A Practical Guide to the Study of Glacial Sediments

Edited by

David J. A. Evans and
Douglas l. Benn

ROUTLEDGE

A PRACTICAL GUIDE TO THE STUDY OF GLACIAL SEDIMENTS

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PREFACE

'*These stones are your friends*' (Doug Benn, ca. 1994)

We have spent large parts of our careers trying to convince geography and earth science undergraduates that success in reconstructing landscape evolution is becoming increasingly more reliant upon the greater integration of geomorphological and sedimentological techniques. Moreover, rather than become intimidated by the variety of techniques on offer, young researchers should find confidence in the knowledge that a diverse armoury of tools is at their disposal, and mastery of the use of those tools makes them stronger scientists. The spectacular growth and evolution of glacial sedimentology over the last few decades has been paralleled by an expanding communal knowledge of sedimentary processes in modern environments. So we now have many methods for reading the sedimentary record and the contemporary analogues to guide us through the assemblage of palaeogeographical jigsaw puzzles. Teaching these methods to undergraduates has made us aware of the need for a textbook that pools the guidelines for practical glacial sedimentology, a clear and accessible guide to recording and interpreting glacial depositional successions. A practical guide can never be totally comprehensive but we have compiled here a range of complementary techniques that we find yield consistent and meaningful results in the diverse glacial environments of the world that we have been privileged to study.

David J.A. Evans & Douglas I. Benn
Mother India, Glasgow 2004

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1 Introduction and rationale

Douglas I. Benn & David J.A. Evans

1.1 INTRODUCTION

Physical evidence for past Earth surface processes is preserved in two basic forms: sediments and erosional forms. Unlike erosion, which progressively removes traces of earlier processes and environments, sedimentation has the potential to build up an archive of events, recording a sequence of processes operating at a locality. Thus, careful examination of sediments has the potential to reveal shifting patterns of surface processes in space and time, and provides a window into the past, allowing us to reconstruct past environments and environmental change. In recent decades, earth scientists have learned to read many forms of sediment archive, including deep-ocean muds, desert loess and annual layers in glacier ice. This book is concerned with the techniques used to read one particular archive, the sedimentary record of former glaciers and ice sheets. Although frequently more complex and fragmentary than other sedimentary records, glacial successions can, when examined systematically and rationally, provide detailed insights into former environments and climates in places where no other evidence is available.

The last few decades have seen the spectacular growth and evolution of glacial sedimentology as a discipline. Knowledge of sedimentary processes in modern environments has increased alongside the rapid development of new methods for reading the sedimentary record. The literature on glaciers and glacial geologic processes is now vast, and covers a potentially bewildering array of techniques. We have become increasingly aware of the need for a modern overview of the subject, to provide students and researchers with a clear and accessible guide to recording and interpreting glacial successions. This book does not provide a comprehensive review of all approaches and methods currently in use. Rather, it aims to describe a range of complementary techniques that we have found to yield consistent and meaningful results in a range of contexts throughout the world, from the high Arctic to the Himalaya.

1.2 ORDER FROM CONFUSION

It is clearly impossible to record everything preserved in a sediment exposure. Constraints of time and sanity mean that we must be highly selective in what we observe and measure, and choices must be made as to what is important and relevant. This immediately raises fundamental methodological questions: How do we know what is important and relevant before we measure it? How can we be sure that the choices we make will not bias the investigation and prejudice the conclusions? It is important to address these questions because otherwise there is a very real danger that we only see what we already believe to be there. There are many unfortunate examples of sedimentological studies in which the conclusions clearly predate collection of the evidence. This is one of the side effects of the methodologies we follow as earth scientists. In the largely inductive and deductive approaches that we take when studying sediments, the types of observations we make are necessarily guided by pre-existing theory or previously reported observations. We usually pursue some form of hypothesis testing, the hypotheses emerging from the body of research that pre-dates our own efforts. In order to avoid going down scientific cul-de-sacs, we need to be armed with several, alternative working hypotheses (Chamberlin 1897). All but one of the competing hypotheses can then be gradually eliminated as research continues, following the principle of *falsification* (Popper 1972). This critical rationalist approach has become increasingly popular amongst earth scientists (Haines-Young and Petch 1986). Problems arise when a researcher chooses only one hypothesis and then, often subconciously, protects it rather than tests it. This inevitably entails the erection of '*ad hoc* protection devices', designed to stop a hypothesis being tested by others (Chalmers 1982), and often results in the selective use of real world observations. Science attempts to be objective, unbiased and reproducible. To achieve this goal, we need to find principles that will guide research design, while making sure that we are as objective as possible.

The best way to do this is to adopt a general approach that is applicable to all sediment successions, regardless of their precise origin. All depositional systems, including glacial systems, exhibit order on many different levels, either as a series of steps in *time*, or on a range of scales in *space* (Benn and Evans 1998). The temporal and spatial dimensions provide a powerful basis for structuring efficient and objective research, without presupposing any particular origin for the sediments. The *time dimension* is important, because sediment properties develop at different points of the erosional, transport and depositional history of debris as it travels towards the site of final deposition. The sequence of steps can be regarded as a type of *debris cascade system* (Chorley *et al*. 1984), and can used as a basis for sediment classification schemes (e.g. Boulton and Deynoux 1981; Dreimanis 1989). The *spatial dimension* allows the *context* of a sediment to be established with respect to adjacent sediments, the wider environment and the landscape as a whole. Study of the spatial arrangements of sediments at a hierarchy of scales allows the development of *facies models*, or summaries of how individual deposits are nested together to form depositional systems. Used correctly, these provide a structured basis for deciphering the environmental meaning of sediment successions.

1.3 STEPS IN TIME: THE DEBRIS CASCADE

Sedimentary deposits can be viewed as outcomes of a series of processes extending through time from the initial release of particles from their source, through to deposition. In Figure 1.1, this *debris cascade system* is broken down into four stages: (1) debris source, (2) position of entrainment, (3) transport path, (4) position and process of deposition. The *debris source* is the primary input to the system. For glacial sediments, this may be subglacial (e.g. plucked and abraded bedrock, or over-ridden sediments) or extraglacial (e.g. rock walls, debris-mantled slopes, wind-blown dust). The *position of entainment* is most usually subglacial or supraglacial. Debris is then carried along one or more *transport paths*, including active or passive glacial transport, rivers, suspension in lake- or sea-water, iceberg rafting and the wind. Debris may pass between transport paths many times prior to final deposition. *Depositional processes* refer to the mechanisms which lay down the final deposit, and include subglacial, fluvial, gravitational, subaqueous and aeolian processes, all of which may operate in different glacial environments.

Different properties of sediments are acquired at different points along the debris cascade:

1| The *debris source* controls the lithology of the particles in a sediment, but can also influence the shape and size of particles (particle morphology and grain-size distribution), through factors such as rock strength, joint spacing, etc.

2| The *transport path* determines the erosional processes experienced by particles as they move through the system. As such, transport exerts a strong influence on particle morphology. Grain-size distributions are also modified during transport as the result of progressive wear and the preferential transport of particular size grades by water, wind and gravitational processes. The lithology of debris can also be influenced by transport, because of the varying durability of different rock types. For glacially and gravitationally deformed sediment, aspects of deformational history can be reflected in sediment fabric and structure.

3| *Depositional processes* generally exert the strongest influence on sediment properties, and can control the geometry and lateral extent of beds, internal sedimentary structures

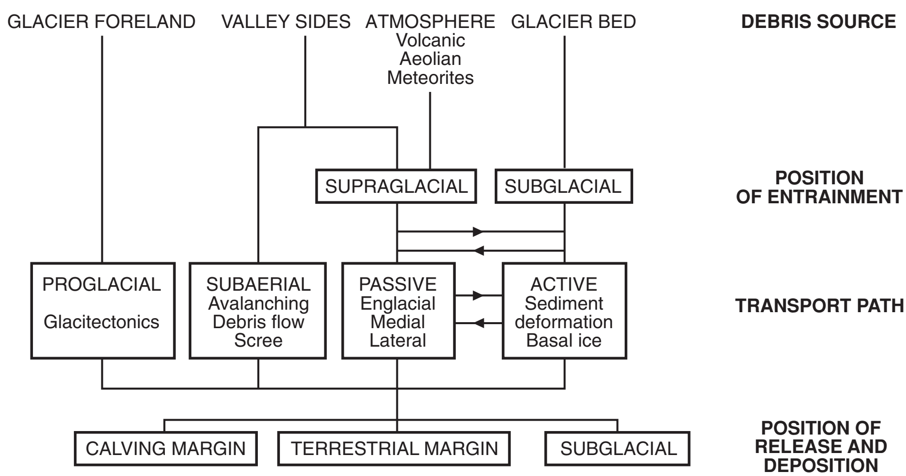

FIG 1.1 Debris cascade system for glacial environments (from Benn and Evans 1998).

(e.g. lamination, cross-bedding and grading), grain-size distributions, particle morphology, fabric, geotechnical properties (e.g. porosity, shear strength and permeability) and others.

4| *Post-depositional processes* include diagenesis, glacitectonic deformation, frost-heaving and winnowing and leaching of fine material by wind and water. They can therefore influence structures (i.e. the superimposition of deformational structures such as folds or faults), grain-size distribution and geotechnical properties.

This temporal framework therefore provides a clear rationale for the choice of techniques employed in a sedimentological study: techniques are chosen to provide information on one or more of the stages of the debris cascade, allowing aspects of the broader sedimentary system to be reconstructed.

1.4 HIERARCHIES IN SPACE: FACIES MODELS

In some cases, the characteristics of individual sediment units are sufficient to define the environment of deposition. Examples include deposits containing fossils with known environmental ranges, or certain types of till. More usually, however, a given sediment type may be formed in many different environments. A debris flow deposit, for example, may look much the same whether it is deposited in front of a glacier, in semi-arid badlands or on a coast. Therefore, the environmental significance of many sediments can only be fully understood *in context;* that is, with reference to the assemblage of adjacent sediments.

In modern environments, sediments are rarely deposited in isolation, but are laid down as part of assemblages that reflect the range of processes active in that environment. Such assemblages can be recognized at a wide range of scales, from the very small to that of a whole depositional basin. For example, cross-bedded sands may be part of an assemblage of sand and gravel infilling a fluvial channel; in turn, the channel fill could be part of an assemblage of channel and bar deposits in a braided river system; and the braided river system part of a yet larger assemblage of deposits laid down along a continental margin. The environmental context of a sediment can therefore be defined at different levels of a spatial hierarchy, beginning with the immediate locality and panning out to wider and wider horizons. At each successive level, the controls on the sedimentary system become larger in scale and longer-lasting in effect. For our example of fluvial sands, at the local level the main controls on deposition are the shape of the immediate river bed and the short-term flow conditions as determined by rainfall, glacier melt and release of stored water. At the largest scale, the formation, location and extent of a braided river system is controlled by global factors such as long-term climatic cycles, relative sea-level fluctuations and tectonics. In marine geology, this approach is formalized in *sequence stratigraphy*, which views depositional events within the context of eustatically controlled marine transgressions and regressions (van Wagoner *et al.* 1988; Posamentier *et al.* 1993). In glaciated basins, sequence stratigraphy is complicated by glacioisostatic effects on local sea level, although the value of the approach has been successfully demonstrated in some studies (e.g. Boulton 1990; Eyles and Eyles 1992; Martini and Brookfield 1995).

A hierarchical approach to sedimentology provides a powerful means of describing how sediments, landforms and landscapes fit together, and of determining how organization in the landscape reflects the organization of depositional processes and external controls in the environment. It forms the basis of *facies models,* which are descriptive and predictive models of relationships between different deposits (Reading 1986; Walker 1992). Somewhat arbitrarily, we can define four levels of organization, at increasing scales (Fig. 1.2): (1) facies, or individual deposits; (2) facies associations; (3) depositional systems, or landsystems; and (4) systems tracts, or large-scale linkages of depositional systems. *Facies* (from the Latin word meaning 'aspect' or 'appearance of' something) refers to a body of sediment with a distinctive combination of properties that distinguish it from neighbouring sediments (Reading 1986; Walker 1992). Facies are formed by single processes or groups of processes acting in close association. In most cases, they are not unique to any particular environment. Rather, depositional environments are characterized by *combinations of processes,* preserved as facies associations sediment–landform associations and, at progressively larger scales, landsystems and systems tracts. At each successive scale, we see deposits in an even wider context.

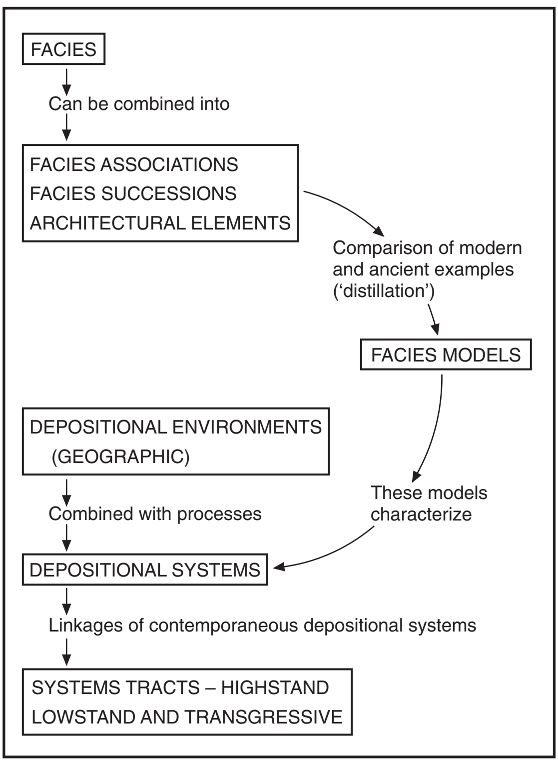

FIG 1.2 Hierarchical sediment classification (from Walker 1992).

While simple in principle, the facies model concept is not always straightforward to apply in practice. As increasingly larger scales are considered, examination of the evidence must necessarily become less and less detailed, particularly for landsystems and systems tracts that may extend over hundreds or thousands of square kilometres. This brings a very real danger that evidence is narrowly interpreted in terms of a preconceived model, magnifying any errors in interpretation made at small scales, leading to misleading conclusions at the largest scales. Basin-wide depositional models may be very neat and intellectually satisfying, but cannot be hurriedly constructed and need to be rigorously tested against new field evidence. Nevertheless, when used critically and carefully, the facies model concept provides a robust yet versatile framework for determining the nested spatial context of deposits. When used in combination with the temporal dimension of the debris cascade, this approach has the potential to yield a dynamic four-dimensional view of events preserved in the sedimentary record.

The focus of this book is the measurement and interpretation of sediments from the outcrop to the microscopic scale, which generally means the scale of facies associations and facies. Most of the techniques are applicable to individual facies and, in combination, can be used to determine their origin in terms of processes. Environmental interpretation, as noted above, requires consideration of associations of facies, in terms of both the range of adjacent facies and the geometric relationships between them. It is therefore very important when logging a section to pay close attention to the geometry of sediment bodies and the nature of their contacts. This topic is discussed in detail in Chapter 2, and we return to it again in a detailed case study in Chapter 9.

1.5 MODERN ANALOGUES

It is common practice to interpret sediments and landforms with reference to *modern analogues*, that is, by invoking similarities to modern examples whose origin and environmental significance are well known. This is a powerful approach, and has become increasingly so in recent years as the literature encompasses a growing range of modern examples. Most importantly, the use of modern analogues replaces unrestrained speculation about the meaning of sediments and landforms, which unfortunately characterized much of the English language glacial literature from the First World War to the 1960s (Evans, in press). The use of analogues underlies Lyell's famous principle of uniformitarianism, that 'The Present is the Key to the Past'. This does not imply that the past was just like the present, but that it is reasonable to suppose that the formation of sediments (and other rocks) was subject to the same physical and chemical principles operating today. From this, it follows that we can use knowledge of modern sedimentary processes and products to guide and constrain our interpretation of the sedimentary record.

There is a very large and expanding literature on modern sediment facies and facies associations, and their significance in terms of processes and environment. In addition, laboratory experiments have expanded our knowledge of process-form relationships. There is a long tradition of flume and wind tunnel experiments into fluvial and aeolian systems, and recently shear-ring and centrifuge experiments have extended this approach to subglacial processes (e.g. Hooyer and Iverson 2000a). Such experiments are important, as they provide knowledge of processes that are seldom directly observable.

It has been objected that the range of past conditions (e.g. during a glacial–interglacial cycle) was far wider than that experienced in modern times, and that certain types of deposits may have no modern analogues (e.g. Kemmis 1996; Shaw 1996, 2002). It is certainly true that some geological events were on scales vastly different to those of today, but the same physical principles should apply. The important point is that the analogue should guide interpretation, not provide a rigid template which exactly replicates past examples. Perhaps a more important limitation than the range of modern environments, is the experience and outlook of individual researchers. One's interpretation of the sedimentary record may be profoundly influenced by personal experience, which may be relatively limited. In such circumstances, it is tempting to give undue emphasis to some aspects of the evidence that fit with one's own experience of glacial systems. It is now clear that glacial environments are very variable (Evans, 2003), and one's repertoire of 'analogues' should reflect this.

1.6 HYPOTHESIS TESTING

As we discussed briefly above, scientific methods predominantly involve the complementary processes of induction and deduction. Induction refers to the formulation of hypotheses or theories from data, whereas deduction is the process of deducing facts from theoretical principles. In the classical sciences such as physics and chemistry, deduction is used to predict the outcome of experiments, and if the prediction agrees with the results, the theory is considered to have passed that particular test (see Chalmers 1982). Good theories are those that have not yet been contradicted by any reliable experimental results or, more positively, those that yield many verifiable predictions. This methodological framework provides a rigorous basis for testing theories, and for weeding out those that are incomplete, inaccurate or just plain wrong.

If we follow the progress of scientific enquiry based upon an inductive philosophy we can identify a series of steps. The first step is to collect data based upon real world observations. Even at this early stage we have, as discussed above, already made decisions about what we choose to observe and what we ignore. The second step involves the ordering of facts by way of measurement, classification, definition and analyses. This is followed by generalizations about the data, the process of induction. We are then ready to create laws or theories and to provide explanation or to predict via the process of deduction. Deduction is a difficult business but we must be bound by the strict rules of the game. This was perfectly illustrated by Sir Arthur Conan Doyle's character, Sherlock Holmes, when he decreed to the bewildered Dr Watson that 'when you have eliminated the impossible, whatever remains, however improbable, must be the truth'. The 'truth' in our practise is the most appropriate interpretation or the one with the highest probability of being correct. Holmes' principle of eliminating the impossible relies on finding evidence that clearly rules out certain interpretations. In other words, making observations that will definitively show, one way or another, whether a hypothesis is false. Eliminating possibilities also requires that hypotheses have clear, unambiguous implications that can be compared with the evidence. The best hypotheses are often the simplest. Hypotheses formulation should be guided by the principle of Occam's Razor, named after the philosopher, William of Occam (1300–49), which states that 'explanations should not assume any superfluous elements not required by the evidence'.

The interpretation of sediments is an art, but it should also be a science. Is the deductive–inductive model, considered by many to be an essential component of the scientific method, applicable in this case? Reaching an interpretation about a particular sediment association certainly involves inductive reasoning, but how can interpretations be tested? The classic experimental approach is seldom applicable in studies that attempt to reconstruct the past, but this does not mean that predictions cannot be tested in any way. Instead of predicting the outcome of experiments, sedimentologists can, and should, test their models by predicting the results of *new observations*. In practice, this means that we should say that *if* a particular interpretation of a sediment succession is correct, *then* we should expect to find certain other evidence to support it. Experienced field workers tend to do this by habit, constantly thinking through the implications of their ideas, and checking new lines of evidence to test them. This approach can also form part of multi-proxy studies, in which several lines of evidence are used to converge upon the most likely interpretation. Finding one's predictions confirmed can be one of the most exciting aspects of field geology. When the opposite happens, and the new evidence contradicts the model, you should think again, and either modify the model or replace it entirely. This should be seen not as a failure and disappointment, but as an opportunity: if the evidence does not fit with existing interpretations, it may point the way towards something entirely new. This opportunity is lost if you are so sure the model is right that you decide that the apparently contradictory observations were actually predicted by the model all along. In effect, this means that the model is *unfalsifiable*, that is, no matter what observations are made, the model is still believed to be correct. As such, the model is useless as science: it has become a tenet of belief. To have value, a model must make firm predictions that are testable against the immutable testimony of the rocks. Learning to follow these rules is ultimately far more rewarding than trying to maintain the illusion that one is omniscient.

1.7 ARE YOU THINKING CRITICALLY?

If you are to avoid the pitfalls of scientific endeavour outlined above, it is crucial that you understand the processes of objectivity and analytical thought and consciously develop the habit of critical thinking. Unfortunately for teachers and students alike, there is no one dominant theoretical recipe for critical thinking. However, Reiter (1991) identifies two major levels to critical thinking that may prove instructive. First, higher order thinking involves the ability to use analysis, synthesis and evaluation skills. Specifically, analytical skills enable the individual to break problems down into managable parts and select the relevant or valid information. The ability to synthesize allows a person to combine information in a meaningful way from a variety of sources. Evaluation skills empower the individual with the ability to make judgements based on the available evidence, data or observations.

The second level of critical thinking is multi-logical thinking, or the ability to reason objectively from multiple viewpoints. This requires the individual to exercise an open-minded approach (openness), an intellectual curiosity and a commitment to think through all the possible connotations (inquisitiveness), and a non-defensive standpoint that acknowledges weaknesses in their own interpretations (objectivity).

Of course, scientists of all denominations are human beings – they often find it difficult to accept that their interpretation of the facts, because it was so hard won, may not be the most appropriate. We must remember, however, that everyone can provide an 'explanation' of a particular collection of observations but only one explanation is strictly correct, and we may never find it! As Wolpert (1992) points out in his book *The Unnatural Nature of Science*, '… a theory that fits all the facts is bound to be wrong, as some of the facts are themselves bound to be in error …'.

1.8 SCOPE OF THIS BOOK

We have included in this field guide overviews of the techniques presently regarded as fundamental to the description, analysis and interpretation of glacigenic sediments. Although in-depth explanations of the procedures involved in analytical techniques, especially those conducted in the laboratory, are beyond the scope of a field guide, we do provide preliminary coverage in the following chapters in order to enable an assessment of the suitability of a technique during the fieldwork stage. Each chapter concludes with short case studies that demonstrate the applications of the techniques covered therein. Because a field guide is designed for use on the job, it should get the message across succinctly and practicably. Therefore, we have chosen to take an illustrative approach, whereby information is delivered through figures and photographs wherever possible.

Chapter 2 introduces the reader to the first stages of sediment description, classification and recording. It covers the principles of facies description and coding and stratigraphic logging and provides explanations of specific structures and bedding in sediments. Chapter 3 covers the principles of particle size analysis, tackling sampling methods and statistical assessments from the outcrop to the laboratory. This is followed by an overview of particle form in Chapter 4. This involves the quantification of the physical changes made to individidual particles during their transport. The macrofabric of sediment is presented in Chapter 5, covering all of the directional properties of a sediment, including the orientation of particles, bedding planes, folds, faults and erosion surfaces. This is followed in Chapter 6 by an overview of the micromorphological technique. This allows us to zoom in to the smallest of scales in order to assess the sedimentary and structural signatures that are not evident at macro scale. Particle lithology is the subject of Chapter 7, covering the petrology, heavy mineral characteristics, geochemical signatures, clay minerology and magnetic properties of materials. Of necessity, this chapter refers to the appropriate laboratory procedures. Similarly, Chapter 8 on the engineering properties of glacial materials provides important information on laboratory procedures designed to yield information on the geotechnical aspects of sediments. The final chapter in the book is a case study, designed to demonstrate how a multi-faceted approach to the analysis of Quaternary glacigenic sediment sequences in a typical quarry can culminate in the reconstruction of complex depositional environments. It goes without saying that our preferred reconstruction is, at present, the one that explains the most observations.

2 Facies description and the logging of sedimentary exposures

David J.A. Evans and Douglas I. Benn

2.1 RATIONALE

The foundation for any detailed investigation of glacial sediments should be an accurate record of the range of sediment facies present at a locality. Usually, this involves recording the facies exposed in sections created by natural processes (e.g. landslide scars, river cuttings or coastal cliffs) or by human activities (e.g. quarries, ditches, road or railway excavations), although information can also be obtained by augering, coring or geophysical methods. In this chapter, we discuss methods of facies description and section logging, with emphasis on characteristics observable in the field.

2.2 FIELD IDENTIFICATION OF FACIES AND FACIES ASSOCIATIONS

2.2.1 Introduction

A sediment *facies* can be defined as a distinctive body of sediment that forms under certain conditions of sedimentation (*cf.* Reading 1986). In other words, a sediment facies exhibits a set of physical characteristics which, collectively, reflect the processes of its formation. For example, a *turbidite* has a distinctive assemblage of bedding structures and grain-size gradations which form during the passage of a turbid underflow (turbidity current), and a *glacitectonite* exhibits distinctive deformation structures recording the over-riding and disruption of pre-existing sediments by glacier ice. However, in most cases we do not *know* the origin of a sediment, but must infer it from the sediment characteristics and our knowledge of what they mean. Thus, the identification of a genetic facies depends on an interpretation, and as such is subject to revision as ideas and perspectives change. This problem is particularly acute for glacigenic sediments, many of which form in dangerous or inaccessible environments and are consequently incompletely understood. As a result, it is often preferable to identify facies purely in terms of their physical and chemical characteristics, without reference to any inferred genesis. To make this distinction clear, the term *lithofacies* is used to refer to a sediment body in purely descriptive and objective terms. Lithofacies can then be interpreted in terms of genetic processes, independently of the description and classification stage. By clearly separating description and interpretation, the lithofacies concept ensures a more objective approach less prone to bias or error, at least in theory.

Lithofacies are identified in outcrops or boreholes from characteristics observable in the field, although definitions can be refined following laboratory analyses. Important defining characteristics are:

1| *grain size*;

2| *depositional structures*;

3| *deformation structures*;

4| *inclusions*;

5| *fossils* and *trace fossils*;

6| *bed thickness*;

7| *bed geometry*;

8| *contacts between lithofacies*.

2.2.2 Grain size

Particle size distributions of sediment facies can be determined by laboratory analysis (Chapter 3). It is useful, however, to estimate modal grain size and sorting in the field using the definitions of grain-size categories shown inside the back cover. For the larger sizes, grain size and degree of sorting can be easily estimated or measured, but for sand-sized and smaller particles, estimation must be done with the aid of charts (inside front and back cover) and rules of thumb. Silt can be distinguished from sand because wet silt can be rolled into a thin sausage shape, whereas sand cannot. Silt feels gritty when gently bitten between the teeth, whereas clay feels smooth. *Diamictons* are poorly sorted sediments, usually with a wide range of grain sizes. The term is often used somewhat loosely, although precise definitions and subdivisions can be adopted if required (e.g. Hambrey 1994). The general subdivisions normally employed are *stratified* and *massive* diamictons, whereby a stratified diamicton is one that displays some stratification at outcrop scale but is still poorly sorted (Figs. G19–23, 25 and 36). (Please note: Figures prefixed with a 'G' refer to the glossary section.)

Grading refers to systematic changes in grain size vertically through a bed (Fig. 2.1). Upward fining, resulting from the varying settling velocities of different grain sizes, is

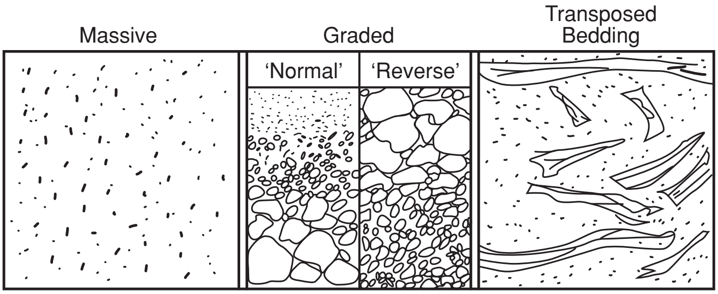

FIG 2.1 Massive and graded bedding (after Fritz and Moore 1988).

termed *normal grading* (Figs. G3 and 5), whereas upward coarsening, due to mechanical sorting in certain types of mass flow (Figs. G7, 10, and 19–23), is known as *inverse grading*. Sometimes grading affects only the coarsest grain sizes in a sediment, in which case it is known as *coarse-tail grading*. A common form of grading in diamictons is a downward increase in the concentration of coarse clasts, formed by sinking of clasts through weak matrix (Fig. G19, Lawson 1982).

2.2.3 Depositional structures

Many lithofacies exhibit internal bedding, consisting of *beds* (>1cm thick) or *laminae* (<1cm thick; Table 2.1). Internal bedding is highlighted by vertical changes in grain characteristics, such as grain size or mineralogy, and may be *bed-parallel* or *inclined*. Beds of similar character form *sets*, which can be further grouped into *cosets* on the basis of physical or genetic affinities. Fine-grained sediments exhibiting cyclic grain-size variations are referred to as *rhythmites* (Figs. G7, 11 and 12) and reflect variations in sediment supply and depositional conditions on a range of timescales (Smith and Ashley 1985; Benn and Evans 1998; Tiljander *et al*. 2001; Fig. 2.2). Rhythmites deposited by the settling out of turbid plumes in glacimarine environments display a vertical transition from silt to mud (*cyclopels*) or sand to mud (*cyclopsams*), thought to be controlled by tidal influences (Fig. G43). Bed-parallel lamination in sandy facies reflects deposition in thin,

Table 2.1 Terminology for describing laminae and internal bedding (Ingram 1954).

Term	Thickness (cm)
Thinly laminated and wisps	0.1-0.3
Thickly laminated	0.3-1.0
Very thinly bedded	1-3
Thinly bedded	3-10
Medium bedded	10-30
Thickly bedded	30-100
Very thickly bedded	100-1000

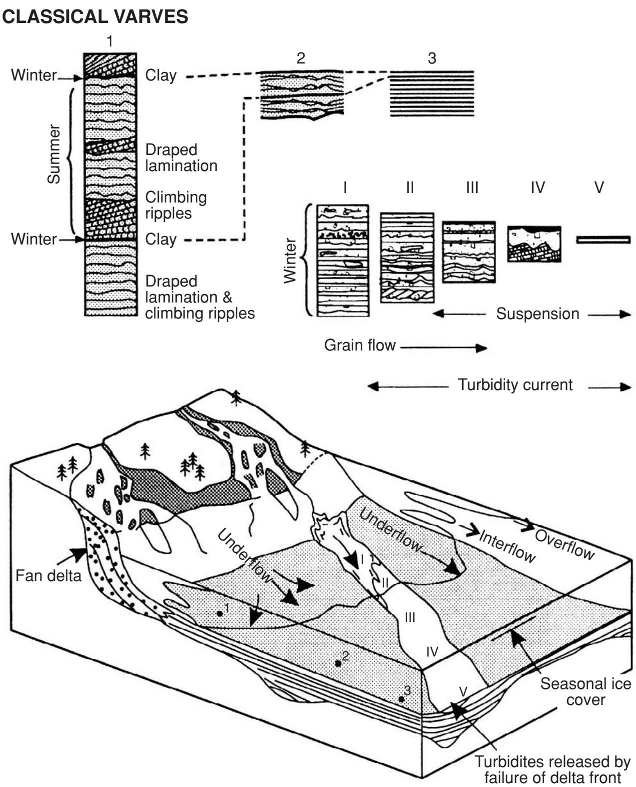

FIG 2.2 Rhythmite deposition in lake environments (modified from Eyles and Miall 1984).

horizontal sheets (*plane bed* forms) under either *lower* or *upper flow regime* conditions (i.e. slowly moving shallow water or rapidly flowing deeper water). Lamination is generally best developed in lower flow regime plane beds due to low flow velocities and efficient grain-size sorting; upper flow regime plane beds can be distinguished by the presence of thin, linear grooves and ridges on the bedding surfaces (parting lineations) parallel to the former flow direction. These are easily seen on bedding planes of lithified sandstones, but can be difficult to observe in unconsolidated sands.

Inclined internal bedding comprises various types of *cross-bedding* and *cross-lamination* (Fig. 2.3), which reflect the migration of bedforms under flowing water or wind. Bedforms can be subdivided into *microforms* (ripples) and *mesoforms* (dunes). The sequential deposition of ripples results in the production of *ripple cross-lamination* (*climbing ripples*) (Figs. G7, 8 and 11). Under unidirectional currents, facies characteristics are determined by the balance between downstream ripple migration and the settling of sediment from suspension (Fig. 2.4). Further variations in structural style are introduced by multi-directional or oscillatory currents, for example in tidal settings (Fig. 2.5). Larger scale cross-bedding structures exhibit a wide range of geometries, reflecting the form and evolution of different dune forms (Fig. 2.6). Sophisticated classifications of cross-bedding

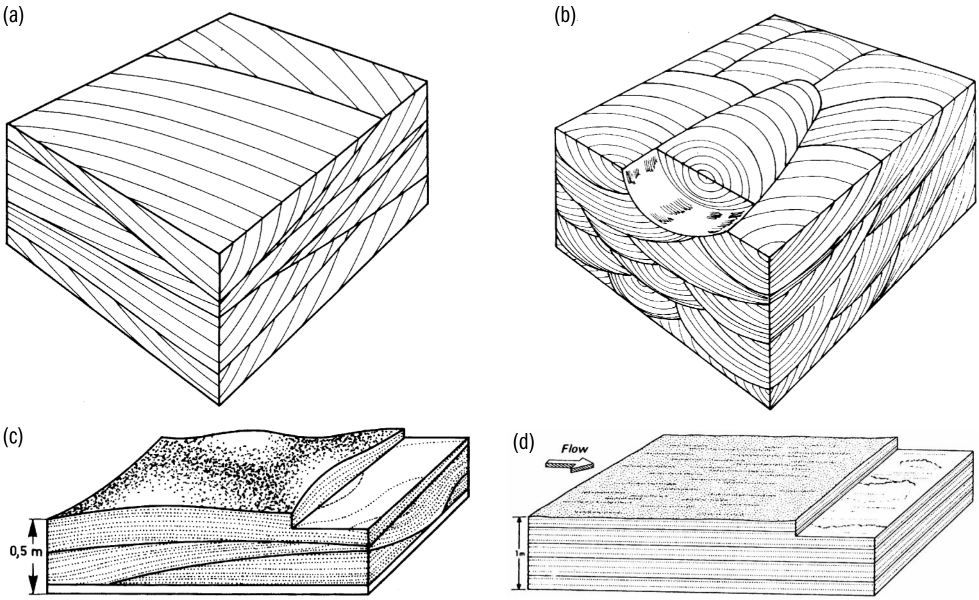

FIG 2.3 Sand and gravel cross-bedding with reactivation surfaces marked in bold: a) planar cross-bedding; b) trough cross-bedding; c) hummocky cross-stratification (HCS); d) plane beds (after Harms *et al*. 1982).

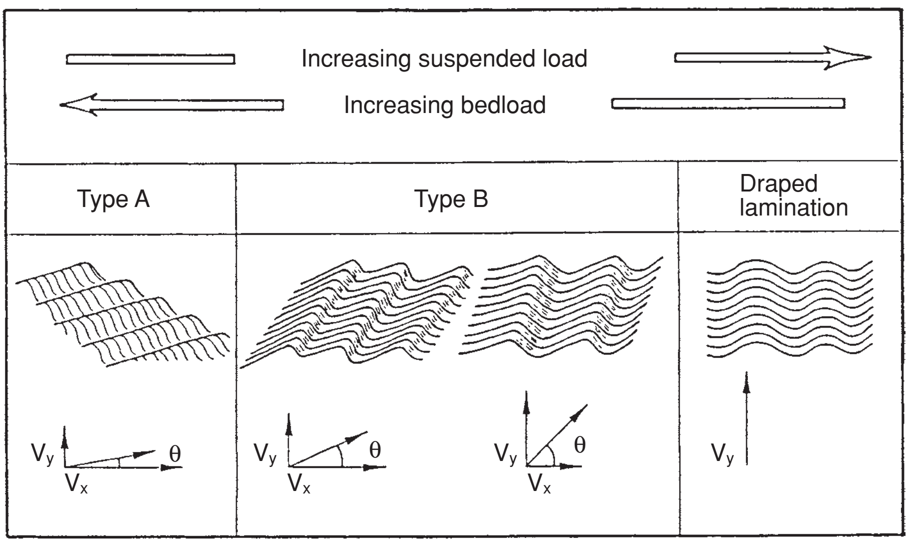

FIG 2.4 The production of ripple cross-lamination. Ripples climb at angle θ whose tangent is the mean aggradation rate V_y divided by the downstream migration rate V_x (from Ashley *et al*. 1982).