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Sedimentary structures

THIRD EDITION

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Preface to the third edition

Since the publication of the second edition of this book in 1989, important advances have been made in many areas of sedimentology and, in view of frequent enquiries about the book's availability, we decided to prepare a third edition. This decision was made much easier by the inclusion of Nigel Mountney in the team, as he brings a fresh approach and a particular expertise in aeolian sediments, one of the main areas of advance in the past few years. The preparation of the book has also been encouraged by Roger Jones of Terra Publishing, who was also responsible for the publication of the first two editions.

The book is still envisaged primarily as an undergraduate text and it provides a starting point for understanding the morphology and process of formation of common sedimentary structures, with examples taken from both modern and ancient settings. The book is especially useful in both field and laboratory settings, and has been written for specialist Earth scientists and for non-specialists from a variety of educational backgrounds and subject areas who want to gain a basic understanding of the origin and form of structures in sediments and sedimentary rocks. It is hoped that this book will provide an introduction to more advanced topics in sedimentary processes and facies analysis

Although much of the book's content is based on basic physics and chemistry, we have tried to minimize the use of equations and have included only those that are essential for clear description and explanation of some of the key processes. We feel that even the most equation-shy reader will benefit from working through the basic explanations relating to important physical processes.

The whole book has been significantly rewritten and substantial changes have been made in the areas of aeolian sediments and trace fossils. Both of these topics have seen major advances in the past 20 years, with major textbooks and many scientific papers being published. In addition, new insights into gravitational mass movement of sediment have been developed. We hope that we have captured the essence of these advances within the confines and limitations of this relatively short book.

Throughout the book, we have tried to suggest ways in which simple experiments can help to reinforce understanding of some of the processes and ideas, and we hope that these will be seen as mere starting points for imaginative developments by teachers, tutors and students alike. The book is to some extent a field manual that allows structures to be recognized for a variety of geological purposes and, to some extent, a process-orientated account that allows students to use a basic experience of physics, chemistry and biology to explain the origins of structures. In this edition, we have simplified and updated the references and bibliographies. We have deliberately avoided referring to websites because many are ephemeral and others are of dubious accuracy.

We hope that this edition not only puts the book back into circulation but also provides a significant improvement on earlier editions. During its preparation, several colleagues have helped us in various ways. In particular we would like to thank John Pollard who has helped enormously with updating the section on trace fossils. We also thank Gilbert Kelling for providing several photographs, and all the authors and publishers who have allowed us to use illustrations from their publications.

John Collinson Nigel Mountney David Thompson
September 2006

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CHAPTER 1
Introduction

The study of sedimentary rocks has come a long way in the past 200 years. In the nineteenth century, they were regarded as the matrix in which fossils occurred and their study, as far as it went, was mainly tied up with the understanding of stratigraphy. Sedimentary rocks had clearly been deposited through time in some way, but little attention was paid to asking exactly how. There was a general appreciation of the idea that ancient processes and conditions of deposition were probably similar to those prevailing at the present day (actualism and uniformitarianism), but, with a few notable exceptions, detailed study concentrated on description of the rocks as materials, rather than as products of dynamic processes and environments. This attitude prevailed until the middle of the twentieth century, although pioneering studies had, by then, used sedimentary structures as indicators of top and bottom (way-up) in deformed successions and as a means of deducing palaeocurrent directions.

The second half of the twentieth century saw the development of the distinct discipline of sedimentology. This sought to explain sedimentary rocks in considerable detail in terms of the processes of sediment transport and deposition, the environments in which the rocks were laid down, and the processes that had influenced post-depositional changes during burial. These developments, initially driven to some extent by the needs of the oil industry in the exploration for hydrocarbon reserves, led to a much more detailed knowledge of the physical, chemical and biological processes of generation, transport and deposition of sedimentary materials. It also led to a greater understanding of the environments in which sediments were laid down and to the development of models (facies models) for the characterization and prediction of the organization of sedimentary successions produced in different settings. At the same time, the effects of animal and plant life in modifying sediments and the role of chemical reactions involving the sedimentary particles and their surrounding pore waters were all studied in great detail. Since the 1980s there has been an important integration of sedimentology and stratigraphy in the subdiscipline of sequence stratigraphy. This seeks to explain sedimentary successions in terms of larger-scale controls, developing around the ideas of relative sea level and accommodation space. The emphasis that such an approach places on the identification of “key surfaces” of transgression (landward retreat of a shoreline) associated with deepening, or on regression (seaward outbuilding of a shoreline) and erosive incision, and on the vertical stacking patterns of sediments drew attention away from the sediments themselves for a time. The balance is now nearly restored and we live in a time when a full integration of sedimentological and stratigraphical skills can yield great insights into the history of sedimentary successions at all scales, from the basin fill to the pore space.

In this context, sedimentary structures have a key role to play in the interpretation of sedimentary processes, which, in turn, provides a starting point for the interpretation of depositional environments and palaeogeographies. We have, therefore, rewritten this book because of the fundamental importance of sedimentary structures to virtually all interpretations of sedimentary rocks and also because they are fascinating and often beautiful features in their own right. Their study brings together diverse aspects of physics, chemistry and biology, often in unexpected and unique ways, and it demands a stimulating combination of observation, imagination and scientific understanding, which can give great intellectual satisfaction to those who enjoy asking questions of the world around them.

1.1 The nature of this book

To give you an idea of what this book is about, see to what extent you can describe and interpret the series of

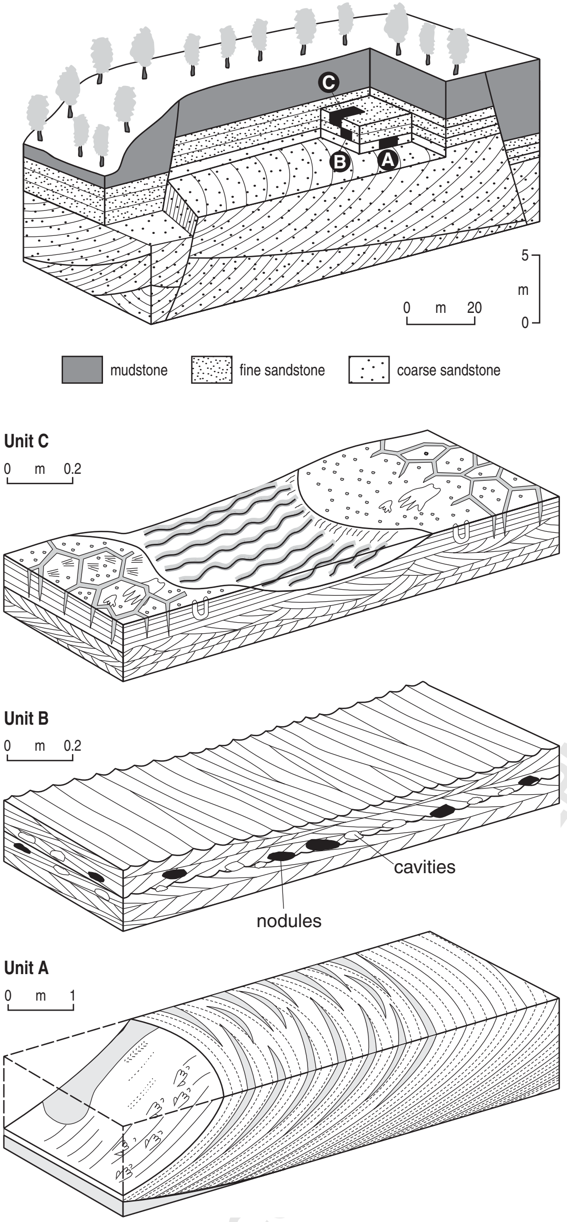

Figure 1.1 Sedimentary structures exposed in three blocks representative of units A, B and C in a hypothetical quarry. Note the scales of the blocks and their orientation within the quarry.

geological structures and relationships shown in Figure 1.1 You might also think of what significance such structures could have for geologists exploring for and exploiting economic resources. Whatever experience you bring to bear on this exercise, it is likely that you will have followed many of the steps that an experienced sedimentologist would have taken in tackling the same problem. We hope that your ability to apply a more complete and detailed analysis will develop from reading this book.

But first, what approaches might you have made in tackling Figure 1.1?

- You will have recognized and described several features on the basis of your everyday experience. This provides you with a valuable information base, but it is clearly inadequate, on its own, to enable you to complete the task.
- You will have observed, compared, and possibly classified certain features and perhaps have inferred and predicted relationships between them. This book should enable you to refine and enlarge this range of descriptive and interpretational skills and techniques.
- You may have tried to explain some of these features based on your understanding of physical, chemical and biological processes that you see operating today. In doing so, you will have applied a set of current beliefs about nature that suggest that it is orderly and uniform; in other words, you have applied the idea that the present is the key to explaining the past. This doctrine of **uniformitarianism** was promoted by Charles Lyell in the mid-nineteenth century; it encapsulated the idea that uniformity in the laws of nature allowed present-day geological processes to be applied to the interpretation of ancient rocks through careful observation and extrapolation.
- You might ask yourself whether you first took in a great deal of information at a glance, produced one or more speculative explanations or hypotheses, and then tested these initial ideas by further, critical, scutiny for examination of the evidence, or whether you first described each part of the jigsaw and then came to a general idea of its meaning. In either case, working deductively (proving certain ideas false on the basis of critical evidence) or inductively (going from the particular to the general), you were applying fundamental processes and methods of scientific enquiry.
- You may have attempted to sort a great many features into time–space relationships: a process of historical ordering of events at a particular place, a technique at the heart of the geological sciences and which helps to distinguish them from the other sciences.

CHAPTER 2

Bedding

Bedding is one of the most distinctive features of sedimentary rocks, and its occurrence is often associated with the development of many of the sedimentary structures that are dealt with in this book. Some broad understanding of the nature of bedding, its genesis and recognition is therefore an important starting point for studying sedimentary rocks, whether they are being considered in terms of their stratigraphy, their sedimentology or their post-depositional structural deformation. This chapter reviews some of these broader aspects of sedimentary successions, which can be important in understanding the context of particular sedimentary structures.

2.1 The nature of bedding

2.1.1 Where to start: recognizing sets of beds

When you approach any exposure of rock, you might usefully start by asking the following questions. You should not be discouraged if you cannot give clear answers to them all, especially if you have rather limited experience.

- Can anything in the rocks be detected that suggests that they are bedded?
- Is there other evidence suggesting a sedimentary origin?
- If they do appear to be of sedimentary origin, is there evidence to suggest which is the top and which is the bottom of the succession observed? (N.B. With very few exceptions, this question will be relevant only where it is clear that the rocks are strongly deformed.)
- Are there any features that are characteristic of particular processes or environments of deposition, for example beds with erosive channel-shape bases?
- Are there any patterns of vertical and lateral change in the rocks that might suggest changing processes and thereby an environment of deposition, for example a distinctive vertical or lateral thinning or thickening of the beds?

2.1.2 The basis of this approach: the origins of bedding at the present day

In trying to answer some of the questions above, it can be helpful to think about simple laboratory experiments on sediment deposition and about processes seen in modern depositional environments. From simple observations it is possible to establish that, if physical conditions and sediment supply remain steady (i.e. constant in time), then a body of sediment is deposited that is internally homogeneous – in its composition and texture and in the nature of any internal lamination. Where physical conditions or sediment supply change over time, layers of sediment somewhat different in character are laid down. The boundaries between such layers may be sharply defined or gradational, depending on the way in which processes or supply changed and on the resulting textural characteristics of the sediments that make up the layers (Fig. 2.1). Many such layers of sediment possess more or less planar bottom and top surfaces, and are very extensive laterally in relation to their thickness. Others are more restricted laterally, possibly reflecting depositional processes that were not uniform (i.e. not constant in space). Depositional units greater than 1 cm thick are known as **beds**; their boundaries, where fairly sharply defined, are known as **bedding** or **bounding planes**, the lower bounding surface often being referred to as the **sole** and the upper as the **upper bedding surface** (Fig. 2.2). Where boundaries are more gradational in character, bedding is defined rather less precisely. The terms **layers** and **strata** are sometimes used rather loosely as equivalents of bedding, but strata may also be used at a larger scale to encompass a whole succession of constituent beds. At less than 1 cm thick, depositional units are termed **laminae**: the smallest units visible in a sequence. Layers and laminae that occur within beds and which are inclined at an angle to the main bedding surfaces are called **cross strata** (which include **cross laminae** or **cross beds**). The general phenomenon of inclined layers is termed **cross lamination** or **cross**

bedding, depending on scale (see Ch. 6). Groups of similar beds may form **cosets** or **bedsets**, which may be **simple** or **composite** (Fig. 2.2).

In some ancient sedimentary successions, the rocks split along surfaces that are parallel to bedding but which occur within internally uniform beds. In such cases, the term **splitting** or **parting plane** should be used, as the surfaces may not necessarily correspond to bedding planes (Fig. 2.3).

Many beds and bedsets maintain their thickness for considerable lateral distances, although all eventually thin out or change their nature, either gradationally or suddenly, if traced far enough. Vertical sections through deposits of river floodplains, estuarine flats or beaches, as seen in excavations or exposed in the erosive banks of migrating channels, typically show successions of beds, the oldest at the base, the most recent at the top, where each bed records a particular set of conditions.

Any sedimentary structure that cross cuts a bedding feature – for example, a channel cutting down into horizontal layers – must have formed after that feature. Also in such a situation, fragments from an older bed could have fallen into, and been incorporated within, the later

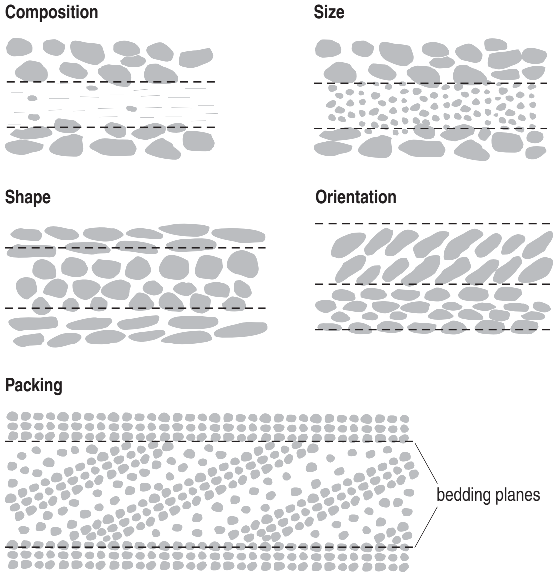

Figure 2.1 Bedding as the product of different combinations of grain composition, size, shape, orientation and packing. Modified after Griffiths (1961) and Pettijohn et al. (1972).

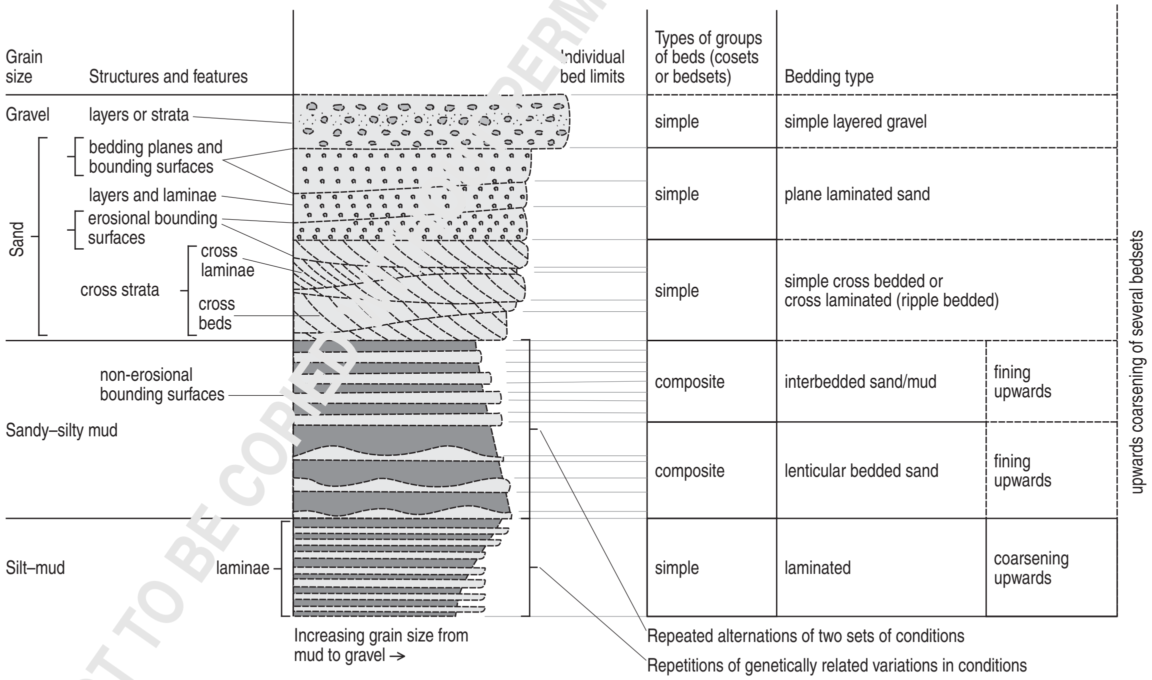

Figure 2.2 A scheme illustrating the terminology used to describe sedimentation units. Modified after McKee & Weir (1953), Campbell (1967) and Reineck & Singh (1973).

CHAPTER 3

Basic properties of fluids, flows and sediment

3.1 Introduction

In order to understand the processes that produce many of the sedimentary structures observed in sediments, it is necessary to have a basic understanding of the physical properties and mechanics of the fluids that erode, transport and deposit the sediment. Most of these processes result directly from movement of a fluid, commonly water, but also air and ice (which, although not a true fluid, does exhibit some similar behavioural properties). Exceptions are sediments emplaced by the direct action of gravity on loose particles and sediment/water mixtures, usually on a slope. During gravity emplacement, water may be important as a lubricant or as an agent that acts to support the moving grains. The moving mass of grains, with or without water, typically behaves as if it were plastic. The difference between fluidal and plastic behaviour is important and is explained later in this chapter.

It is also important to understand something of the physical properties of sedimentary particles themselves, as both individuals and populations. The variation of size, shape and density found in natural sedimentary particles clearly influences their response to the flows that erode, move and deposit them.

Therefore, this chapter examines some of the properties of fluids and plastics, and shows how these influence the way in which they move. It also considers the physical properties of sediments and shows how particles and fluids interact during certain sedimentary processes.

The chapter may seem rather theoretical, but it mainly describes common phenomena. Many of the features can be illustrated by simple experiment and by experience of everyday events. Try wherever possible to develop a feel for the physical reality of the various processes described. We indicate where we think experiments and observations of this type are helpful, but with a little imagination it may be possible to model features of fluids and flows other than those we suggest.

3.2 Properties of low-viscosity fluids and flows

3.2.1 Basic properties of fluids

The two simple fluids that account for virtually all sediment movement on the surface of the Earth are water and air. Ice is also important in moving sediment, because, when its behaviour is observed on a long timescale, it flows as a plastic. Additionally, mixtures of sediment and water, such as slurries and mudflows, flow under gravity when on a slope and essentially show plastic deformation.

The media of water and air differ significantly in certain physical properties, in particular **density** and **viscosity**. The fluid density (ρ_f) determines the magnitude of forces such as shear stress that act within the fluid and on the bed, particularly when the fluid moves down a slope under gravity. Density also determines the way in which waves are propagated through the fluid and controls the buoyant forces acting on sedimentary particles immersed in the fluid by influencing their effective density ($\rho_s - \rho_f$), where ρ_s is the density of the solid particle. For example, quartz grains in water have an effective density of $1650\,\mathrm{kg\,m^{-3}}$ compared with $2650\,\mathrm{kg\,m^{-3}}$ in air, a difference that strongly influences the ability of the different fluids to move the grains.

The viscosity (μ) describes the ability of the fluid to flow. It is defined as the ratio of the shear stress (τ shearing force/unit area) to the rate of deformation (du/dy) sustained by that shear across the fluid:

$$\mu = \frac{\tau}{du/dy} \tag{3.1}$$

The viscosity of a fluid is not constant and its magnitude varies with temperature (compare, for example, hot and cold oil or syrup).

At the simplest level, we can visualize flow by a model where a fluid is trapped between two parallel plates moving relative to one another. The fluid may

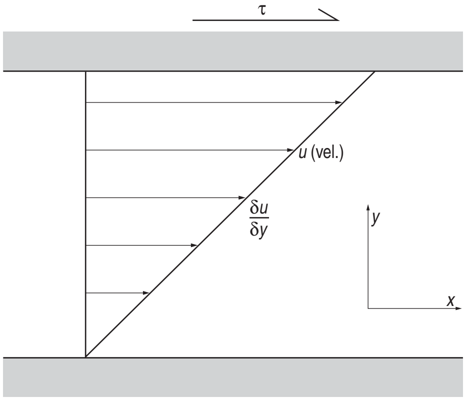

Figure 3.1 Definition diagram for viscosity. Two rigid parallel plates enclose the fluid. A shear stress (τ), acting parallel to the sheets, sets up the steady-state velocity profile shown by the inclined line. The length of the arrows is proportional to velocity (*u*) relative to the lower plate.

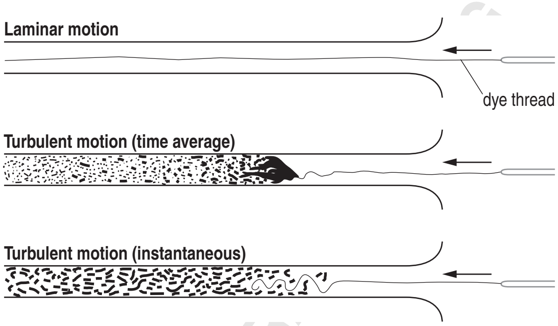

Figure 3.2 The Reynolds experiment to illustrate the difference between laminar and turbulent flow. Dye injected into the flow from a point source behaves in different ways depending on the velocity and viscosity of the flowing fluid. (After Allen 1968)

then be envisaged as a stack of sheets parallel to the plates. These sheets move relative to one another at a uniform rate, so that an initial straight line drawn perpendicular to the plates will deform into an inclined straight line, leaning in the direction of shear (Fig. 3.1). The viscosity reflects the force needed to produce a particular rate of deformation or sliding of the imaginary sheets. Increased viscosity demands a greater shear stress to produce the same rate of deformation.

As density and viscosity both play an important role in determining fluid behaviour, it is usual to combine them into a single term, the so-called kinematic viscosity (ν):

$$\nu = \frac{\mu}{\rho_f} \tag{3.2}$$

3.2.2 Laminar and turbulent flow

Some of the basic features of fluid flow can be investigated by means of a simple experiment. Inject a thin stream of dye into a very slowly moving flow of a viscous fluid, such as glycerine, in a narrow channel and carefully observe the form of the dye down stream of the injection point. Repeat the procedure at progressively increasing flow speeds, or with fluids of progressively lower viscosity. You will notice that, with low speeds and high viscosity, the dye persists as a fairly coherent and reasonably straight stream, whereas with increased velocity or decreased viscosity the stream breaks down and moves as a series of deforming masses, within which there are components of movement perpendicular to the overall flow direction (Fig. 3.2).

With low velocity and high viscosity, the flow corresponds to the model outlined in §3.2.1 and the flow is said to be **laminar**. With more rapid flow or a lower fluid viscosity, the flow can no longer be visualized as a series of parallel sheets or filaments, but clearly has some form of secondary motion superimposed upon the unidirectional flow. This motion is the very important phenomenon of **turbulence**.

3.2.3 Turbulence

An appreciation of turbulence is vital to understanding the origin and form of many of the sedimentary structures described later. The turbulence seen in the flow of water in a smooth-sided channel is a random movement of parcels of fluid superimposed upon the overall flow. By slowing down the flow sufficiently or increasing the viscosity of the fluid, it is possible to eliminate this random motion and achieve conditions of laminar flow. However, in virtually all natural conditions involving air or water, turbulent flow is the norm (Fig. 3.2). Velocity measured at a point in a laminar flow is constant through time, whereas velocity at a point in turbulent flow will fluctuate, often widely, about a time-averaged value. This distinction between the two flow types suggests that it should be possible to use some combination of flow properties to predict the boundary conditions separating them. The factors that control the level of turbulence are usually combined to derive a **Reynolds number** (*Re*) for the flow. This dimensionless

CHAPTER 4

Erosional structures

4.1 Introduction

Most areas of present-day sediment accumulation reflect complex interactions between erosion, transport and deposition. Even in areas of net long-term accumulation, deposition may be interrupted by periods of erosion. Similarly, most ancient sequences are not the products of steady continuous deposition but result from alternating periods of deposition, non-deposition and erosion. This chapter deals with features that indicate that erosion has taken place.

As with most depositional structures (Chs 5–7), the chances of an erosional structure being preserved in the rock record are very small. For erosional structures to be preserved, the eroded sediment has to be sufficiently cohesive and strong to maintain the erosional relief until it is buried by contrasting sediment, usually almost immediately. Small-scale erosional structures are almost always recognized as relief on the base of the bed immediately overlying the erosion surface. Erosion is also recognized in vertical sections by truncation of bedding or lamination in the sediment below the erosion surface. However, if erosion has been widespread, no discernible relief may be preserved and recognition of erosion may then depend upon indirect evidence. Where relief is observed, this may not reflect the total amount of erosion. Widespread erosion of a large thickness of sediment may result in preservation of only small-scale features. Observed relief therefore reflects only the minimum thickness of sediment removed.

Many erosional structures are valuable indicators of both way-up and palaeocurrent direction. They can, therefore, help in structural and palaeogeographical analysis, as well as giving insights into processes active during sediment accumulation.

Classification of erosional structures has to be arbitrary, as different types grade into one another. The scheme adopted here is based on both descriptive and genetic criteria (Fig. 4.1). Three broad categories are recognized, within which further subdivision is possible:

- sole marks on the bases of coarser beds in interbedded sequences
- small structures seen on modern surfaces and more rarely on upper bedding surfaces in ancient strata
- large structures normally recognized in vertical section in ancient sediments (i.e. channels, slump scars).

4.2 Sole marks

4.2.1 Preservation

Sole marks comprise a diverse group of structures found as casts on the bases of coarser-grain beds interbedded with mudstones. The coarser-grain sediments are commonly sandstones, but exceptionally may be limestones or conglomerates. The sole marks result from the erosion of cohesive fine-grain sediment, usually mud, which passes on erosion directly into suspension. The cohesive strength of sediment allows details of the erosional relief to be maintained until they are buried by coarser-grain material (Fig. 4.2). Erosion of mud and deposition of coarser material can often be phases of the same current, separated by only a short period of time. Subsequent lithification usually renders the coarse-grain sediment more resistant than the finer material to eventual weathering, so that the fine-grain sediment is preferentially removed to expose a cast of the erosional relief on the base of the sandstone bed. Resumption of deposition of fine-grain sediment, similar to that eroded, without any deposition of coarse-grain sediment, would not normally provide the lithological contrast needed to pick out the structures on weathering. It is very important to understand this mode of preservation and to recognize that the structures observed are negative impressions of the erosional relief.

Sole marks are typically the products of environments characterized by episodic sedimentation. Background deposition of mud is punctuated by sudden

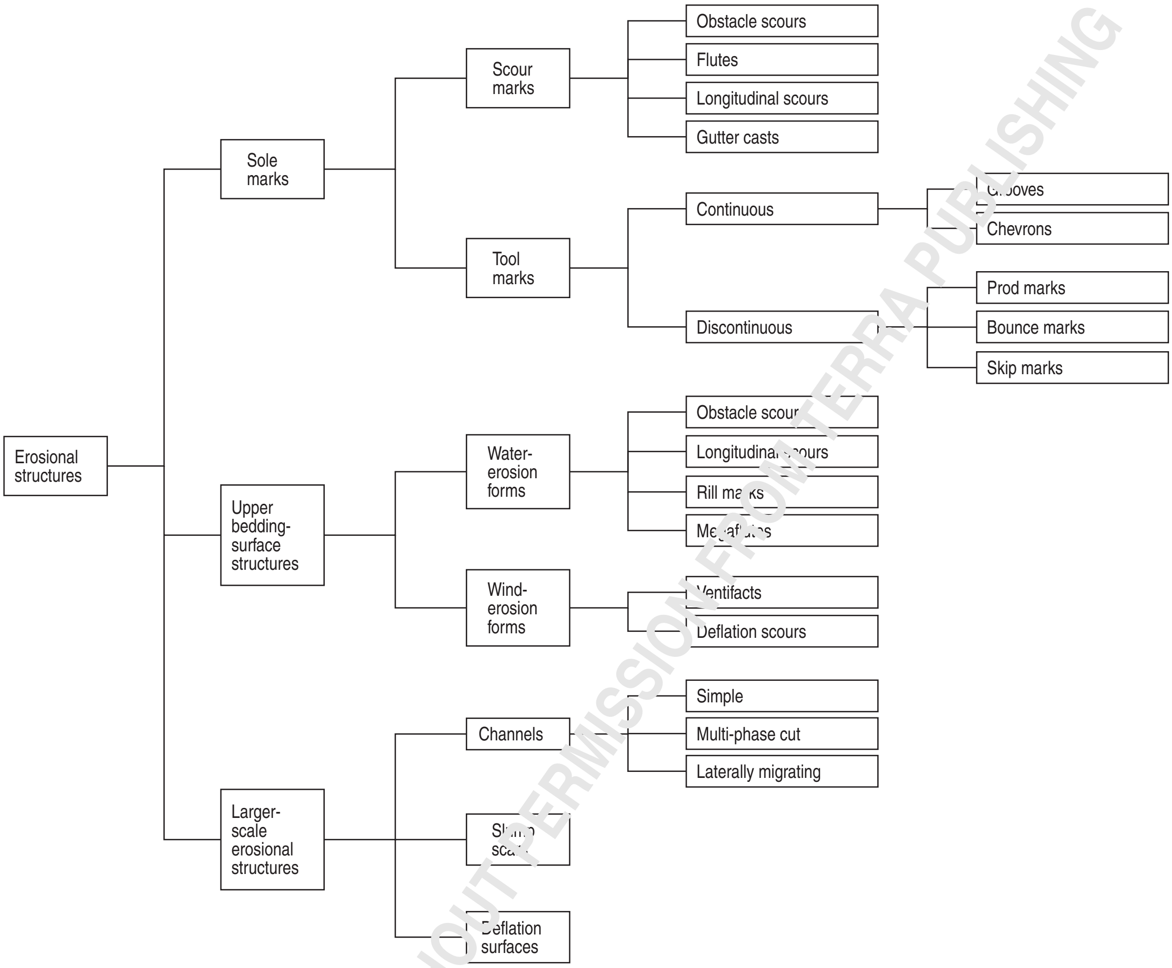

Figure 4.1 Scheme for the classification of erosional sedimentary structures.

influxes of coarser sediment in events comprising an early erosive phase and an immediately succeeding depositional phase. A common example of such an event is the turbidity current (see §3.7.2). It was once thought that sole marks were diagnostic of turbidites; however, storm surges in shallow seas, sheet floods in semi-arid environments and crevasse surges into floodplains all have the properties necessary to produce such structures. Interpretation of sole marks should initially be restricted to the processes involved, rather than to the type of event or the environment, until the full context of the structures is understood.

Sole marks are divided here into two broad classes that differ principally in the way the structures are generated: turbulent scour (scour marks) and objects moved by the current (tool marks).

4.2.2 Scour marks

Scour marks are distinguished by their generally smooth shape and often by their rather streamlined appearance. They may occur as isolated casts or in groups covering a bedding surface in distinctive patterns. A variety of shapes occur, among which it is possible to recognize groups that can be named and described together. Four main groups cover the range of forms: obstacle scours, flutes, longitudinal scours and gutter casts.

CHAPTER 5

Depositional structures in muds, mudstones and shales

5.1 Introduction

The terminology of fine-grain siliciclastic sediments is rather confusing. A range of terms have been used in overlapping and sometimes ambiguous ways. These are discussed quite fully in most books dealing with sedimentary petrology; here we use the following loosely defined terms:

- **Mud and mudstone** Unconsolidated and lithified (respectively) sediment in which grains of sand size (4φ or coarser) are absent or are an insignificant component. Where coarser grains are conspicuous, the terms can be suitably qualified (e.g. sandy mud, pebbly mudstone). These terms include the more precisely defined terms "silt", "siltstone", "clay" and "claystone", and are useful in the field because of the difficulties of accurately judging the grain size of fine-grain sediments, especially where they have been deformed or metamorphosed.
- **Silt and siltstone** These are rather more narrowly defined terms for sediments containing a dominance of grains in the range 4φ to 8φ. Rubbed against or between the teeth, these sediments feel gritty. Grains are not generally visible to the naked eye, but may usually be distinguished with a lens.
- **Clay and claystone** Unconsolidated and lithified (respectively) sediment where the dominant grain size is less than 8φ. Such sediments feel smooth and greasy to the touch, even between the teeth. Although many clays and claystones contain a high proportion of clay minerals (i.e. hydrated alumino-silicates), grain size rather than mineral composition is the basis of the definition.
- **Shale** A widely and often loosely used field term for mudstone that often shows a conspicuous lamination and a fissility on weathering. It is somewhat unsatisfactory in that weathering plays a part in its recognition and it cannot be consistently used in comparing rock at outcrop with, say, that of a borehole core.

Muds and mudstones are exceedingly abundant in both modern depositional environments and the rock record, accounting for about 60 per cent of the latter. They are derived from the products of chemical weathering of many unstable source rocks (e.g. basic igneous rocks) and from extreme physical attrition. The fine-grain debris, produced by chemical weathering of silicate minerals other than quartz, comprises mainly clay minerals and chlorite, whereas physically derived sediment, for example in glacial "rock flour", has a mineral content dependent upon the rocks of the source area.

Although most mudstones were deposited from suspension, some may result from *in situ* weathering of unstable source material. In the latter case, the resultant soil profiles (**palaeosols**), when found within a rock sequence, may be associated with depositional breaks or even unconformities. Other mudstones may result directly from resedimentation of original suspension muds as mudflows (Figs 5.1, 5.2). In many cases, this

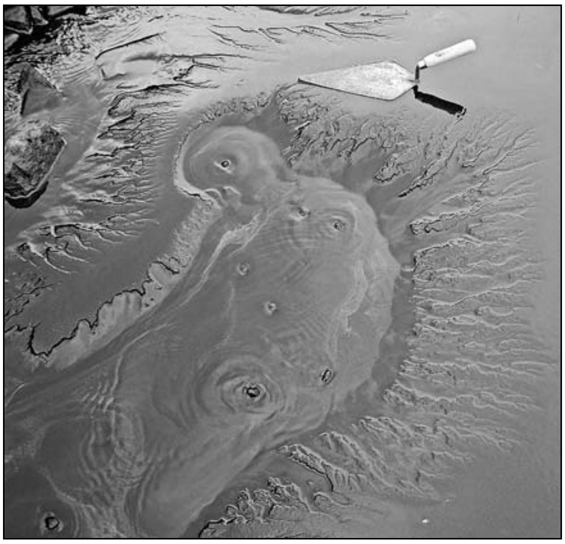

Figure 5.1 A highly fluidized mud explained by high pore-water content; note the water escape features. Jökulsá á Fjöllum, Iceland.

Figure 5.2 A small active mudflow in which water-saturated muds have been remobilized through the addition of water. Note that the surface of the flow is highly irregular because of small aggregates and pebbles being rafted along with the flow. Modern, Svalbard.

movement leads to the incorporation of coarser grains, which tend to "float" within the predominantly muddy sediment (Fig. 5.2; see also §3.7.1).

In addition, fine-grain sediments are generated directly by explosive volcanic activity resulting in both **airfall** and **water-lain tuffs**, which may be prone to subsequent reworking by currents or as mass flows (**lahars**). Such volcanic deposits are often recognized by their distinctive colour and weathering state. Confirmation of volcanic origin commonly requires laboratory analysis of clay minerals. High volcanic eruption columns (tens of kilometres in Plinian eruptions) give very widespread sheets of **ash** through pyroclastic fall. After settling from the stratosphere, widespread distribution is achieved by winds in the upper atmosphere. Material may be transported world wide, with the paradox that the most powerful processes give rise to extremely thin but laterally widespread horizons in the geological record, which are often used for correlation and dating purposes. However, fine ash may fall close to the volcanic centre as a result of a weak explosion or because of rain flushing grains from the eruption cloud. In the latter case, fine ash may occur as **accretionary lapilli**. Bed thickness will be controlled by the pattern of rainfall rather than by distance from the vent.

Many muds and mudstones are also rich in organic matter, which occurs as either finely divided organic (most commonly algal) debris or as organic molecules chemically attached to the clay-mineral particles.

It is difficult to interpret the physical conditions of deposition of muds and mudstones compared with those of coarser-grain sediments (Chs 6, 7). There are two main reasons for this. First, the range of physical processes that operate during deposition of muds is more restricted than for coarser-grain sediments. Secondly, fine-grain sediments, particularly those rich in clay minerals and organic matter, have a much higher initial porosity than most coarse-grain sediments, and this makes them highly susceptible to compaction on burial. This has the effect of distorting and compressing any depositional and organic structures, sometimes to the point where they are completely obliterated. The amount of compaction will vary with the composition of the sediment and with its burial history. Although some carbonate muds appear to have suffered little compaction, it is not uncommon for some clay- or organics-rich mudstones to have been compacted to a quarter or even an eighth of their initial depositional thickness. This effect can be observed by study of the internal structure of concretions that formed soon after deposition of the mud (see §9.3.1). Carbonate-cemented concretions that formed soon after deposition, before significant burial, sometimes preserve relatively uncompacted depositional structures as well as uncrushed fossils. If concretions occur in a mudstone sequence, it is always worth examining their internal structure, as this may help in understanding the deposition of the mud (Fig. 5.3).

Tectonic movements have much more drastic effects on fine-grain sediments than on coarser ones. During folding, fine-grain sediments generally behave in an incompetent manner and also readily develop cleavage through rotation and recrystallization of clay minerals,

CHAPTER 6

Depositional structures of sands and sandstones

Structures developed in siliciclastic or carbonate sands, and in sandstones and calcarenites, reflect a variety of transport processes and they are our clearest indicators of the types and strengths of currents that move and deposit sediment. The transporting medium may be water or air. Deposition of sand generally occurs through accumulation from bedload transport during steady flow with excess sediment supply, or by fall-out from suspension from powerful decelerating currents. After deposition from suspension, sand may continue to move as bedload before it finally comes to rest. To classify structures in sand we have adopted a scheme that is partly descriptive and partly interpretive. Sand-size sediment of pyroclastic origin may also form many of the structures described in this chapter. However, most pyroclastic deposits are of coarser grain and are described in Chapter 7.

6.1 Ripples and cross lamination

6.1.1 Introduction

Ripples are quite regularly spaced undulations on a sand surface or on a sandstone bedding plane. Their spacing (wavelength) is usually less than 0.5 m and relief seldom exceeds 3 cm. Bedforms with larger dimensions are referred to as **dunes** or **sandwaves** (see §6.2). Ripples show a wide variety of shapes, many of which relate to particular sedimentary processes and hence are useful in interpreting conditions of deposition.

Cross lamination is the pattern of internal lamination that develops within sand deposited by ripple migration. It can be seen on both bedding planes and vertical surfaces. Patterns of cross lamination are often specific to particular types of ripple and so can aid interpretation.

6.1.2 Material

Although ripples and cross lamination are principally features of sand-grade sediment, they also occur in coarse silts. They are most common in fine- to medium-grain sand and are rare in material coarser than coarse sand, except where they are the result of wave action or of strong winds.

6.1.3 Ripple morphology

Ripples are characterized in terms of both profile and plan view (Fig. 6.1). The important distinction between symmetrical and asymmetrical ripples is based on their profile perpendicular to the crestline. Although there is some truth in the generalization that ripples with symmetrical profiles are the product of wave action and those with strongly asymmetrical profiles are attributable to current activity, the reality is rather more complex. The shape and continuity of ripple crestlines is at least as important for interpretation.

A whole range of patterns is seen in the rock record and on present-day beaches, river beds and tidal flats. Detailed measurement and description of ripple morphology can be very informative and should always be attempted in any serious study. Basic dimensions can be measured and their values combined to yield indices that point towards the dominant process, even if interpretation may still be ambiguous (Fig. 6.2).

The relationship between profile symmetry and crestline continuity and curvature is complicated. Although symmetrical ripples commonly have straight and rather continuous crests (Fig. 6.3), not all straight or continuously crested ripples are symmetrical. Some straight-crested ripples show a marked asymmetry (Fig. 6.4).

Ripples with highly sinuous crests (Fig. 6.5c) and those with a strongly three-dimensional shape (e.g. linguoid ripples, Fig. 6.5d) usually have asymmetrical profiles. They have steeper concave-upwards lee faces and more gently sloping convex-upwards stoss sides. Such ripples result from currents flowing in one direction only (unidirectional). However, there is a continuum of asymmetrical current ripples ranging in shape from straight crested through sinuous crested to linguoid

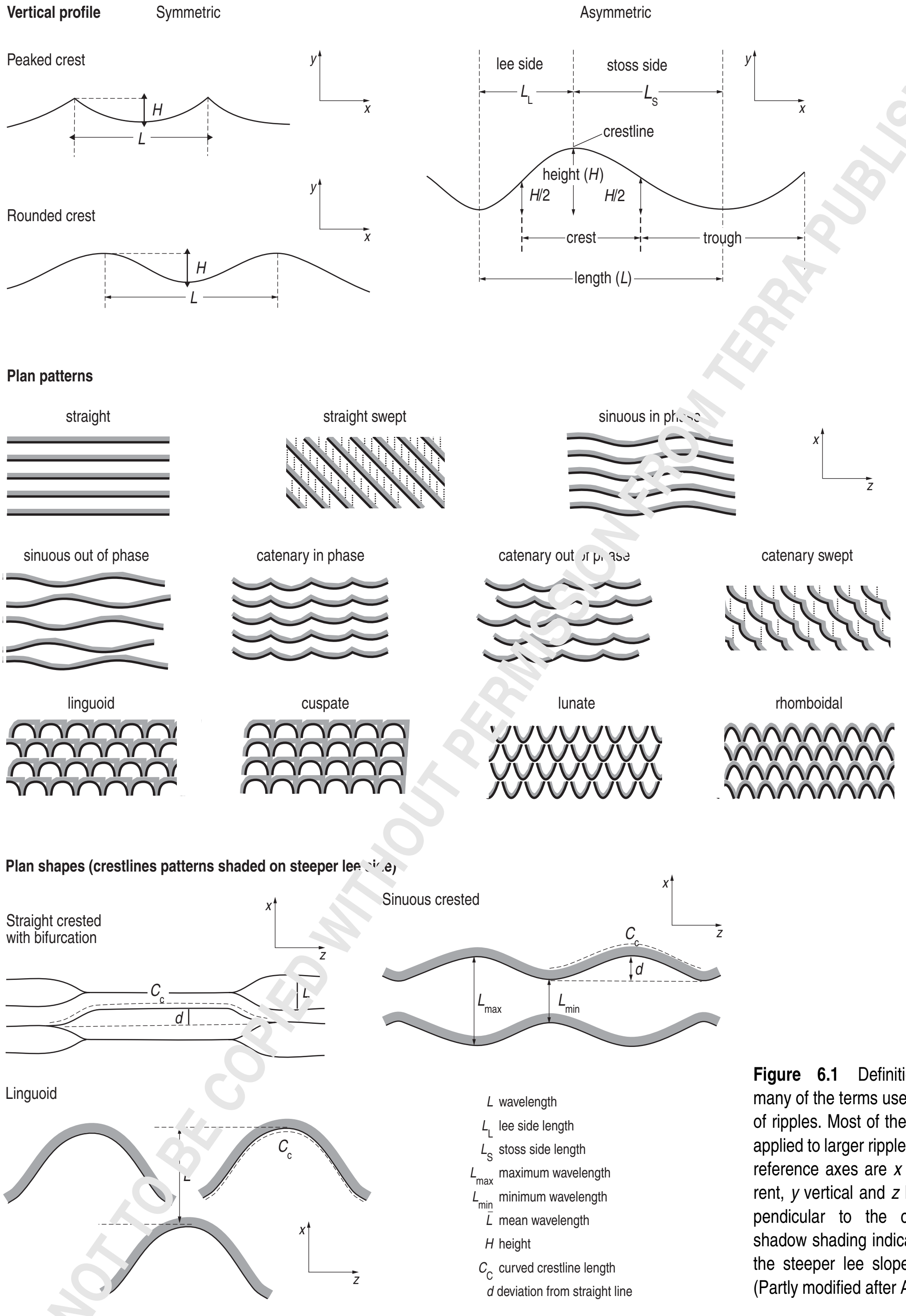

Figure 6.1 Definition diagrams for many of the terms used in the description of ripples. Most of the terms can also be applied to larger ripple-like bedforms. The reference axes are *x* parallel to the current, *y* vertical and *z* horizontal and perpendicular to the current. The grey shadow shading indicates the position of the steeper lee slope of the bedforms. (Partly modified after Allen 1968)

CHAPTER 7

Depositional structures in gravels, conglomerates and breccias

7.1 Introduction

The general name for sediments containing a significant proportion of gravel grade or coarser material is **rudites**. Studies of the depositional processes and structures of rudites are limited because the entrainment, transport and deposition of such sediments occur in high-energy environments where flow conditions make direct observations difficult. Direct-recording instruments, including the human body, tend to be severely damaged by the motion of large clasts, and the situations in which they may be deployed for successful data collection are limited. However, as our knowledge of processes becomes more refined, so the features to be observed, measured and recorded become clearer. The transport and deposition of rudites is closely associated with a variety of both continental and marine environments, including rivers, alluvial fans, reef talus slopes, storm beaches, submarine canyons and volcanic slopes, and as a result the compositions of rudites are extremely varied (Fig. 7.1). The installation of sediment traps in stream beds can give useful information on transport *rates* during floods, but tells little else of the *style* of transport and deposition. Some workers have attempted to overcome these problems by studying the day-by-day results of diurnal rise and fall of discharge on bedforms, for example in proglacial outwash areas. Processes are deduced from the products, revealed by both the surface morphology and the internal structures revealed by trenches. Such methods are usually applicable only in accessible sub-aerially exposed settings. Laboratory experiments on gravels are increasingly attempted, but have been restricted by the need to build large and costly flumes or wave tanks. Even then, the scales of flows and structures are much smaller than the real phenomena. The study of conglomerates and breccias is yet another area of geology in which detailed observation and interpretation of ancient deposits can aid the better understanding of present-day processes, particularly in deepwater settings. The careful analyses that have allowed these advances have involved the recording of bed contacts, bed thicknesses, the style of framework or matrix support, and the sizes and orientations of the larger clasts.

7.2 Problems of classification

7.2.1 Defining rudites

There is no universal agreement on the percentage of clasts above 2 mm (–1φ) that need to be present in a deposit before it is classified as a rudite (Fig. 7.2). Where there is a mixture of mud, sand and gravel, we recommend that the rock should contain more than 30 per cent of clasts larger than 2 mm before the terms **gravel**, **conglomerate** and **breccia** are used. In the field or in the laboratory, first try to estimate the percentage of gravel, sand and mud present, and refer the sediment to the classes shown in Figure 7.2. The interpretation of the environmental origin of a rudite, for example whether a very clay-rich conglomerate is a till of glacial origin, the product of a sub-aqueous or sub-aerial debris flow or an agglomerate, or lapilli-ash of volcanic origin, will depend on detailed description of its composition, the shape of its clasts, its relation to surrounding beds, and consideration of its overall context.

7.2.2 Defining a sedimentary "structure" in rudites

The term sedimentary "structure" is here interpreted broadly to include several mass properties that include textural features:

- features based on composition
- features such as shape, roundness and surface morphology of the constituent clasts

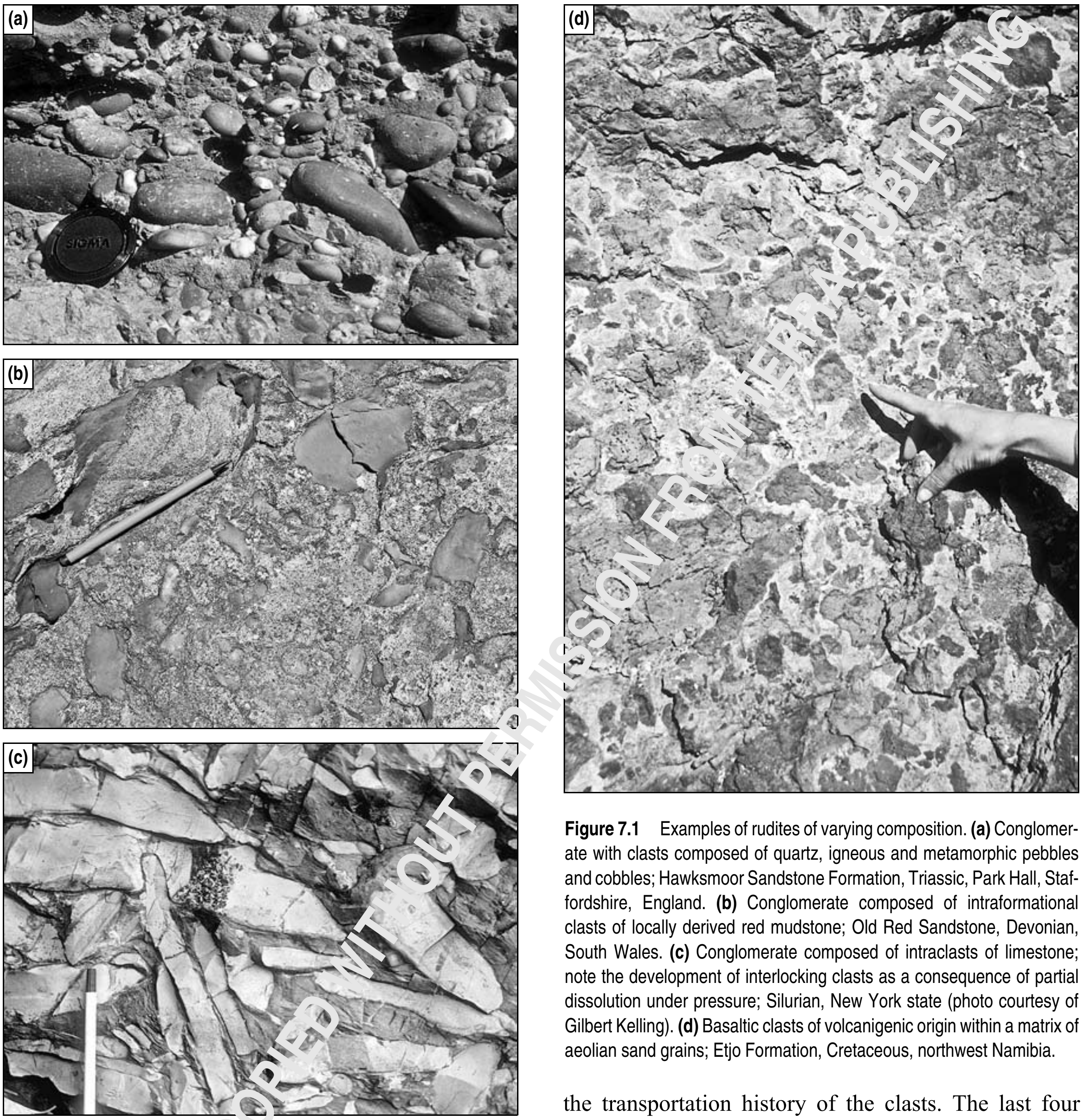

Figure 7.1 Examples of rudites of varying composition. **(a)** Conglomerate with clasts composed of quartz, igneous and metamorphic pebbles and cobbles; Hawksmoor Sandstone Formation, Triassic, Park Hall, Staffordshire, England. **(b)** Conglomerate composed of intraformational clasts of locally derived red mudstone; Old Red Sandstone, Devonian, South Wales. **(c)** Conglomerate composed of intraclasts of limestone; note the development of interlocking clasts as a consequence of partial dissolution under pressure; Silurian, New York state (photo courtesy of Gilbert Kelling). **(d)** Basaltic clasts of volcanigenic origin within a matrix of aeolian sand grains; Etjo Formation, Cretaceous, northwest Namibia.

- stratification and cross stratification
- features based on grain-size distribution, sorting and clast-support systems
- features based on fabric, packing and porosity
- the presence and type of graded bedding.

The first two properties should be recorded in any preliminary survey and they provide useful pointers concerning the provenance (i.e. the source regions) and the transportation history of the clasts. The last four properties demand particular attention if the aim is to understand processes and environments of deposition.

7.2.3 Composition and classification of rudites

One of the first properties to be recorded in the field is the composition of the larger clasts (Fig. 7.1). This allows useful preliminary conjectures concerning their possible provenance and their processes of origin, for example whether the rocks may be pyroclastic. Further

CHAPTER 8

Depositional structures of chemical and biological origin

8.1 Introduction

Much of the material weathered and eroded from land areas is transported to the seas as ions in solution. From geochemical studies it is known that the composition of sea water has remained fairly constant throughout much of geological time and it follows that ions must have been taken out of solution by the precipitation of new minerals. This precipitation can be inorganic or it can be aided by or due entirely to organic agencies.

The most abundant minerals precipitated from sea water are aragonite and calcite, and most of this precipitation is organic in nature. Although inorganic precipitation of carbonates is possible, most inorganic precipitates are evaporite minerals, the most abundant of which are gypsum, anhydrite and halite. In non-marine settings such as saline lakes, the brine chemistry may be different from that of sea water, and different assemblages of evaporite minerals may form.

In this chapter we deal first with the structures and textures produced by inorganic precipitation from bodies of saturated brine, and then with structures resulting from organisms acting either to precipitate sediment or to bind existing particles.

8.2 Chemical precipitation

Inorganic precipitation of minerals from solution is mainly confined to evaporite minerals, commonly gypsum or halite. For any mineral to be precipitated inorganically, an aqueous solution must be supersaturated with respect to that mineral. Irrespective of whether the water body is connected to the sea or is enclosed as a lake, conditions of net evaporation must occur and this usually implies a hot arid setting. When supersaturation is achieved, precipitation takes place, provided that other ions in the solution do not interfere with crystal growth. Nucleation can occur spontaneously anywhere within the water column or on objects already on the floor of the basin. Crystals that nucleate at the water surface may float for a while, held by surface tension, and may exceptionally form surface rafts or crusts (Fig. 8.1a). Eventually they sink to the floor of the basin

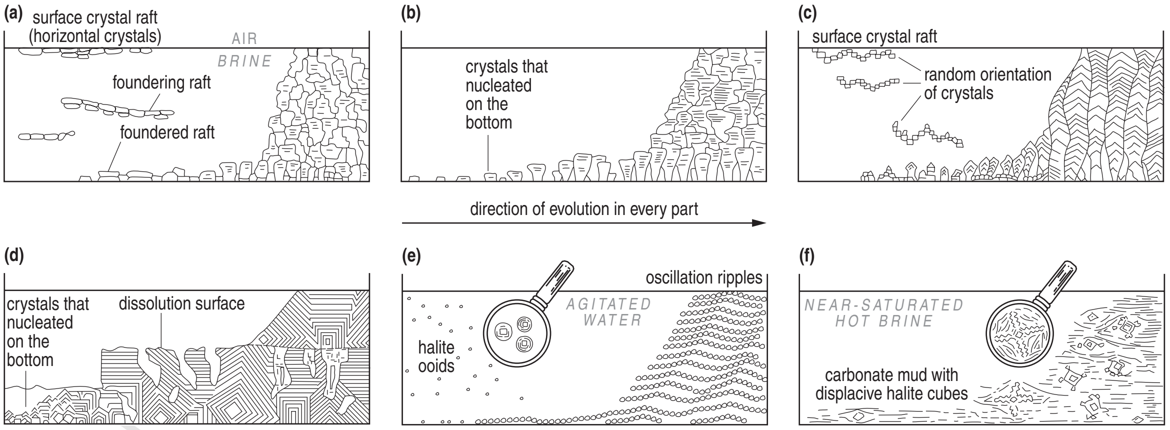

Figure 8.1 Idealized textures associated with the growth and emplacement of halite under differing conditions (modified after Schreiber in Reading 1986; based on Arthurton 1973, Shearman 1971, 1978 and Weiler et al. 1974).

where most of the precipitation and crystal growth takes place. For well formed crystals to develop, both free space and an interval of time are required.

Processes of nucleation and crystal growth can be modelled in the laboratory, for example by allowing 1 L of a saturated solution of sodium chloride to evaporate gradually in a suitable tank. A hand lens can be used to observe the growth of crystals, both as they form at the water surface and after they have fallen to the bottom. Is it possible to distinguish crystals that nucleated at the water surface from those that nucleated on the floor of the tank? How do crystals continue to grow once they are on the floor? Try to monitor the temperature and rate of evaporation during the experiment. For a more elaborate experiment, try to do the same thing with about 4 L of sea water. With the aid of some chemical analysis it may be possible to study the order of crystallization of different minerals and the changing chemistry of the remaining brine as evaporation proceeds.

8.2.1 Laminated evaporites

A common feature of many ancient evaporite-bearing sequences is a fine millimetre-scale interlamination of different mineral phases or of an evaporite mineral and organic-rich material. Where two minerals are present, these are most commonly calcite ($CaCO_3$) and anhydrite ($CaSO_4$). Individual layers show great lateral continuity and may show grading, in terms of individual crystal size or mineral type or form (Fig. 8.2). Ungraded laminae probably record periods of settling of crystals precipitated at the water surface, possibly on a seasonal basis. In contrast, graded layers, especially those composed of randomly orientated crystals, suggest reworking and resedimentation of previously precipitated crystals

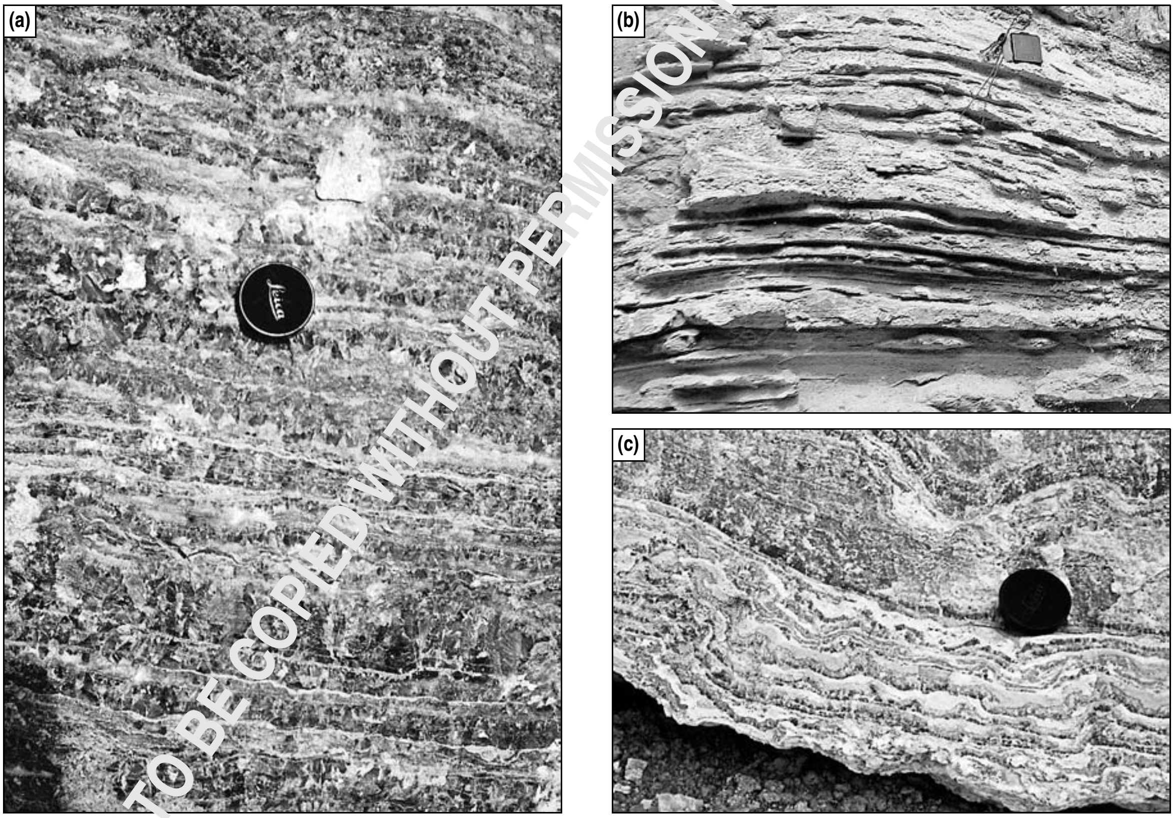

Figure 8.2 Examples of laminated and bedded evaporites: **(a)** Thinly bedded gypsum with bedding defined by slight grain-size differences and impurities; Miocene, southern France. **(b)** Interlaminated gypsum and mudstone; Yesares Member, Sorbas, southeast Spain; **(c)** laminated and deformed gypsum; Miocene, southern France.

CHAPTER 9

Structures created by deformation and disturbance

9.1 Introduction

Any sediment may be disturbed after deposition, but disturbance is most common in sands and finer-grain material. Depositional structures may be disrupted and distinctive new structures may form as a result of physical, chemical and biological processes. It is often difficult to tell when physical and chemical disturbance took place. Sometimes, it occurred soon after deposition at, or close to, the contemporaneous surface, and in other cases was associated with later burial and lithification.

Many deformational structures are valuable as way-up indicators and all record something about conditions within the sediment or at its surface after deposition.

9.2 Physically induced soft-sediment deformation

This results from mechanical forces, commonly gravity, acting upon weak sediment, usually silts or sands, at the sediment surface or soon after burial (Figs 9.1, 9.2). There is no neat way of classifying these structures. Here we use a broadly morphological scheme, based upon where they most commonly occur. However, several structures are seen in both vertical section and on bedding surfaces, and might, therefore, be placed in more than one class. They are described under only one heading, usually their most common occurrence.

Most types of soft-sediment deformation depend on unconsolidated sediment being in a weak condition. The resistance of sediment to deformation is most commonly expressed by its shear strength τ, which is a function of grain cohesion C, intergranular friction and the effective pressure between the grains:

$$\tau = C + (\sigma - \rho)\tan\varphi \qquad (9.1)$$

where σ is pressure normal to shear, ρ is pore-fluid pressure and φ is the angle of internal friction.

For sediment to be deformed, its shear strength must be reduced or the applied shear stress increased. This can be achieved by loss of cohesion, by re-adjustment of grain packing to reduce $\tan\varphi$, or by increasing the pore-fluid pressure ρ. Cohesion is the least readily changed property, as it is mainly controlled by grain size. A shock applied to waterlogged, loosely packed sediment can change the packing and, in the process, increase the pore-fluid pressure to the extent that the sediment undergoes temporary **liquefaction** (Figs 9.1, 9.2). In this condition, sediment and water together behave as a liquid, deforming very readily. This will continue until the pore-water pressure falls because of escape of the excess water, and the grains take on a closer packing and re-establish frictional contact with one another. The shocks that cause liquefaction may be either widespread and external (e.g. earthquakes) or local, for example a rise in water level or an episode of sudden deposition.

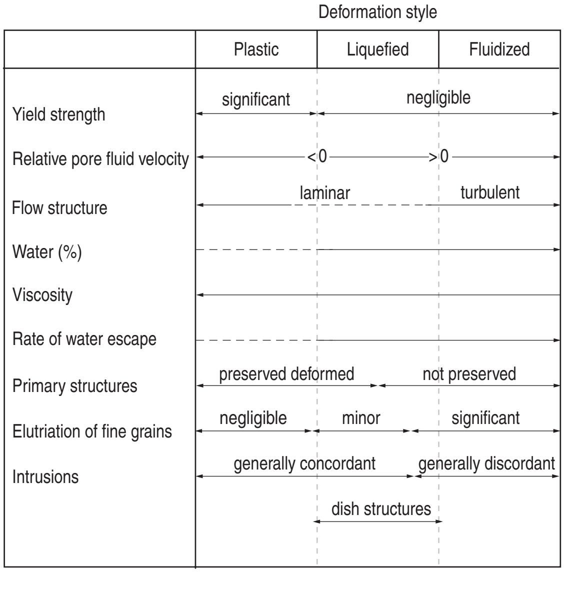

Figure 9.1 Characteristic properties of plastic, liquefied and fluidized styles of deformation (modified after Owen 1987).

		LOSS OF STRENGTH				
		Exceed strength of sediment			Liquidize	
		Internal tensile (brittle)	Internal cohesive (plastic)	External surface cohesive (plastic)	Liquefied	Fluidized
Gravitational body force on slope		Slides	Slumps	Slumps and slides	Debris flows	
Unequal confining load		Growth faults	Loaded ripples; shale ridges and diapirs		Loaded ripples and sole marks	
						Clastic dykes Sand volcanoes
Gravitationally unstable density gradient (density inversion)	Continuous	Soft sediment faults			Convolute lamination	
	Within a single layer				Dish structures	Water-escape pipes and pillars
	Multiple layer, not pierced				Bedding-surface load clasts	
	Multiple layer, pierced		Shale ridges and mud diapirs		Ball and pillow/pseudo-nodules Isolated load balls	
Applied shear stress	Current drag				Overturned cross bedding	
	Vertical					Water-escape pipes and pillars

Figure 9.2 Types of physical deformation structures in relation to the nature of the deforming force (modified after Owen 1987).

This effect is illustrated by jumping up and down on a sandy beach close to the water's edge. The surrounding sediment liquefies, as frictional contacts break down and water escapes to the surface. Once this has happened, the same patch of sand is not easily liquefied again as a closer grain packing has been created.

In addition to shock and repacking, excess pore-fluid pressure can be produced during rapid deposition of fine-grain sediment. The low permeability of such sediments prevents the escape of pore fluid and, thus, the compaction of the sediment at a rate that balances the increasing overburden. **Overpressured** or **under-compacted** conditions are then said to occur, in which state the sediment is highly susceptible to deformation.

Liquefaction of sediment may be total, so that all grain contact is broken and the mass of sediment and water flows freely. In such cases, original lamination is destroyed, giving massive or "slurried" bedding. In other cases, where loss of strength is less comprehensive, deformation is limited and more plastic in nature, so that original lamination is preserved, although distorted. A mass of liquefied sediment will remain mobile or weak until the excess pore-fluid pressure is dissipated either by general intergranular flow of pore water, usually upwards, or by water escape along restricted pathways. If vigorous enough, the upward escape of fluid may lead to the **fluidization** of sediment within escape pathways (Figs 9.1, 9.2). Rapid fluid movement between the grains causes a loss of strength and increased pore space. The relative movement of grains and fluid during fluidization allows some grain sorting to take place, usually by upward removal of fines. In liquefied sediment, fluid and grains move essentially together, giving little scope for sorting.

9.2.1 Features visible both on bedding surfaces and in vertical section

Load casts and flame structures

Load casts and flame structures occur most commonly on the lower surfaces of beds of sandstone that are interbedded with mudstones (i.e. they are a type of sole mark; see §4.2). They also occur within sandstone units and are commonly recognized in vertical section. **Load casts** on soles of sandstone beds are rounded, rather irregular lobes of variable size and relief. Small examples are measured in millimetres and large ones may be tens of centimetres or even metres in diameter. They seldom occur in isolation and usually cover a whole bedding surface (Fig. 9.3).

Upwards-pointing fingers or wedges of the underlying unit occur between the sandy lobes. These are **flame**

CHAPTER 10

Assemblages of structures and environmental interpretation

10.1 Introduction

In earlier chapters we have shown how sedimentary structures relate to erosional, depositional and post-depositional processes. Although the ability to interpret sediments in these terms is useful in its own right, it is often more important to use that information as a step towards interpreting the depositional environment of sediments found in the rock record. In earlier chapters little mention was made of environments. This omission was deliberate so as to highlight the fact that many structures and processes are common to a range of environmental settings. However, it is necessary to determine the processes responsible for generating a particular set of structures as a first step in making an environmental interpretation. In order to move from an interpretation of process to one of environment, further analysis is required. This involves trying to establish spatial and temporal relationships of the processes that can be deduced from the sedimentary structures, as these relationships can help to narrow the range of environmental possibilities. It is also useful to know something of the directional properties of sedimentary structures so that we can test and refine our ideas, because the relative directions of flows and wave movements help to characterize certain environments. Directional information also helps to orientate an inferred palaeoenvironment in space and thereby give it palaeogeographical significance.

Therefore, in characterizing a modern environment or establishing an environmental interpretation for sedimentary rocks, it is important to record and present observations of sediments, their physical and chemical sedimentary structures, body and trace fossils, in addition to their directional properties and their positions in space or in measured sections in clear and well structured ways.

10.2 Mapping of modern environments

The main aims of mapping sedimentary structures in modern environments are to learn something of the distribution of hydrodynamic or wind energy within the environment and to predict the likely patterns of lithology and sedimentary structures, should deposits of the environment be preserved. The second aim has particular relevance for the application of uniformitarian principles to the interpretation of sedimentary rocks.

The most common method of investigating the distribution of water-generated bedforms, for example those encountered on intertidal areas or on river beds, is on foot and at low water. Notes on such methodology are presented in Appendix 3. Although the mapping is typically quite straightforward, interpretation is more complex, as the patterns observed are probably the product of a succession of flow conditions. All bedforms need time to respond to changes in flow. Large bedforms, produced under conditions of strong flow, may be stranded if the water level and flow strength fall rapidly. Small bedforms, such as ripples, adjust more quickly, and many continue to respond to the flow almost to the point of emergence. It is important to try to interpret exposed surfaces in terms of an evolving flow history rather than one specific set of flow conditions.

Predicting the vertical sequence of sediment that will be generated by a particular set of processes operating in a given environment requires answers to several questions. Which of the observed bedforms is most likely to generate preserved internal structures? What is the distribution of such bedforms across the broader topography of the environment? How is the environment as a whole changing through time? In particular, is a systematic migration of sub-environments taking place over time? If so, it can be predicted that structures developed in topographically low areas will occur low in a vertical

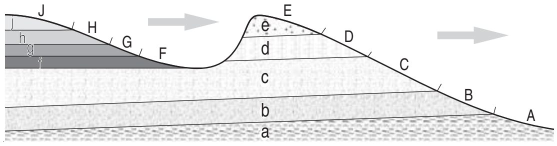

Figure 10.1 A schematic diagram to illustrate Walther's principle of succession of facies. Sub-environments A–E are on a sloping surface that is building out to the right, generating lithological units a–e. A channel comprising sub-environments F–J is cut into the top of this topography and is migrating via lateral accretion in the same direction, and generates lithological units f–j. The boundary between lithological units c and f represents a break in deposition.

sequence, with structures from successively higher topographical areas coming in above in the same vertical order as their horizontal distribution (Fig. 10.1). This method of relating the lateral distribution of surface features or sub-environments to a vertical sequence of lithology and sedimentary structures is Walther's principle of succession of facies and is one of the fundamental starting points for any environmental interpretation of ancient sediments (see §1.3).

One complicating factor that is particularly important in many environments (e.g. in intertidal settings) is the activity of burrowing animals. Animals that live below a surface subjected to particular conditions of currents, waves or emergence may extend their burrows down into layers of sediment that were deposited under conditions quite different from those now at the surface (see §9.4). By the time the burrowing takes place, these different conditions may have shifted some distance from the site of burrowing. In other words, burrows can cut across the vertical sequence, and the animals that produce burrows in a particular unit of sediment cannot be assumed to have lived under the conditions in which those sediments were laid down.

10.3 Measurement of sections in rock sequences

Many environmental interpretations of sedimentary rock sequences rely heavily on measured sections through the sedimentary succession (Fig. 10.2). Such sections can give a record of changing sedimentary processes through time, an important clue to the nature of the environment and its evolution. In Chapter 2 we outlined the importance and some of the problems of section measurement, and one or two points mentioned there warrant reflection and emphasis here. In logging a sedimentary section it is important to decide upon its subdivision into lithological units, which may be based on grain size or on compositional differences. The simplicity or complexity of the scheme chosen will depend upon the nature of the succession itself, the eventual aims of the exercise and the refinement or resolution of the interpretation being attempted.

Having established a basis for lithological subdivision, it is next necessary to describe and record the thickness and internal features of each unit and to determine the nature of its contact or boundary with units above and below. If beds conspicuously thicken and thin laterally within the extent of the exposure, record this either by noting it on the single measured section or by measuring and correlating more than one laterally equivalent section. When drawing up the section as a graphic log, remember to adjust the thicknesses of units so that the total thickness of the sequence is accurately recorded. For example, where beds are conspicuously lenticular, it is important to record their average thicknesses rather than maximum values, as recording the latter would introduce a systematic error that would exaggerate the total thickness of the succession.

The features recorded will vary with the nature of the sequence and with the detail of interpretation required. It cannot be stressed too strongly that there is no absolute standard of description. Each investigation has its own aims and timetable, and these will determine the detail of the description and the criteria for subdivision.

The feature of measured sections most commonly ignored is the nature of the contacts between units. Some contacts are gradational, sometimes to a degree that it is difficult to decide exactly where a boundary should be placed. Other contacts are sharp and some are clearly erosive, with conspicuous relief truncating underlying bedding or with erosional structures superimposed upon the surface. In §4.4.3 we suggest clues that may indicate an erosional contact, even when such features are missing. Always consider the possibility of erosion whenever a sharp contact is seen, although, of course, not all sharp contacts are erosive.

Recording your obervations from measured (optional) vertical sequences demands a disciplined method of working. Some geologists prefer to draw a graphic log while in the field, either in their notebooks or on

APPENDIX 1

Directional data: collection, display, analysis and interpretation

In earlier chapters, much has been made of the importance of certain sedimentary structures as palaeocurrent indicators. An individual measurement from a particular structure can, in most cases, have only local significance; in order to develop a feel for directions of wider significance, it is usually necessary to collect a considerable number of measurements. This appendix deals with some of the methods by which such data may be collected, displayed and analyzed, so that they give the most representative and reliable basis for interpretation.

Collection, restoration and presentation of data

Collection

From the various chapters in this book, it should be clear how directional data can be derived from particular structures. Palaeocurrent indicators revealed by sedimentary structures are of two basic types: **planar** features such as the foresets of cross bedding and cross lamination, and **linear** features such as groove marks, axes of trough cross beds or primary current lineation. For modern sediments and for ancient ones that have undergone little or no tectonic displacement, the data can be collected and used directly.

Restoration

When the rocks have undergone considerable tectonic tilting, it may be necessary to reorientate the directional measurements by removing the effects of the tilting and restoring the original bedding to horizontal. In doing this, the structures within the beds that act as the palaeocurrent indicators will themselves be restored (rotated) to their original attitude at the time of deposition. Restoration is performed using the following procedures.

For linear structures such as flutes, primary current lineation, the alignment of ripple crests or the axes of sets of trough cross bedding, deviations induced by tectonic dips of less than 20° are small enough to be ignored. However, serious deviations occur when measurements are made on the foresets of cross-bedded sets. Tectonic dips of greater than only 5° then require reorientation.

In order to restore cross beds to their original attitude, it is necessary to plot and manipulate the data on a stereogram or in a dedicated computer programme. This requires the magnitude and direction of dip, both of the foresets as they now occur, and of the overall sequence (i.e. local tectonic dip). The procedure outlined here applies only if fold plunge is negligible. A more complex procedure is needed for plunging folds. Plot poles (normals) to both the foresets and the bedding on a stereographic projection (Fig. A1.1a). Rotate the points until the normal to the bedding lies on a great circle of the projection (Fig. A1.1a,b). To restore the beds to horizontal, this point must be moved to the centre of the projection. As that shift is carried out, the normal to the foreset must be moved the same angular distance along the small circle upon which it lies (Fig. A1.1b). The new position of this point shows the normal to the foreset at the time of deposition and this can be converted back to a direction and magnitude of dip (Fig. A1.1c). This direction (foreset azimuth) may then be used as an indicator of palaeocurrent direction.

For linear data in steeply dipping beds, plot on the stereogram the attitude of the lineation in space (Fig. A1.2a) and rotate both the normal to bedding and the lineation as described above (Fig. A1.2b). This restores both the bedding and the lineation upon the bedding back to their original attitude prior to tectonic tilting. The orientation of the restored lineation may then be used to indicate palaeocurrent direction (A1.2c).

The principle of this restoration procedure is perhaps best grasped through practice and an example exercise is provided at the end of this appendix.

Presentation

Once directional measurements are restored to their original orientation, it is usually helpful to display them graphically. This can be done in several ways. The method chosen usually depends upon the quantity of data and the variety of structures from which they were collected. Compilation inevitably leads to some loss of information; in particular the distribution of various directions, both laterally and vertically, within the sampled sequence. Compiling directional data is a useful way of visualizing flow patterns, but it is no substitute for relating directions to specific structures in a measured section when the aim of the exercise is to support environmental interpretation. Where compilation is carried out, it is important to produce plots that clearly distinguish the types of sedimentary structure from which they are measured. This can be done either by producing separate plots for each type of structure or by using clearly distinguished symbols, colours or designs for each type of structure on a combined plot. It is also important to bear in mind that some structures can be recorded as a single direction to which flow is directed, whereas others give only a trend along which flow could have been in either direction. Examples of the second group must be shown as double-ended lines or sectors in any display.

Where data are few and have been collected from only a

APPENDIX 2

Sampling and preserving unconsolidated sediments

The collection and preservation of sedimentary structures from unconsolidated sediments for further study in the laboratory requires special techniques. These allow the artificial consolidation of the sediment and often cause the lamination and bedding to be made more apparent. There are two main ways of doing this: taking box cores and making lacquer peels. Some ideas on doing this are set out below, but it is often possible to improvise if purpose-made equipment is not readily available.

Box cores

To take box cores, simple metal or plastic boxes are pushed into the sediment and then removed carefully to retrieve a relatively undisturbed sample. This sample can then be impregnated with glue or resin, either directly in the field or later in the laboratory. If the impregnating glue or resin is distributed evenly, it will penetrate to different depths according to slight differences in porosity and permeability between individual layers and laminae.

The simplest corer is the so-called Senckenberg box, a rectangular box with a removable sliding door panel on one side. On present-day surfaces it is pushed vertically into the sediment and then dug out after insertion of the cover. On a vertical face of a pit or trench it is pushed in horizontally in an upright position. The cover is then slid into place vertically after slight excavation of the top of the box.

A more complex and slightly more difficult corer to use is the tapering Reineck box. This is valuable in shallow water or where the water table is too high to permit the use of a Senckenberg box. The corer is pushed vertically into the sediment and is followed by the cover. The flanges of the box and the grooves in the side of the cover hold the two parts of the corer together, but sediment can obstruct sliding of the flange. The box and the cover are then pulled vertically out of the sediment, giving a downwards-tapering wedge-shape core that can later be impregnated with resin, following careful removal of the cover. After the resin has hardened, the sample can be further strengthened by glueing a sheet of hardboard or thick cardboard to the exposed surface. When this has set, the sample may be freed from the box, if necessary by cutting around the margins of the box. Any loose sediment can be removed from the newly exposed surface by gentle brushing or blowing. This should be done several times as the sample dries out. If permeability differences are present between laminae, the internal lamination should be picked out in relief.

Some glues are soluble in various solvents and this can be useful if, for example, you wish to investigate the grain-size distribution of particular laminae. Cutting out the laminae from the box core and dissolving the glue with a suitable solvent can give loose grains suitable for sieving and other grain-size measurement. Be aware, however, that organic solvents can present health hazards, and appropriate precautions should be taken.

Lacquer peels

Lacquer peels can be taken from the walls or floors of trenches. The surface should be carefully scraped flat and then sprayed, using a garden spray, with a dilute solution of an appropriate resin. Lacquers that use volatile organic solvents such as acetone were often used formerly and, in such cases, the surface could be ignited after spraying, causing the sediment to dry out and the lacquer to penetrate more deeply. Epoxy resins are now more commonly used. The result is to cement and harden a surface layer. However, to remove the layer it must be strengthened by reinforcement. This is done by carefully plastering several layers of resin-soaked bandage or gauze onto the surface. When the resin is thoroughly cured, the peel can be carefully removed, often with the support of a rigid board. Loose sediment can then be removed from the exposed surface, and the surface fixed by further spraying. Peels have the advantage over box cores of allowing the sampling of larger areas and being lighter to carry. However, this preparation makes rather greater demands on field time.

APPENDIX 3

Methods for studying present-day environments

Many types of observation can be made and many methods for recording data can be applied on present-day sediment surfaces. In order to understand and characterize a tidal flat, a beach or an exposed river bed, for example, it can be useful first of all to form a quick-look overall impression and then to carry out a systematic survey of a selected area that is thought to be "typical" or "representative". In some cases a single traverse will be appropriate, whereas elsewhere more detailed mapping might be called for. Generally, the features to be recorded and mapped are predetermined or self-evident and the main problems relate to navigation and positioning, particularly on extensive, low and somewhat featureless areas such as tidal flats or wide beaches. When working on intertidal areas, it is best when possible to work during the falling tide. Not only are sedimentary features fresher but it is also safer. If working during a rising tide, make sure that you understand the way in which the tide flows and make one person responsible purely for safety, to the exclusion of participating in the field observations. Always allow a generous margin for safety and take local advice in unfamiliar areas. Never work alone in intertidal areas.

If observations are to be made along a straight-line traverse, two sighting posts placed some distance apart at one end of the traverse, and in line with it, are a great help. By keeping them in line it is possible to steer an accurate straight-line course on foot or by boat. With the advent and increasing availability of affordable global positioning system (GPS) receivers, establishing position along a traverse is no longer difficult in featureless terrain. However, if one has a topographical map at an appropriate scale, positioning should still be possible without a GPS. Compass bearings on nearby features of known position off the line of section can provide good fixes on long traverses. Measurement by tape or range finder may be used over shorter distances or for more detailed work.

Mapping an area presents more complex problems. On a small scale it may be possible to mark out a measured grid; on a larger scale a series of cross-cutting traverse lines can be established by marker posts around the edge of the mapped area, like those set up for single traverses. A hand-held GPS receiver will be useful for establishing position. In the absence of such a device, it will be necessary to take bearings or other angular measurements on surrounding fixed points. A sextant is an accurate and efficient tool for doing this. Two angles measured between any three fixed points establish position quite accurately.

When surveying on foot, remember that surface features on loose sediment are easily ruined by footprints, so photographs should be taken at an early stage. For the same reason, try to use a few strategic pathways. When working from boats, problems of disturbance are less acute, but observing the sediment surface can present problems. In shallow and reasonably clear water, a glass-bottom box is very useful, and polarizing sunglasses can help to reduce reflection. In deeper or turbid water, indirect methods of observation such as echo sounding become essential.

Descriptions of sediment surfaces can be made at various levels of detail, from the qualitative description of the type of bedform to detailed measurement of dimensions, orientations and distribution densities of particular structures. Systematic recording is often helped by a data sheet, which can be completed at each locality. Setting up an appropriate data sheet may necessitate a preliminary reconnaissance visit before the main study. An example for a tidal-flat setting is shown in Figure A3.1.

Presentation of directional data is discussed in Appendix 1. The resulting rose diagrams and so on can be shown on maps or profiles in a variety of ways. Rose diagrams can be superimposed on maps. Maps can be contoured for parameters such as height and spacing of bedforms, pebble size or distribution density of burrows. In addition, qualitative features such as types of organisms, the plan-view shape of bedforms or the superimposition of different types of forms may be displayed on maps.

Examination of internal structures of modern sediments can be achieved by digging trenches or by taking shallow cores (Appendix 2). Allowing carefully cleaned sides of trenches to dry will often highlight lamination in more detail than on a freshly cut surface. When time is short or the water table is too high for trenching, cores of considerable length can be obtained by pushing boxes or tubes into the sediment. When taking cores, be careful to record their orientation. In the laboratory, cores can be impregnated with resin to preserve them permanently and to show structures more clearly. Procedures for collecting and impregnating shallow cores are given in Appendix 2.

Figure A3.1 (overleaf) Example of a sample data sheet for the systematic collection of observations on a tidal flat.

APPENDIX 4

Techniques for the study of trace fossils

The study of trace fossils requires one to try to relate fragmentary, usually two-dimensional patterns to complex three-dimensional records of behaviour left by a diverse range of organisms. Although a wide range of techniques have been developed, we concentrate here on cheaper, simpler techniques, which rapidly enlarge experience.

Observation and recording of trace fossils in the field and in the laboratory

In present-day sub-aerial and intertidal environments, direct and "after-the-event" observation is possible. In sub-aqueous settings, observation is more costly, as diving equipment or underwater cameras (or both) are needed. Estuaries provide accessible locations for a variety of case studies, but bear in mind the safety issues highlighted in Appendix 3. Exercises based in such settings can also develop skills such as plane tabling, aligning transects, siting quadrat surveys, sampling sub-environments for sediments as well as for organisms and the records of their activity, photographing evidence to scale, orientating data, drawing scaled diagrams and collecting and curating samples. Other useful techniques include the taking of box cores, vertical and horizontal peels using lacquer, polyester resin and epoxy resin, and the casting of burrows, both sub-aerially and under water (Appendix 2).

In dealing with trace fossils in rocks, the drawing of scaled field diagrams and the photographing of traces may be helped by outlining inconspicuous features with chalk (not permanent ink). Burrows, along with other types of poorly defined lamination, may be accentuated by wetting a rock surface with water, glycerine, paraffin or light mineral oil (whereupon uptake of stain is controlled by differences in porosity). Delicate scratches and fine detail may be whitened with powdered chalk or ammonium chloride, and photographed in strong oblique light.

Whatever the environment, it is important to define a problem and plan an appropriate programme of sampling, description and analysis. Graphic logs of sections should include data on occurrence and distribution of trace fossils in relation to other sedimentary features (Fig. 10.6b).

Methods for enhancing the visibility of structures

In the laboratory the following procedures may be appropriate, depending of facilities and the aims of the study. They may help to reveal at least traces of structures where none appears to exist. Some apparently massive beds have intense bioturbation (i.e. maximum rather than minimum organic activity); but this, supplemented by diagenetic effects, enhances their apparent homogeneity.

- The making of peels from box cores.
- Staining of fine-grain carbonate and rocks rich in clay minerals by organic dyes such as alizarin red, methylene blue, or Indian ink.
- Making acetate peels by polishing a cut surface and etching it with acid, then applying acetone and covering this with an acetate sheet, which, when adherent, can be peeled off.
- Subjecting 1 cm-thick sawn blocks of sedimentary rocks, whether naturally cemented or impregnated, to X-radiography or infrared and ultraviolet photography. Ultraviolet photography is best applied to limestones that contain little iron.
- Infrared photography is cheap, in that it requires only a special film and filter, although the cutting of thinner slabs (0.5 cm), which give the best results, is difficult. Exposure time should be proportional to the organic content of the rocks, arenaceous ones being more transparent than argillaceous ones.
- Artificial weathering of apparently homogeneous rocks for a short period using sandblasting equipment with an abrasive of unsorted sand slightly finer than the grain size of the rock.
- Making thin sections of impregnated sediment or rock. These should be made larger (about 5×5 cm) and slightly thicker (0.04 mm) than normal, whereupon they can be mounted in a slide projector or scanned into a computer. Thin sections may be stained to good effect (see above).

Experimental approaches to understanding the behavioural aspects of trace fossils

This approach involves the study in the field or the laboratory of the factors that influence the behaviour of organisms and the form of the resulting traces. Such an approach is mainly concerned with invertebrates rather than vertebrates or plants. Studies commonly focus on burrowing organisms, often bivalves, and the way in which they destroy primary sedimentary structures and form biogenic structures. Studies may vary from the simple observation of the marks made by organisms moving on the sediment surface, or the burrowing of given organisms placed upon a carefully prepared succession of particular composition and consistency, to ones that try to relate the functional morphology of the animal to its behaviour and to its burrow. More complex studies can try to match natural conditions more closely and describe the burrowing behaviour, its effect on the substrate, and the interaction with processes of erosion and sedimentation. See, for example, Bromley (1996) and Goldring (1999).

APPENDIX 5

Techniques for sedimentary logging

Sedimentary logs that give a bed-by-bed graphical depiction of the various lithologies and structures encountered within a succession of rocks are one of the primary methods that sedimentologists use to depict sedimentary data. Although there are many differing styles of sedimentary log, each with their own relative merits, we offer here some general advice about how to represent a sedimentary succession in log form. A sedimentary log template is depicted in Figure A5.1, copies of which can be used in the field.

Before starting the logging exercise

1. Perform a reconnaissance of the outcrop to be logged in order to identify the younging direction of the succession and the lowest and highest points in the stratigraphy that are exposed.
2. Identify which part of the outcrop will be logged. Suitable sections need to be both well enough exposed to be able to generate a reasonably continuous log and also sufficiently accessible. Ideally, try to pick a location where a single continuous log can be made through the study section. However, bear in mind that this is not always possible and be prepared to construct several overlapping logs that are laterally offset from each other, in order to construct a complete run through the stratigraphical study section. Good logging sites include gulleys and ravines, dry stream beds, stepped hillsides, coastal cliffs and wavecut platforms. In regions where the beds have been tectonically tilted, good log sections can be constructed by traversing laterally along the base of cliff lines, and so on.
3. Decide on a scale for the logging exercise. This will be dictated by factors such as the complexity of the stratigraphy, the scale or thickness of the bedding, the outcrop quality, the thickness of the section to be logged, the time available for the exercise and the overall aims of the project.
4. Decide how many log sections you are likely to need in order to characterize the study section adequately. One log may suffice for simple successions with little lateral variability, whereas more detailed studies of laterally complex and variable successions will need many logs.
5. In starting the logging exercise, try and choose a prominent bed as a start point and accurately record its geographical position and, where possible, its elevation above sea level.

The logging exercise

1. The thickness that you record on your log section for each bed should be the true bed thickness, which is not necessarily the same as the exposed bed thickness, especially when logging on a hillslope or when the beds have been tectonically tilted.
2. The amount of detail that you should include on your log will be dictated by the scale at which you are logging. For detailed logs, attempt to include individual beds down to 5–10 cm, whereas for broader-scale logs it may be sufficient to group sets of similar beds together and record them as a single coset. If appropriate, you can schematically sketch in any finer-scale details, such as laminae, between the major bed boundaries.
3. If beds have irregular bounding surfaces, these should be recorded graphically on the log section. For example, erosive channel bases should be drawn cutting down into the underlying unit, and lens-shape bodies should be drawn tapering at their ends. For each bed, it is important to record its thickness at the point where you are logging, although a note should be made if the bed clearly changes thickness when viewed along strike.
4. Pay careful attention to the grain size, both within a single bed and between adjacent beds. Carry a grain-size card and a hand lens, and use them for every bed. Look out for normally or inversely graded beds. Subtle grain-size changes between beds can be important in identifying gradual fining-up or coarsening-up successions over thicknesses of tens of metres, which may indicate something about gradual temporal changes in the energy regime.
5. For each bed look carefully for sedimentary structures, both in section and on exposed bedding surfaces, bearing in mind that they may be preserved on the undersides of beds. Adopt a systematic search approach for each bed. Where structures are evident, they should be included graphically on the log, using a standard set of symbols (Appendix 6). Additionally, record them in as much detail as possible, taking measurements, photographs and making sketches if necessary, especially if you are uncertain of their origin. Pay particular attention to fossils and trace fossils, as these can be useful palaeoenvironmental indicators.
6. Make additional notes where structures can be used to identify way-up or palaeocurrent direction. Record palaeocurrent data in a separate column, either as a dip and dip direction (azimuth) for planar data such as cross bedding, or as plunge and plunge direction for linear features such as groove marks. In tectonically deformed successions, you should also record the dip and strike of the bedding, so that the palaeocurrent data can be restored at a later date (Appendix 1).
7. Make separate notes alongside the log, describing potentially significant features. In many instances you may also be able to infer something about the nature of the depositional process. Indeed, as the log is being constructed, you may even develop hypotheses about possible environments

APPENDIX 6

Key to common sedimentary lithologies and structures

When constructing sedimentary logs or panels, most sedimentologists augment their diagrams with symbols that represent the various types of lithologies and structures encountered. Although there is no formal scheme for depicting these features, the symbols used to represent some of the more common lithologies and structures have become virtually standardized, and an example set of commonly used symbols is depicted in Figure A6.1. These symbols can be adapted to suit the suite of sediments or rocks being investigated. Similarly, additional symbols should be devised to represent those features that are not listed here. It is important when presenting graphical sedimentary data in the form of logs or panels always to include a full explanatory key to all the symbols used. Graphic symbols should be qualified, where necessary, with written descriptive notes and preliminary interpretations of process or environment of deposition.

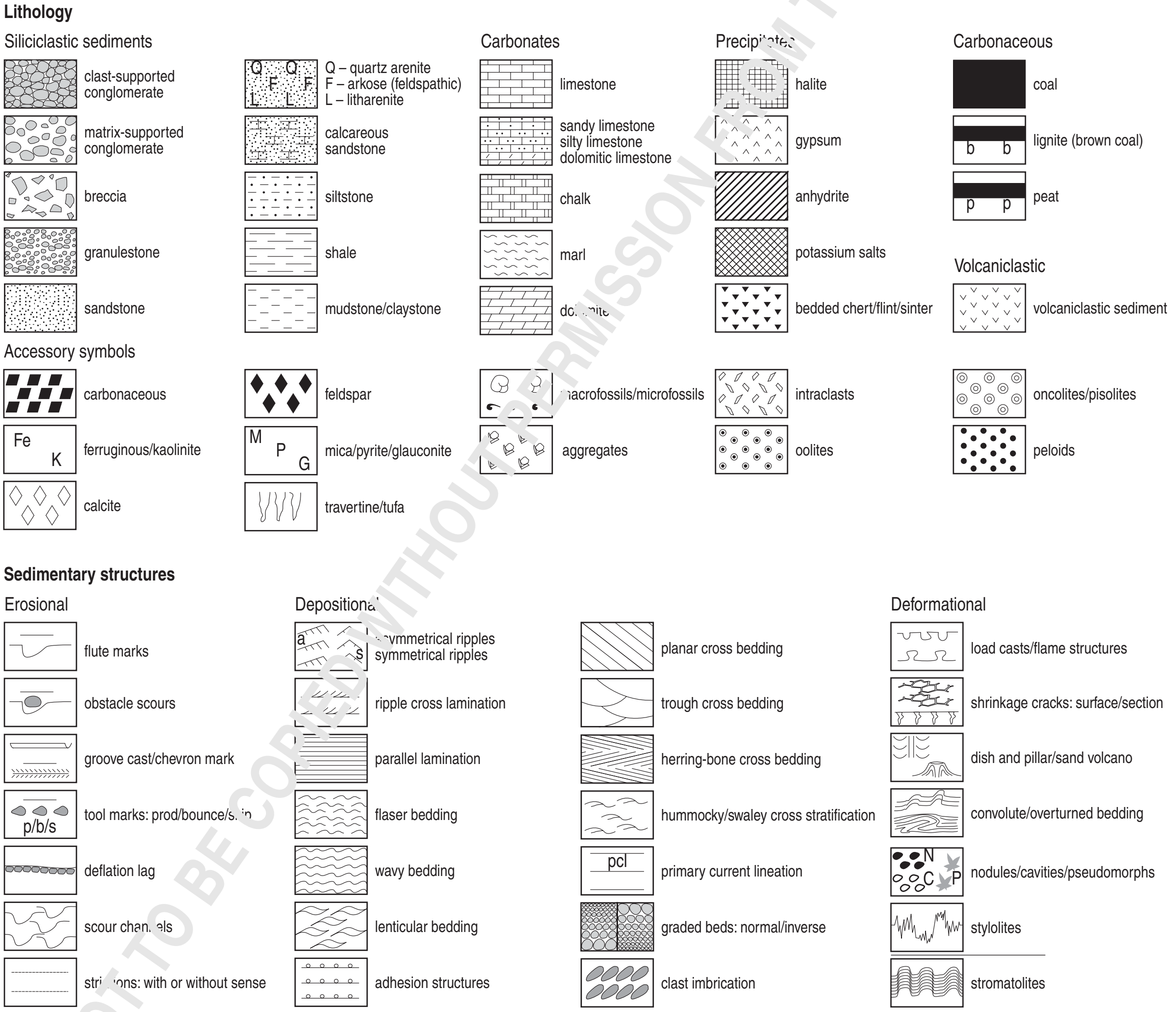

Figure A6.1 Scheme for the graphic depiction of lithologies, sedimentary structures, fossils and trace fossils in sedimentary logs and panels.

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