both the polarising and analysing filters inserted (under ***cross-polars***), it appears black. However, an anisotropic mineral will distort the light passing through it, and some of the light passes through the analyser. The mineral will then appear to have a colour, a ***birefringence colour***, which will vary in hue and intensity depending on the mineral type and the orientation of the particular grain (and, in fact, the thickness of the slice, but thin-sections are normally cut to 30 microns, so this is not usually a consideration).

For any given mineral type there will be a 'maximum' birefringence colour on a spectrum of colours and hues that can be illustrated on a birefringence chart. In a general sense, minerals can be described as having one of the following: 'low' birefringence colours, which are greys (quartz and feldspars are examples), 'first order' colours (seen in micas), which are quite intense colours of the rainbow, and 'high order' colours, which are pale pinks and greens (common in carbonate minerals). Petrology reference books (e.g. Gribble & Hall 1999; Nesse 2004) include charts that show the birefringence colours for common minerals.

Angle of extinction

When the stage is rotated, the birefringence colour of a grain of an anisotropic mineral will vary as the crystal orientation is rotated with respect to the plane-polarised light. The grain will pass through a 'maximum' colour (although this may not be the maximum colour for this mineral, as this will depend on the three-dimensional orientation of the grain) and will pass through a point in the rotation when the grain is dark: this occurs when the crystal lattice is in an orientation when it does not influence the path of the polarised light. With some minerals the grain goes black – goes into ***extinction*** – when the grain is oriented with the plane of the polarised light parallel to a crystal face: this is referred to as parallel extinction. When viewed through the eyepiece of the microscope the grain will go into extinction when the crystal face is parallel to the vertical cross-wire. Many mineral types go into extinction at an angle to the plane of the polarised light: this can be measured by rotating a grain that has a crystal face parallel to the vertical cross-wire until it goes into extinction and measuring the angle against a reference point on the edge of the circular stage. Different types of feldspar can be distinguished on the basis of their extinction angle.

Twinning of crystals

Certain minerals commonly display a phenomenon known as ***twinning***, when two crystals have formed adjacent to each other but with opposite orientations of the crystal lattice (i.e. mirror images). Twinned crystals may be difficult to recognise under plane-polarised light, but when viewed under crossed polars the two crystals will go into extinction at 180° to each other. Multiple twins may also occur, and in fact are a characteristic of plagioclase feldspars, and these are seen as having a distinctive striped appearance under crossed polars.

2.3.6 The commonest minerals in sedimentary rocks

Almost any mineral which is stable under surface conditions could occur as a detrital grain in a sedimentary rock. In practice, however, a relatively small number of minerals constitute the vast majority of