Environmental Sedimentology

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Blackwell
Publishing

BLACKWELL PUBLISHING
350 Main Street, Malden, MA 02148-5020, USA
9600 Garsington Road, Oxford OX4 2DQ, UK
550 Swanston Street, Carlton, Victoria 3053, Australia

First published 2007 by Blackwell Publishing Ltd

1 2007

Library of Congress Cataloging-in-Publication Data

Environmental sedimentology / edited by Chris Perry and Kevin Taylor.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-1-4051-1515-5 (pbk.: acid-free paper)
ISBN-10: 1-4051-1515-7 (pbk.: alk. paper)
1. Sedimentology. 2. Geology–Environmental aspects.
I. Perry, Chris (Chris T.) II. Taylor, Kevin (Kevin G.)

QE33.E58 2007
551.3–dc22
2006023456

A catalogue record for this title is available from the British Library.

Set in 10/12.5pt Sabon
by Graphicraft Limited, Hong Kong
Printed and bound in Singapore
by Fabulous Ltd

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Case studies

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Preface

It will be clearly apparent to students of the earth sciences that a number of environmental issues have gained in importance over the past few years, and that sedimentology has a role to play in informing the debate about their impacts. These issues include recent and future climate change, and a wide range of anthropogenic pressures that influence earth surface systems from a range of physical, chemical and ecological perspectives. Many sediment systems act as excellent archives of past environmental change, allowing us a window into the recent past, as well as providing tools for monitoring change within active sedimentary environments. These in turn can be used to inform management strategies.

Sedimentology text books traditionally do a good job of introducing the concepts of sedimentology and dealing in detail with the principles of sedimentology. These text books, however, tend to focus primarily on facies analysis and basin processes of sediment accumulation, and on the interpretation of ancient sedimentary environments. Although these cover many aspects of modern depositional environments, the emphasis is primarily on using modern systems to interpret the geological record. More applied sedimentology text books effectively focus on the application of sedimentology to the oil and gas industry. It is increasingly being recognized that a more environmental approach to sedimentology is needed. In this context Environmental Sedimentology represents a rapidly expanding research field, which draws upon both the traditional aspects of sedimentology and the more applied areas of the discipline, and also interfaces with the fields of hydrology, geomorphology, engineering, biogeochemistry and ecology. Essentially it is concerned with understanding the development of recent sedimentary systems, and examining their response to both natural and anthropogenically induced disturbance events.

The aims of this text book are:

1 to outline the boundaries of the field of Environmental Sedimentology;
2 to allow those students with a prior grounding of sedimentological principles to develop their knowledge in the environmental aspects of the subject;
3 to allow environmental scientists and physical geographers access to the field of environmental sedimentology;
4 to allow more specialist groups (e.g. civil engineers, legislators) to gain information on this topic.

The target audiences for this book are earth scientists, environmental scientists, physical geographers, hydrologists and civil engineers. Although we assume that earth scientists will have a grounding in the principles of sedimentology, we recognize that some of the other groups may not have. Therefore, the introductory chapter not only summarizes the principles of environmental sedimentology, but also provides an overview of the basics of sedimentology. We encourage readers of this text to make free reference to the available text books on fundamental sedimentology where appropriate.

The book is structured such that it outlines processes and issues associated with a range of terrestrial (i.e. upland, fluvial, lake, arid and urban) and coastal and shallow-marine sedimentary environments. We do not incorporate aspects of groundwater hydrology, which, although often recently described as an environmental sedimentological topic, essentially deals with water, rather than sediments. We also do not intend to specifically address the topic of soils, which are not strictly sediments, but the initial products of bedrock and organic material degradation. Each chapter has a similar structure and, for each specified environment, examines aspects of: sediment sources and sediment accumulation; the processes and impacts of natural disturbance events; the processes and impacts of anthropogenic activities; sediment system management and remediation; and issues likely to be of concern in the future, such as short to medium term (< 100 years) climatic change, sea-level rise and increased anthropogenic influence. Each chapter is authored by a leader in their particular field and by the very nature of this approach, each chapter should not be considered to be uniform in its format. Each author has presented the major environmental processes and products in a manner in which they feel most appropriate, inevitably reflecting that author's strengths. The reader will, therefore, find some chapters that focus on physical processes, others on the chemical aspects, and yet others with a more numerical eye on environmental sedimentology. This reflects the wide range of disciplines that inform the subject.

Each chapter provides a wealth of up-to-date references to allow the student to follow up on the processes and products discussed in the chapters in more detail. Most, but not all, of these references are in primary scientific journals and reports, but where it is felt advantageous, reference is also made to text books in the field. An important part of each chapter is the inclusion of a number of case studies, which act as self-contained examples to illustrate some of the key concepts discussed in the respective chapters. Each case study, geographically specific, has additional references pertinent to that example.

Numerous individuals have provided inputs into the development of this book, but in particular we would like to thank the following for their comments and reviews at various stages: Helene Burningham, Sue Charlesworth, Ian Drew, Simon Haslett, Piers Larcombe, David Nash, Phil Owens, Laura Shotbolt and Chris Vivian. We would also like to thank Delia Sandford, Ian Francis and Rosie Hayden at Blackwell for help and advice throughout this project.

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Environmental sedimentology: introduction

Chris Perry and Kevin Taylor

1.1 ENVIRONMENTAL SEDIMENTOLOGY: DEFINITION AND SCOPE OF CHAPTERS

Environmental sedimentology represents a relatively new subdiscipline of the earth sciences and, as such, the boundaries of the field are not clearly defined. Herein we define environmental sedimentology as . . . '*the study of the effects of both man and environmental change upon active surface sedimentary systems*'. Consequently, environmental sedimentology can be regarded as the study of how both natural and anthropogenic inputs and events modify the production and accumulation of the physical and biogenic constituents of recent sedimentary deposits. The field of environmental sedimentology has evolved gradually over the past two decades, largely owing to an increased recognition of the influence that anthropogenic activities are exerting upon sediment production and cycling. Studies in these areas reflect a need to address issues of sedimentological change driven by environmental or land-use modification or contamination. This, in turn, has promoted increasingly integrated approaches to examining the dynamics of, and interlinkages between, sedimentary environments, the nature of which can be illustrated by one example, namely studies that link catchment processes (and anthropogenically induced changes in catchment sediment yields) with sediment supply to (and through) the coastal zone. Here, disciplines such as slope geomorphology, fluvial sedimentology, hydrology, coastal and marine sedimentology, and coastal management combine to assess interlinked issues of sediment production, transport and accumulation.

This book is divided into nine main chapters, each of which deals with a distinct sedimentary system. These are delineated as follows; mountains, fluvial, arid, lacustrine, urban, temperate intertidal (estuarine and deltaic), temperate coastal (beach, barrier island and dune), tropical coastal (coral reef and mangrove) and continental shelf. Although this structure provides a convenient approach for distinguishing and describing individual sedimentary environments, such subdivisions are to some extent arbitrary and, in light of the sediment exchanges that occur between environments, not necessarily ideal. As a result, the linkages that exist between environments are highlighted where appropriate. In addition, the book does not set out to review every type of sedimentary environment, but rather to provide a framework for the subject in the context of a number of key sedimentary systems and settings. Given these caveats, each of the chapters examines aspects of sediment supply and accumulation, the response of the individual sedimentary systems to natural and anthropogenic change, and issues of sediment management and remediation, and reviews the potential responses of these sedimentary systems to issues such as climatic and environmental change.

The chapters in this book essentially deal with sedimentological processes and geomorphological changes that have been operating over short-to-medium (< 100 yr) time-scales (*biological* time-scales of Spencer 1995; *secular* time-scales of Udvardy 1981), although many of

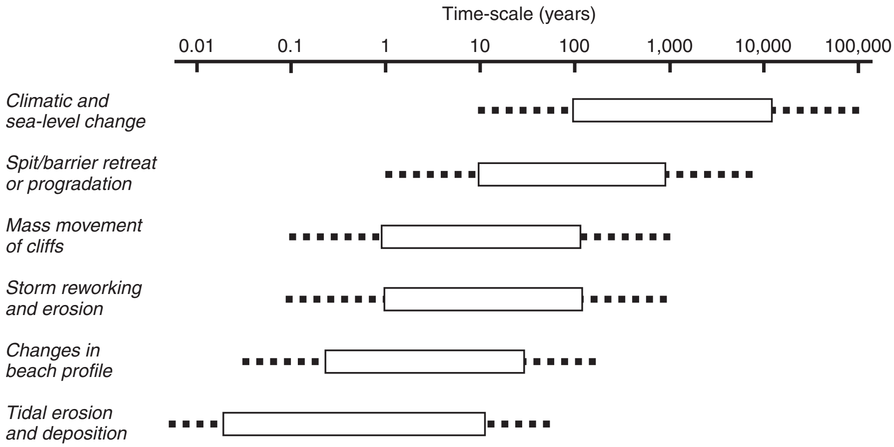


Fig. 1.1 Time-scales over which different geomorphological processes operate within a hypothetical coastal environment. (Adapted from Woodroffe 1992.)

the sedimentary landforms discussed also inevitably represent the products of longer-term sediment accumulation. Hence, in each chapter these may encompass the daily processes of sediment transport and reworking, through to the effects of rapid climatic and sea-level change (Fig. 1.1). In this context, short-term changes (< 1 yr) within a coastal sedimentary environment may, for example, include the processes of tidal erosion and deposition, seasonal changes in beach profiles or morphological change due to storm events; in the short-to-medium term (< 10 yr), mass movement of unstable cliffs, spit progradation, or barrier breaching; and in the medium-term (up to 100 yr), coastal landform progradation, changes in delta morphology, or coastal retreat. Superimposed upon these processes may be a range of anthropogenic activities (e.g. sea-wall construction, sand dredging or contaminant inputs), which may influence not only the dynamics of the sedimentary system, but also the associated floral and faunal components of the system. Many of these biological components (e.g. dune plants, mangroves or corals) are often of sedimentological significance in their own right, either as sources of sediment or as agents of sediment trapping and stabilization.

This introductory chapter reviews the fundamentals of sediment production and the principles of sediment transport and deposition. In addition, consideration is given to the types of issues that are discussed in the respective chapters, and which help to define the discipline of environmental sedimentology. This chapter also outlines the magnitude and frequency of predicted shifts in global climatic and environmental conditions that have relevance to the development of both terrestrial and marine sedimentary systems over the coming century. These include issues such as sea-level change, global warming and changes in temperature, precipitation and storm frequency, and thus provide a framework for discussion within the respective chapters.

1.2 SEDIMENT PRODUCTION AND SUPPLY WITHIN SEDIMENTARY ENVIRONMENTS

The composition of sediments that accumulate within individual sedimentary environments is primarily a reflection of three main factors:

1 the sediment source;

2 the processes of sediment transport and deposition, which determine whether sediment is retained or transported through a specific environment (these mechanisms are outlined in section 1.3);

3 the chemical processes operating within the sediment or water column, for example, carbonate and evaporite precipitation, chemical diagenesis.

In terms of the initial supply of sediment into a sedimentary system, three basic sediment types can be delineated. These are: (i) detrital minerals, (ii) biogenic or organic sediments and (iii) anthropogenic particles and compounds.

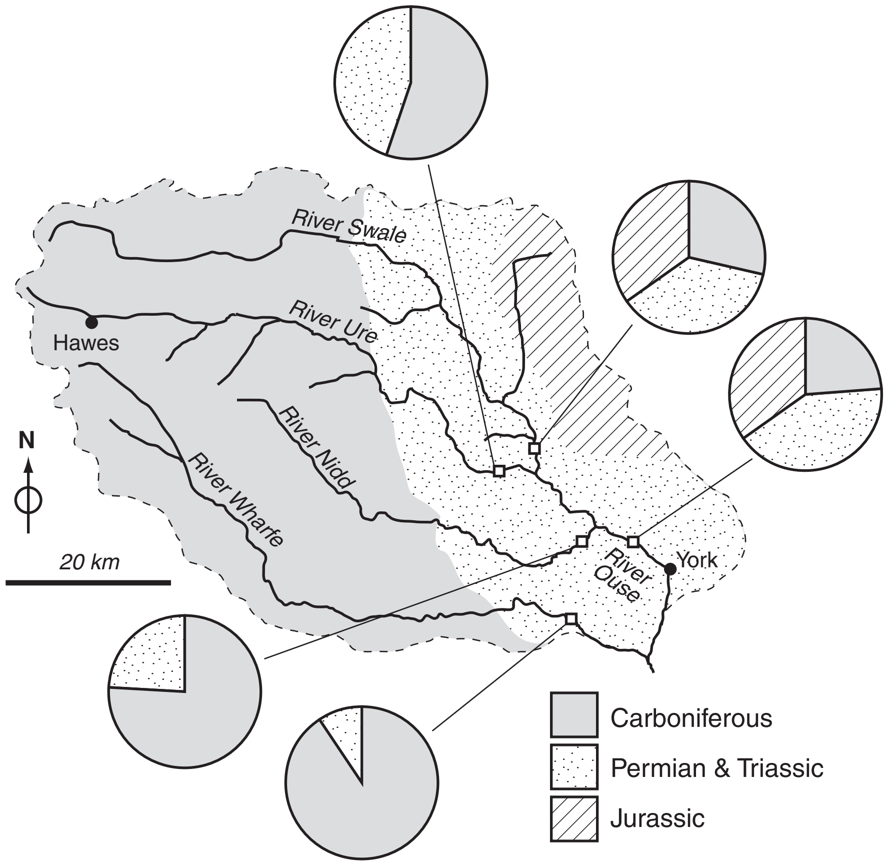


Fig. 1.2 Composition of suspended sediment samples recovered from the River Ouse (UK) and four of its tributaries that have different underlying geologies. (Adapted from Walling et al. 1999.)

1.2.1 Detrital minerals

Detrital minerals, such as quartz and feldspar, along with heavy minerals, form a primary component of many terrestrial and marine sediments. These minerals are initially released by weathering processes and are progressively eroded and transported into, and through, a range of sedimentary environments. As a result, initial mineralogical composition of the bedrock often influences the relative abundance of the individual minerals that are released. This control is clearly illustrated in studies of suspended sediment compositions within river catchments where individual tributaries are underlain by bedrock of differing geological compositions. In the River Ouse catchment (north-east England), for example, individual tributaries drain areas of differing geology (Carboniferous, Permian/Triassic and Jurassic). Suspended sediments in the different tributaries have distinct mineralogical and magnetic signatures that demonstrate variations in the relative importance of different rock units as sources for fluvial sediment (Fig. 1.2). Local variations are attributed to variations in the rates of erosion and sediment supply from the different geological units (Walling et al. 1999).

In reality, these detrital minerals rarely undergo a simple source to sink transport route, but instead are subject to numerous phases of weathering, transport, deposition, storage, lithification, reworking and redeposition. For example, detrital sands in the Orinoco drainage-basin of South America are derived from similar bedrock material, but the nature of relief and chemical weathering markedly alter the grain composition (Johnsson et al. 1991). Material derived from steep, orogenically-active terrains undergoes limited chemical weathering, whereas

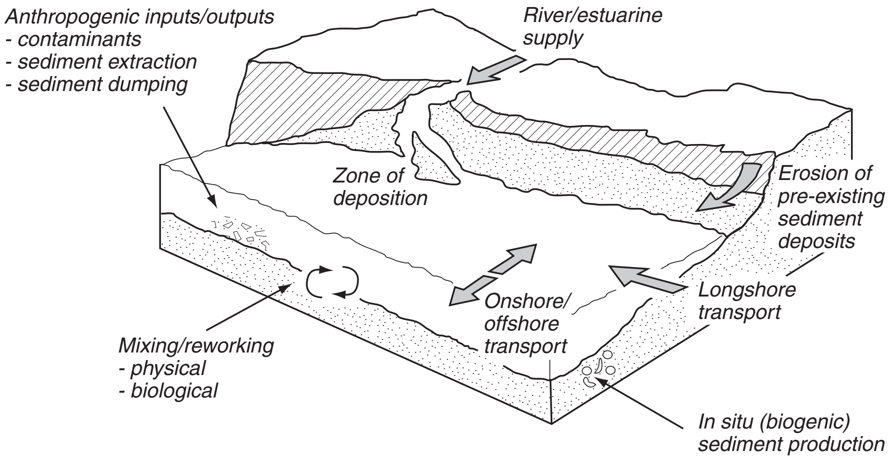


Fig. 1.3 Schematic diagram illustrating the different potential natural and anthropogenic sources of sediment into a nearshore marine environment.

in low-relief parts of the catchment thick soils accumulate and the detrital grains become highly altered chemically. Furthermore, sediment deposited in low-lying alluvial floodplains undergoes additional chemical weathering and alteration, further modifying their composition. Consequently, within any individual environment sediments tend to be derived from a range of source areas and weathering regimes, and these both contribute to, and influence, the composition of the accumulating sediment (Fig. 1.3). Over the time-scales considered in this book, the release of sediment from previously deposited sedimentary sequences should, therefore, also be regarded as a key sediment source.

1.2.2 Biogenic and organic sediments

In addition to detrital minerals, significant amounts of sediment are derived from the remains of skeletal carbonate-secreting organisms. These form across a wide range of marine environments (Schlager 2003), although marked latitudinal variations occur both in the types and rates of biogenic sediment production (Lees 1975; Carannante et al. 1988). Such production peaks in the low latitudes and, in particular, in the vicinity of coral reefs, where carbonate sediments often represent the primary sediment constituents (see Chapter 9). Even in these environments, however, marked variations in the composition of sediment assemblages are evident across individual reef or platform environments and reflect subtle spatial variations in marine environmental conditions (e.g. light and wave energy). These influence the composition of the reef community and, hence, the composition of the sediment substrate. In high-latitude settings, biogenic carbonate production may remain important but in many settings is volumetrically 'swamped' by terrestrial inputs of detrital minerals.

Carbonate deposits are also relatively common within a range of intertidal, terrestrial and freshwater settings, and are associated primarily with physico-chemically induced carbonate deposition. On a localized scale these represent important sources of carbonate to the sediment record. For example, within intertidal and supratidal settings that are characterized by high aridity and high evaporation rates, the precipitation of evaporite minerals such as gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$) is common. At present, extensive evaporite-rich sediments occur in the south-east Arabian Gulf and an excellent review of their occurrence is given by Alsharhan & Kendall (2003). The hydrology of such depositional settings has been reviewed by Yechieli & Wood (2002).

In some freshwater fluvial and lacustrine settings carbonate deposition also occurs and can lead to the development of significant carbonate bodies (in some cases these have been described as forming 'freshwater reefs'; Pedley 1992).

Deposition is driven by a range of physico-chemical and biologically mediated processes, the latter in association with microbial mats that facilitate local reductions in CO_2 and thus carbonate precipitation (Pedley 2000). These deposits are termed *tufa* where deposition occurs under ambient environmental conditions, or *travertine* where the deposits are associated with thermal activity (Ford & Pedley 1996) and have been shown to have potential as recorders of palaeoclimatic information (Andrews et al. 1994).

Organic inputs, derived from plant material, can also contribute abundant material to sediment substrates. This is particularly the case in salt marshes (see Chapter 7) and mangroves (see Chapter 9). Along mangrove-colonized shorelines, where external inputs of sediment (siliciclastic or carbonate) are minimal, this organic material can be the main substrate contributor and leads to the development of mangrove peat (Woodroffe 1983). Biogenic, but non-carbonate sediment, contributors such as diatoms are also important within, for example, lake environments (Chapter 4). The progressive accumulation of such microfossils within lake sediments has proved to be an effective long-term recorder of a range of environmental parameters such as effective moisture, i.e. lake water levels, and of temperature (Battarbee 2000) and have thus been widely used as proxy records of climatic and hydrological change (e.g. Bradbury 1997).

1.2.3 Anthropogenic particles and compounds

Increasingly important in many sedimentary systems are inputs of anthropogenically sourced sediments. These include both sediment grains that come from material that is anthropogenic in origin (e.g. building material, industry) and sedimentary materials that have been heavily impacted by anthropogenic activity. A good example of anthropogenic-derived sediment is that present within urban environments (see Chapter 6). In this environment, as well as soil and vegetation sources, sediment is sourced from vehicle wear, building material, combustion particles and industrial material. All of this material has chemical and mineralogical properties distinct from natural sediment grains and, as a consequence, interacts with the environment in a different manner.

Another significant component of modern sediment, mostly absent from pre-industrial age sediments, are contaminants. A *contaminant* is commonly defined as a substance released into the environment without a known impact (Farmer 1997), or the presence of elevated concentrations of substances in water, sediments or organisms (GESAMP 1982). In neither of these definitions is the potential to cause environmental harm attributed to a contaminant. This is in contrast to a *pollutant*, which is more specifically defined as a substance that either causes harm to the environment or exceeds an environmental standard. Contaminants in sediments take a variety of forms, including metals, inorganic elements, nutrients, organic compounds and radionuclides, and the major sources of these contaminants are highlighted in Chapter 3 (Table 3.2). It is important to be aware that many of these contaminants can be sourced from natural processes as well as anthropogenic activities, although in most cases anthropogenic inputs tend to dominate.

Contaminant sources to sediments may be of particulate, dissolved or gaseous form, but for most contaminants the particulate form is dominant (Horowitz 1991). Although contaminant sources are predominantly particulate, there are important exceptions. Contaminants from sewage treatment works (e.g. Zn and P) can be predominantly in solute form, and metals from acid mine drainage are also in dissolved form at source owing to the low pH of the waters. These dissolved contaminants, however, commonly become associated with the sediment phase, via mineral precipitation or surface adsorption, as solution concentration, pH and Eh change through mixing with dilute river water (Boult et al. 1994).

Contaminant sources may take one of two general forms, point source and diffuse (non-point) source. Point sources of pollution originate from a single location and include mines and mine waste, landfill sites, factories, waste water treatment works and bedrock mineralization. Diffuse sources of contaminants originate from

(a)

Udden–Wentworth	Phi (φ)	mm	μm
Cobbles	*−7*	*128*	
	−6	*64*	
Pebbles	*−5*	*32*	
	−4	*16*	
	−3	*8*	
	−2	*4*	
Gravel	*−1*	*2*	
Sand – *V. coarse*	*0*	*1*	
Sand – *Coarse*	*1*	*0.5*	500
Sand – *Medium*	*2*		250
Sand – *Fine*	*3*		125
Sand – *V. fine*	*4*		63
Silt	*5*		31
	6		15.6
	7		7.8
	8		3.9
Clay	*9*		2.0

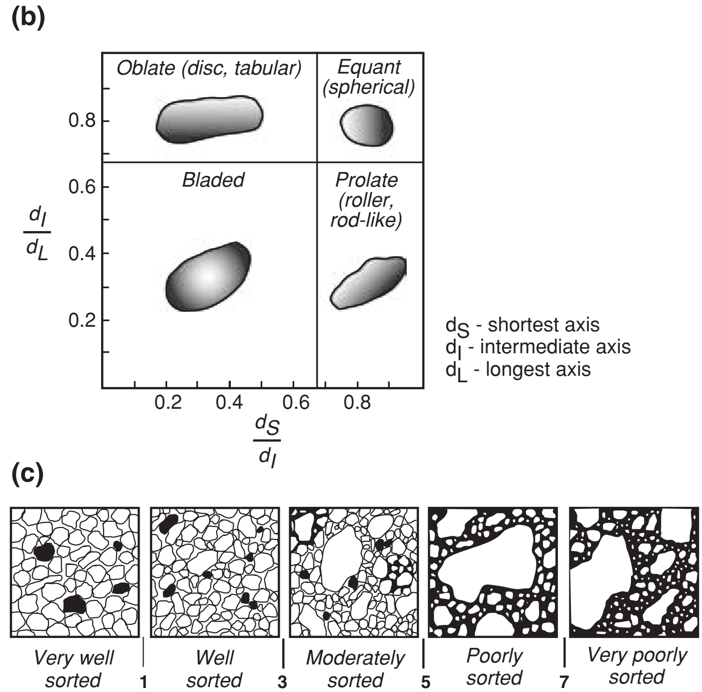


Fig. 1.4 (a) The Udden–Wentworth scheme, which is widely used to describe grain-size categories. (b) Classification scheme used to describe particle form based on the ratio between the short, intermediate and longest grain axes. (Adapted from Graham 1982.) (c) Visual comparison chart used for describing the degree of sediment sorting within a sediment deposit. (Adapted from Graham 1982.)

a wide area and can be defined as 'pollution arising from land-use activities (urban and rural) that are dispersed across a catchment or subcatchment, and do not arise as a process of industrial effluent, municipal sewage effluent, deep mine or farm effluent discharge' (Novotny 2003). Examples include direct atmospheric deposition, urban runoff and sediments (i.e. from the road network), agricultural runoff and sediments (i.e. from soil erosion), the reworking of floodplain sediments (i.e. by bank erosion) and background geology.

1.2.4 Particle description and classification

Regardless of origin, individual sedimentary particles are typically described in terms of their grain size and shape. Grain size is an important parameter both from a descriptive perspective and in relation to understanding sediment transport and deposition (see section 1.3). For larger particles, measurements of three orthogonal axes are typically made and are used to calculate a mean diameter. For smaller particles, grain size is typically determined by grading the samples through a set of sieves (see McManus 1988). A number of schemes have been devised to describe and measure grain size, but one of the most widely used is the Udden–Wentworth scheme (Fig. 1.4a).

Descriptions of sediment shape are somewhat more complex and may be taken to comprise elements of a particle's form, roundness and texture. Roundness is usually described on the basis of comparisons with visual identification charts. Form is also usually quantified by describing grains in terms of one of four standard classes: oblate, equant, bladed or prolate, which reflect the relationship between the short, intermediate and long axes of grains (Fig. 1.4b). Other useful schemes combine elements of both roundness and sphericity in visual comparison charts (e.g. Powers 1982). Particle sorting describes the range of grain sizes that occur within a sedimentary deposit (Fig. 1.4c) and can be calculated by measuring the dispersion of grain size around the mean. This is again a useful parameter as it can be used, along with grain size data, to infer information about the environments of sediment deposition and the history of sediment reworking (e.g. McManus 1988).

1.3 MECHANISMS OF SEDIMENT TRANSPORT AND ACCUMULATION

The transport and deposition of sediment within and through different sedimentary environments may occur within a variety of mediums (water, wind or ice), and the thresholds for sediment entrainment and transport represent a fundamental control on both the character and development of specific sedimentary deposits, as well as their response to fluctuating energy regimes. The classic work of Hjulström (1935) demonstrated the relationship that exists between the velocity of fluid flow and the size (diameter) of sediment that can be moved within a fluid. At its most simplistic this demonstrates that sediment will be deposited when flow rates drop below the fall velocity for a particle of a given size. However, the relationship between these two parameters is non-linear so that, for example, much higher flow velocities are required to entrain highly cohesive fine clay and silt-rich sediments (Fig. 1.5). Although in reality these entrainment/transport thresholds vary from this model depending upon sediment substrate and individual grain characteristics (e.g. shape, structure, density) as well as the flow characteristics of the fluid medium, a basic grain-size–flow-velocity relationship is demonstrated that can be broadly applied within both fluvial and marine settings. This section outlines some of the key physical parameters that control sediment entrainment, transport and settling (deposition), and highlights the main sedimentary processes that operate within the different sedimentary environments discussed in this book. For further details about the physics of sediment transport and deposition reference should be made to texts such as Allen (1985) or Leeder (1999).

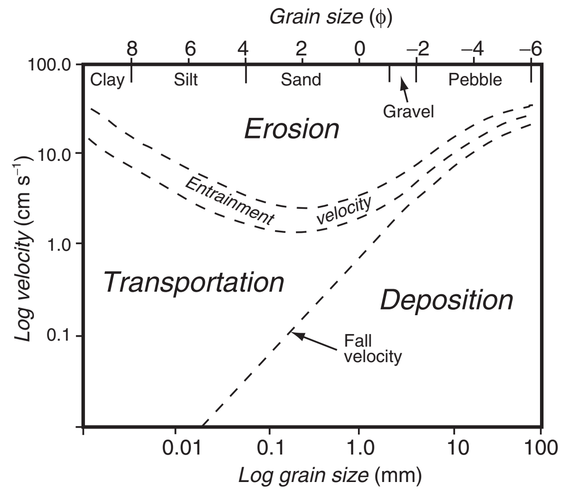


Fig. 1.5 Hjulström's (1935) graph showing the relationship between flow velocities and sediment grain size and the corresponding fields in which erosion, transport and deposition occur.

1.3.1 Sediment entrainment

The entrainment of sediment by a fluid (most commonly water or wind), and thus the potential for sediment transport, is determined by the relationship between (i) fluid density (which is the weight per unit volume of a fluid – usually expressed as 'specific gravity'), (ii) fluid viscosity (the resistance of a fluid to deformation or flow – this is measured as a ratio between the shear stress and the rate of deformation) and (iii) the velocity of fluid flow. These parameters exert an influence on the nature of the flow regime within a fluid medium and, in particular, determine whether flow that occurs immediately above the sediment substrate (within the boundary layer) is laminar or turbulent. In situations characterized by laminar flow, flow streamlines run parallel to the substrate, flow velocity is low and viscosity is high (Fig. 1.6a). Under turbulent flow, the streamlines move in a series of random eddies, flow velocity is high and viscosity is low (Fig. 1.6a). The threshold between these two flow states is expressed by the Reynolds number (R), which describes the ratio between mean velocity over a defined distance or depth, and

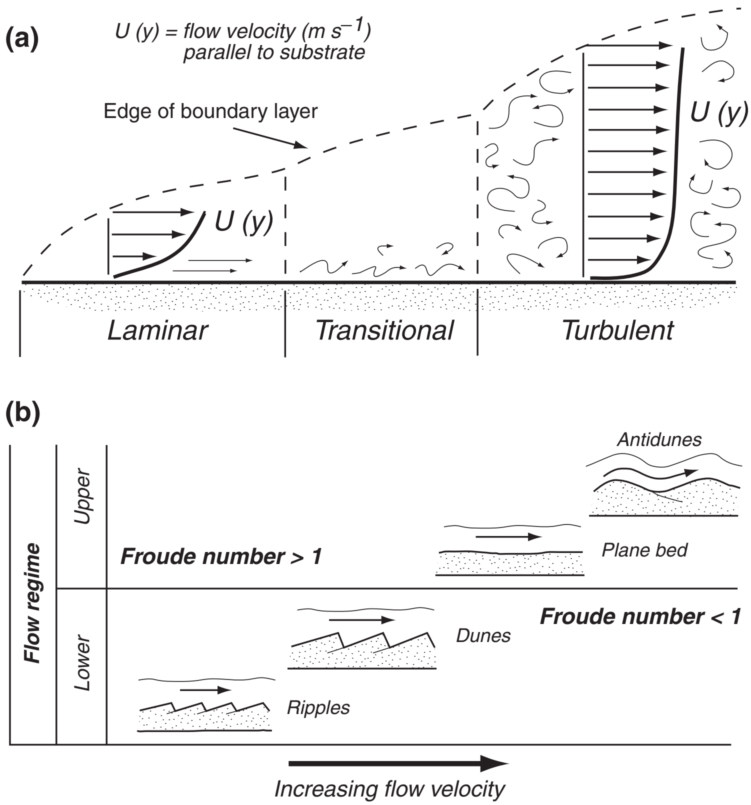


Fig. 1.6 (a) The nature of flow regimes within a fluid medium. During laminar flow, the flow streamlines run parallel to the substrate, flow velocity is low and viscosity high. Under turbulent flow, the streamlines move in a series of random eddies, flow velocity is high and viscosity low. Intermediate flow is described as being transitional. (Adapted from Allen 1985.) (b) The relationship between flow regime and sediment bedform development. As flow velocity increases from lower to upper flow, the amount and size of sediment that can be entrained and transported increase, leading to a change in sediment bedform structure. (Adapted from Selley 1994.)

fluid viscosity, and is determined by the following equation:

$$R = Udp/\mu$$

where U is the particle velocity, d is the particle diameter, p is the particle density and μ is the fluid viscosity. In the context of particles moving in a fluid, a low Reynolds number (< 500) describes fluid flow occurring in a laminar fashion, whereas at high Reynolds numbers (> 2000), fluid flow is turbulent. Between these two values flow is described as transitional (Allen 1985). Flow turbulence increases both proportionally with velocity and as bed surface roughness increases.

Another important coefficient in terms of fluid dynamics (the Froude number) explains the ratio between the force required to stop a moving particle and the force of gravity. Within open channels the Froude number (F) is determined as:

$$F = U/\sqrt{g}D$$

where U is the average current velocity, g is acceleration due to gravity and D is the depth of the channel. As flow velocity increases the Froude number approaches 1, a value that separates lower (< 1) flow regimes from higher (> 1) flow regimes (Allen 1985). Flow velocities increase from lower to upper flow and associated with this is an increase in the amount and size of sediment that can be entrained and transported. This, in turn, will influence the structure of the sedimentary bedforms that develop (Fig. 1.6b and section 1.4.1).

A number of forces act upon a sediment lying on a substrate surface (Fig. 1.7a), and these influence the potential for entrainment. The key force here is bed shear stress, which is related to the velocity of flow. This represents the force acting per unit area parallel to the bed and exerts a fluid drag across the grain. If this drag exceeds the frictional and gravitational forces acting on the grain, then lift and entrainment will occur. Sediment entrainment thresholds thus

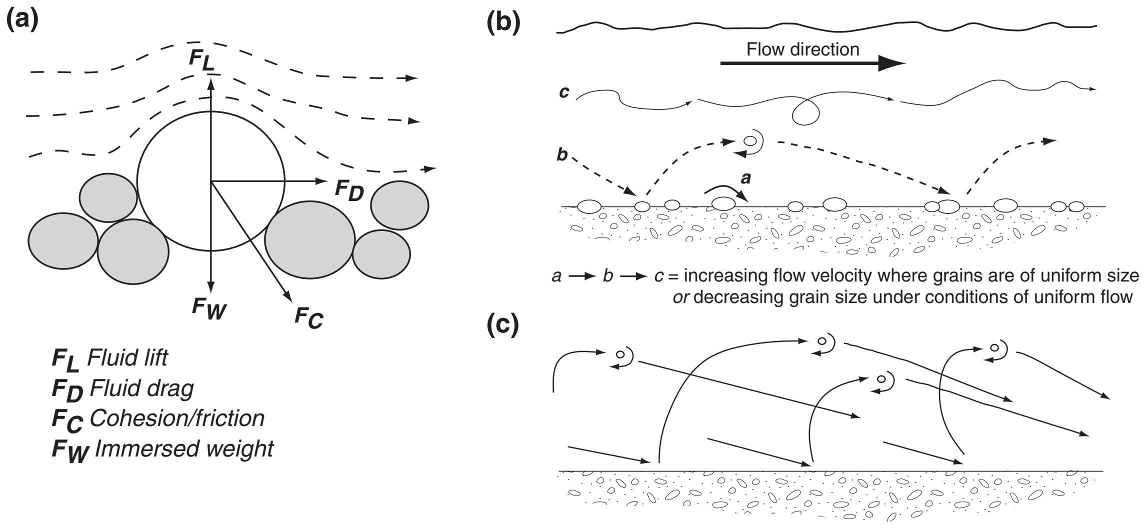


Fig. 1.7 (a) Schematic diagram illustrating the main forces acting on a sediment particle within a moving fluid medium. (Adapted from Allen 1985.) (b) The processes of sediment movement within flowing water; *a*, rolling; *b*, saltation; *c*, suspension. (c) Grain transport due to saltation under conditions of aeolian transport. Grains typically exhibit steeper and longer trajectories during aeolian transport.

occur at a critical shear velocity, the value of which varies with sediment grain size (although this is complicated by substrate specific variations in grain size, particle density, sediment packing and grain imbrication). The interrelationship between these variables is highlighted in the Hjulström graph (Fig. 1.5), which illustrates a general (and fairly intuitive) rule whereby increasing flow velocities are required to entrain increasingly larger sized particles. This rule, however, breaks down where the substrate is dominated by very fine sands, silts and clays because of the cohesive nature of such material. In such cases, much higher flow velocities are required to entrain particles and this helps to explain why fine silts and clays can accumulate within tidally influenced estuarine and deltaic environments (see Chapter 7). Velocity–entrainment relationships are also complicated as fluid moves across a sediment substrate because grains protruding from the substrate cause flow to be constricted. This causes the streamlines above the grain to accelerate and thus to exert a fluid lift (Fig. 1.7a). Within aeolian environments, wind velocities that exceed the critical shear stress for specific sediment grain sizes are also required for entrainment, although they occur at higher velocities than in water.

1.3.2 Sediment transport

Once entrained, sediment movement occurs in three ways:

1 as bedload material that is too heavy to be lifted up into the water and moves by *rolling* along the substrate (Fig. 1.7b);

2 via the process of *saltation* whereby lighter grains are temporarily lifted into the fluid and then settle out (in water, saltating grains typically exhibit short, flat trajectories due to the cushioning effects of fluid viscosity, whereas in air the trajectories tend to be steeper and longer; Fig. 1.7b);

3 in *suspension* where the lightest particles are held within the fluid and moved, often in an erratic path (Fig. 1.7b).

For sediments of a given grain size these transport mechanisms occur along a gradient of increasing flow velocity. Consequently, for a sediment deposit comprising a mix of grain sizes it follows that the occurrence of different sediment size fractions can be attributed to different transport mechanisms. In aqueous environments, solute transport can sometimes also be an important medium for the transport of contaminants (see Chapters 3 and 6). These transport mechanisms, which operate in a range of fluid mediums and in different environments, produce very different types of sedimentary deposits. These are discussed below in the context of (i) aqueous environments, (ii) aeolian environments and (iii) glacial environments. Consideration is also given to the movement of material by gravitational processes.

1.3.3 Sediment settling

As with sediment entrainment and transport, the major controls on sediment deposition relate to grain size and flow velocity. The rate at which sediment settles (the settling velocity W) within a fluid of a given density is determined by Stokes law:

$$W = [(P_1 - P)g/18\mu]\, d^2$$

where $(P_1 - P)$ is the density difference between the fluid and particle, g is the acceleration due to gravity, μ is the fluid viscosity and d is the grain diameter. The law states that the settling velocity of a spherical particle is related both to its diameter and to the difference between the density of the particle and that of the surrounding fluid. In simple terms this means that larger sediment grains will settle faster than smaller grains providing they are of equal density. Within most sedimentary systems this process is complicated, however, by three factors:

1 the fact that few grains are completely spherical;

2 the fact that grains are often continually in contact within one another and hence disrupt settling;

3 the fact that different minerals have different densities (e.g. quartz 2.65 g cm^{-3}, feldspars 2.55–2.76 g cm^{-3}, biotite 2.80–3.40 g cm^{-3}; Allen 1985).

Hence, in the case of terrigenous sands, which are commonly dominated by quartz, but with variable amounts of other detrital and heavy minerals, the different particles have different settling velocities and thus different transport and settling thresholds. Differences in settling velocities are even more complex in systems dominated by skeletal carbonates because the grains not only have very different internal skeletal structures (and hence densities), but also very different morphologies (see Chapter 9).

1.4 SEDIMENT TRANSPORT IN DIFFERENT SEDIMENTARY ENVIRONMENTS

1.4.1 Sediment transport in aqueous environments

Sediment transport within aqueous environments occurs primarily in association with either traction or turbidity currents. Within traction currents the primary mechanisms of sediment movement are rolling and saltation (Fig. 1.7b), whereas within density currents transport is associated both with traction and suspension. Consideration is given first to traction currents, which are important within both fluvial and shallow marine environments. Within fluvial systems, current flow is nearly always unidirectional and progressive reworking of fine sediment commonly leads to the finest material being transported furthest downstream. Hence, fluvial systems are typically characterized by downstream reductions in mean grain size (see Chapter 3). In contrast, within nearshore settings and in the marine-influenced lower reaches of rivers, currents tend to be bi-directional (owing to the variable flood- and ebb-tide influence) and hence sediments will be reworked both on- and offshore during the tidal cycle (see Chapters 7 and 8).

Studies of flow regimes under unidirectional conditions have highlighted clear changes in sediment transport mechanisms and sedimentary structures associated with different current velocities. As flow increases, the critical velocities required to entrain sediment particles are reached and at this stage sediment starts to move by rolling and saltation. This leads to the development of ripples and, at slightly higher velocities, dunes (Fig. 1.6b). Such structures are associated with lower flow regimes (Froude numbers < 1).

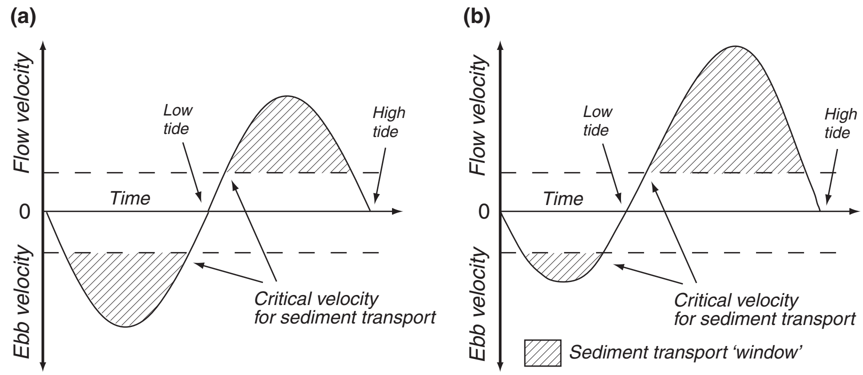


Fig. 1.8 Graphs showing changes in ebb- and flood-tide velocities within (a) symmetrical and (b) asymmetrical tide-cycle settings. Within each phase of the tidal cycle sediment transport occurs only when velocities exceed the critical thresholds for transport. In symmetrical settings, sediment is moved back and forth but there is no net sediment transport direction. In asymmetrical settings, a stronger ebb- or flood-tide phase may result in a net direction of sediment transport.

As flow velocities increase, upper flow regimes (Froude number > 1), characterized by turbulent flow, are reached and under these conditions the sediment bedforms are initially smoothed out to form planar beds and eventually antidunes which may migrate upstream (Fig. 1.6b). As flow reduces, a reverse sequence is followed. Hence through cycles of river flooding, the mechanisms and processes of sediment movement change with flow velocity (see Chapter 3).

In contrast, shallow marine environments are characterized by bi-directional flow, although the magnitude and frequency of the flood- versus ebb-tidal phase varies depending upon local tidal regime and nearshore geomorphology. The potential for sediment transport changes through each tidal cycle as flow velocity increases through either the ebb- or flood-tide phase and then decreases approaching either low or high tide ('slack' water). In settings where the tide cycle is symmetrical (Fig. 1.8a) sediment will be reworked first seaward and then landward, but there will be no net transport in either direction. It is more common, however, for tidal cycles to be asymmetrical (Fig. 1.8b), and under these conditions there will be a net sediment transport direction. This situation is common in many estuaries where fluvial outflow exerts an influence on the tidal cycle (see Chapter 7), or in mangrove settings where strong ebb-tide flows in the mangrove creeks can occur owing to the frictional effects of high vegetation cover on the mangrove flats (see Chapter 9).

Sediment transport is also initiated in near-shore (marine or lacustrine) environments where wave-generated water motion interacts with the shoreline substrate. Waves are generated by the frictional effects of wind and this initiates water particle motion within the upper part of the water column. The orbital particle motion decreases with depth (Fig. 1.9a) until it reaches effective wave base (defined as half the wavelength), below which there is no wave-induced water motion. In open, deeper water, water motion therefore exerts no influence on sea-floor substrates, but as the water shallows nearshore the oscillating water particles start to interact with the sea-bed (Fig. 1.9b). As this occurs, the water particles move in an increasingly ellipsoidal fashion and initiate on- and offshore movement of sediment.

Transport in aqueous fluids may also occur in density currents. These are associated both with traction and suspension transport, and occur due to density differences between two fluid bodies. Within aqueous environments, density differences commonly result from variations in temperature, salinity or suspended sediment load where two bodies of water meet. Where the fluid entering a body of water has a higher density, for example where sediment-laden water enters a lake, the denser fluid will flow beneath the less dense fluid

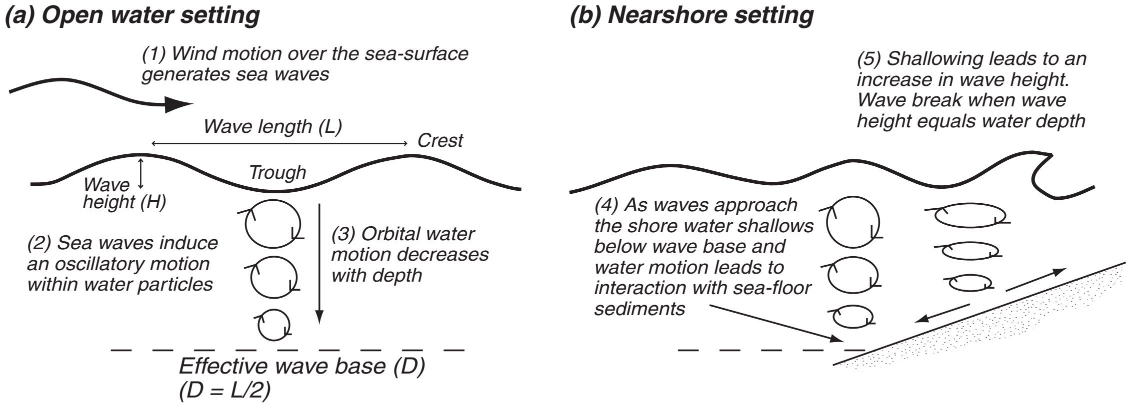


Fig. 1.9 Schematic diagram illustrating wave motion in (a) open-water settings, and (b) as waves approach the shoreline.

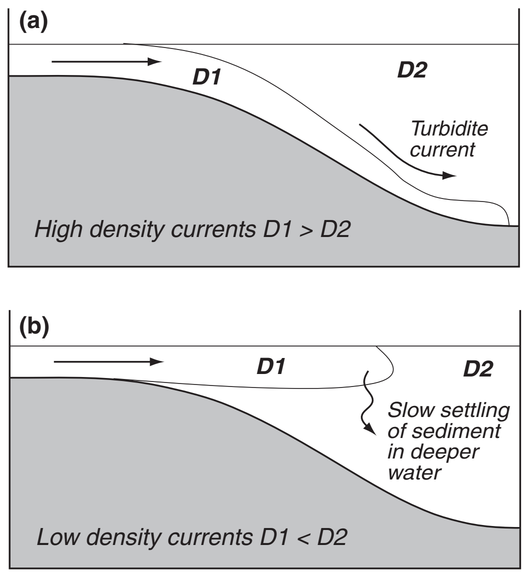


Fig. 1.10 Schematic diagrams illustrating differences in density flows as fluid enters a standing body of water. (a) High density flows occur where the entering fluid has a higher density than the standing water body. (b) Low density flows occur when the situation is reversed. (Adapted from Selley 1994.)

and create a density current (Fig. 1.10a; see Chapter 4). Where the fluid entering the body of water has a lower density, for example where freshwater enters the sea, flow will typically occur as a plume across the water surface (Fig. 1.10b). In the former case, a specific type of density current, known as a turbidity current, is commonly generated. These are capable of transporting very large volumes of sediment across even very low slope angles and are thought to be a major cause of sediment distribution across continental shelf (see Chapter 10) and slope settings. In low-density flows, most of the fine sediment is transported in suspension. This mechanism of transport is common at the distal ends of turbidite deposits where the finest sediment has remained in suspension, and along the distal margins of deltas where fine suspended sediment settles out along the delta front (see Chapter 7). Settlement of fine grained suspended sediment is enhanced where mixing of fresh and saltwater occurs. Under these conditions, even slight increases in salinity (> 1) will promote the aggregation of fine clay particles. This process is known as flocculation and leads to an increase in grain size and thus in grain settling velocity. Flocculation is a common process in estuarine environments (see Chapters 7 and 9) and in salt marshes, and may lead to the development of zones of high turbidity and fine sediment deposition.

The largest proportion of the contaminant load in sediment systems is transported by the particulate matter. For example, Gibbs (1977) suggested that up to 90% of the metal load is transported by sediments in rivers, but this can vary from metal to metal. Similar observations have been made for organic contaminants, such as chlorinated organic compounds. This particulate portion of the contaminant load comprises contaminant-rich grains (e.g. metal sulphide grains from tailings effluent) or contaminant element-bearing Fe and Mn oxide coatings on other particles. Some metals, however, especially under low pH conditions, can be transported in solution (see Chapter 3). This dissolved portion encompasses contaminants that are either truly dissolved, or in colloid form. The partitioning of contaminants between the dissolved and particulate load in aquatic systems depends on both physical and chemical factors, including pH, redox, sediment mineralogy, sediment texture, suspended sediment concentration and sediment grain size. Grain size is possibly the most significant factor controlling the concentration and retention of contaminants in both suspended and bottom sediment. Metals in particular have been shown to be enriched in the fine silt and clay fractions of sediments, as a result of their large surface area, organic and clay contents, surface charge and cation exchange capacity (see Chapters 3 and 6).

1.4.2 Sediment transport in aeolian environments

Sediment transport within aeolian settings occurs primarily associated with either traction carpets or in suspension and is common in three main environments:

1 arid deserts;
2 associated with shoreward areas of beaches and barrier islands;
3 developed around ice caps.

Sediment transport in deserts (Chapter 5) and coastal dunes (Chapter 8) is associated primarily with rolling and saltation of grains in the traction carpet. As in aqueous environments, the critical velocities required to entrain sediment increase with grain size, and high velocities are required to entrain fine silt and clay-sized material. Once entrained, however, such sediment may be transported long distances as dust clouds, a mechanism that is known, for example, to transport large volumes of Saharan dust across the Atlantic and into the eastern Caribbean (Prospero et al. 1970). Controls on the development of aeolian sediment bedforms are discussed in Chapter 5, but are strongly influenced by wind direction and its variability, and by the rate of sediment supply. Aeolian sediment deposition around ice caps is thought to be primarily associated with suspension transport and these silica-rich sands are commonly termed 'loess'.

1.4.3 Sediment transport in glacial environments

Sediment transport within glacial environments occurs associated with a range of transport processes, which include suspension, aqueous suspension and aqueous traction currents. These form different types of deposits and are associated with different glacial environments. Suspension transport, as outlined above, results in the deposition of loess deposits in glacial marginal areas. Aqueous suspension is associated with the deposition of fine, laminated clay sequences (varves), whereas aqueous traction currents are responsible for extensive fluvioglacial sand and gravel transport, and the development of extensive outwash plains (see Chapter 2). Glacial ice also acts as an important sediment transport medium and, although the movement of ice is slow, it is responsible for significant erosion of underlying bedrock and sediment. The resultant debris is transported under and within the ice, and is deposited either along the flanks of glaciers or at the terminal end after the ice starts to melt. These deposits are typically structureless and comprised of poorly sorted boulder to clay-sized material. The descriptive term for the sediment is diamict and when deposited directly by glacier ice is termed till. Consequently till is a major component of glacial landforms such as moraines and drumlins. High-magnitude sediment transport events in glacial environments can occur associated with jökulhlaups – a flood caused by the sudden drainage of a subglacial or ice-dammed lake, commonly triggered by a volcanic eruption (see Chapter 2). These events can transport huge volumes of sediment, and result in extensive deposition of outwash deposits.

1.4.4 Sediment transport associated with gravitational processes

Within each of the settings described, an additional agent of sediment transport is gravity and three main categories of gravitational sediment

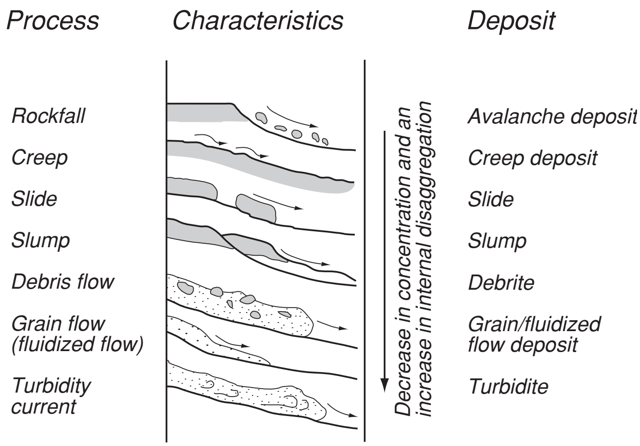


Fig. 1.11 Processes and deposits associated with rock and sediment movement along a continuum of decreased concentration and increased internal disaggregation. (Adapted from Stow 1986.)

transport are recognized: (i) rockfalls, (ii) slides and slumps, and (iii) mass flows. These are recognized to occur along a continuum whereby there is an increase in the degree of internal disaggregation and a reduction in the concentration of the sedimentary material (Fig. 1.11). Rock falls are defined as the collapse of rock or sediment primarily along a vertical plane. They may be caused by tectonic movement or by weathering in upland settings and typically produce scree deposits. Slides and slumps occur over lower angled slopes and involve transport along an inclined shear plane. They are thus characterized by movement over both vertical and horizontal displacement planes. In slides, the sediment generally remains undisturbed, whereas in slumps the original sedimentary structures are normally disrupted or destroyed. The presence of water along a shear plane acts as a medium to initiate both slumping and sliding. At higher water contents the process of slumping grades into that of mass flows, a term used to encompass a spectrum of transport processes including debris flows and grain flows. Debris flows involve the transport of rock and fine sediment that 'flows' downslope as a chaotic mass and these occur in a range of environments from deserts to continental slopes. They typically require the presence of unconsolidated sediment and steep slopes and, on land, low vegetation cover and heavy rainfall to initiate movement (Chapter 5). Grain flows occur within finer sediments and require steep slopes and a confined channel margin. They occur most commonly on the continental slopes and form graded deposits.

1.5 POST-DEPOSITIONAL PROCESSES

Processes acting internally and externally upon a sediment after deposition can be physical, chemical or biological. Physical processes include compaction, resuspension, erosion or dredging of sediment. Chemical and biological processes include the series of early diagenetic, bacterially mediated redox reactions, which result in the oxidation of carbon species (organic matter) and the reduction of an oxidized species. Although post-depositional processes acting upon sediments are varied and have a range of impacts, of most importance in the context of environmental sedimentology is the chemical remobilization of nutrients and contaminants during early diagenesis, and the release of contaminants from floodplains.

1.5.1 Early diagenesis in aquatic sediments

Upon the consumption of O_2, a series of anaerobic bacterial reactions are favoured, utilizing oxygen in species such as nitrate (NO_3^{2-}), iron oxide (FeOOH), manganese oxide (MnO_2) and sulphate (SO_4^{2-}). These anaerobic early diagenetic reactions are many and complex. The most significant reactions are nitrate reduction, Mn(IV) reduction, Fe(III) reduction, sulphate reduction and methanogenesis. All of these reactions break down organic matter and, therefore, lead to an overall decrease in organic matter content as sediments are buried. Many of these reactions can only utilize simple organic molecules, such as acetate and hydrogen, as the reductant. However, some bacterial communities, particularly iron-reducing bacteria, have been shown to possess the ability to utilize complex organic molecules (Lovley & Anderson 2000). Therefore, such diagenetic reactions may act to break down persistent organic contaminants in aquatic sediments. Bacteria can also directly mediate the reduction of some contaminant metals, for example Cr, U, Se, Hg and Tc (e.g. Lovley 1993).

Early diagenetic reactions have an impact upon the short- and long-term fate of contaminants in sediments through two principal mechanisms: release of contaminants into sediment porewaters; and the uptake of contaminants into authigenic mineral precipitates. The oxidation of organic matter and the reduction of iron and manganese oxides result in the release of contaminants associated with these mineral phases to sediment porewaters (Rae & Allen 1993). These increased porewater contaminant concentrations can result in the molecular diffusion of contaminants into the overlying water column (commonly termed a 'benthic flux'). There is a growing awareness that benthic contaminant fluxes to intertidal environments can be as significant as riverine input and may act as a major long-term input of contamination into water bodies. Rivera-Duarte & Flegal (1997a; b) documented that benthic fluxes of Co and Zn from sediments in the San Francisco Bay were of the same magnitude as riverine inputs. Similarly, Shine et al. (1998) showed that the flux of Cd and Zn from coastal sediments in Massachusetts, USA was of a similar magnitude to that within the water column itself.

In marine and brackish intertidal sedimentary environments, sulphate reduction is a major pathway for organic-matter oxidation and as a result sulphide is released into porewaters. Sulphide forms a highly stable complex with most metals (Cooper & Morse 1998) and consequently metals released by Fe(III) and Mn(IV) reduction will be precipitated out as sulphides. These precipitates are predominantly in the form of iron monosulphides, and metals may be adsorbed onto the sulphide surfaces, or incorporated into the sulphide structure (Parkman et al. 1996). Early diagenetic metal sulphides have also been documented in mining-impacted estuarine sediments, acting as a long-term sink for contaminants in these sediments (Pirrie et al. 2000; see Chapter 7). In contrast to natural sediments, early diagenetic mineral precipitates within contaminated sediments can be varied and unique. For example, Pirrie et al. (2000) described the occurrence of early diagenetic simonkolleite (a Zn–Cl mineral) from metal-contaminated estuarine sediments. Early diagenetic minerals (e.g. vivianite – iron phosphate) can also be important in non-marine sediments (see Chapter 6).

1.5.2 Remobilization from floodplains

Contaminants may also be remobilized from river floodplains. Floodplains are sites of sediment accumulation within river basins and, therefore, are classically considered to be contaminant sinks, thereby preserving good temporal records of contaminant input (e.g. Smol 2002; Chapter 3). These sinks of contaminants, however, can also become sources as a result of post-depositional processes, both chemical and physical. For example, Hudson-Edwards et al. (1998) demonstrated that remobilization of Pb, Zn, Cd and Cu within overbank sediments of the River Tyne, England, occurred as a result of changes in water-table levels and the breakdown of organic matter above the water table (see Chapter 3).

Contaminants stored on floodplains also may be remobilized through physical erosion, and this may take place long after the primary contaminating activity (e.g. mining) has ceased. For example, Macklin (1992) showed that the primary source of Pb and Zn to the contemporary River Tyne, northern England, was remobilized floodplain alluvium originally deposited during eighteenth and nineteenth century metal mining.

Contaminant remobilization is often triggered by natural (climate) or anthropogenic (land use) changes that cause modifications, first in sediment load and delivery, and eventually in erosion and deposition. Macklin (1996) warned that floodplain contaminant remobilization is increasing as a result of the hydrological changes associated with global warming, and stressed that the long-term stability of contaminant metals with respect to changes in physical (river bank and bed erosion, land drainage and development) and chemical conditions (redox and pH) is poorly understood. The remobilization of contaminants through the physical erosion of contaminated saltmarsh sediment can also be a significant source of contaminants to estuaries and coastal waters (see Chapter 7).

1.6 SEDIMENTARY RESPONSES TO ENVIRONMENTAL CHANGE

1.6.1 Sedimentary responses to natural disturbance events

Although daily or ongoing processes of fluvial or tidal flow and water/wind velocity influence background levels of sediment transport and accumulation, the amount of sediment transport that occurs during 'normal' conditions is relatively low. Most sediment transport and, as a result, much of the morphological change that occurs within sedimentary environments takes place during low-frequency but high-magnitude events. These may be associated with storms or high (seasonal) rainfall episodes, or with episodic high-energy events such as cyclones and tsunami. At these times, sediment transport rates can dramatically increase and hence a high proportion of annual sediment movement may occur over a period of only a few days. This is particularly the case in many arid and semi-arid environments, which are characterized by highly 'flashy' discharge events and where short-lived but high-intensity rainfall events lead to very high-energy flows (see Chapter 5). High-magnitude discharge events also characterize many seasonally influenced fluvial systems. In the Burdekin River catchment, North Queensland, tropical cyclones dramatically increase discharge rates through the catchment (Fig. 1.12a), resulting in increased suspended (Fig. 1.12b) and bedload sediment transport (Amos et al. 2004). These high-energy events also influence spatial variability in sediment transport and storage within fluvial catchments. For example, in the Rajang River Delta of Sarawak, eastern Malaysia, sediments are stored on the delta plain during the 'dry' season, but undergo rapid offshore transport during the 'wet' season when discharge rates increase (Staub et al. 2000).

In coastal environments, storm waves are directly responsible for extensive reworking of unconsolidated sedimentary deposits and this is manifested in changes in beach profiles and the breaching of coastal barriers (see Chapter 8), and the on- and offshore transport of sediment and rubble (see Chapter 9). In the tropics, high wind speeds and storm waves associated with cyclones can lead to tree damage and mortality within mangroves. This, in turn, can facilitate substrate destabilization and erosion of intertidal sediment substrates. These events can thus result in significant localized ecological damage and often marked short-term changes in patterns of nearshore sediment accumulation. However, cyclones and other high-energy episodic events are also important controls on the longer term distribution and development of sedimentary environments. On the Great Barrier Reef shelf, for example, cyclones generate northward flowing alongshore currents, which result not only in significant along-shelf sediment transport, but also a marked partitioning of sediment across the shelf (Larcombe & Carter 2004; see Chapter 9).

1.6.2 Anthropogenic modifications of sediments and sedimentary systems

Although seasonal and natural (i.e. storm-induced) changes in energy levels can lead to changes in sediment dynamics and accumulation rates, anthropogenic activities also have potential to modify rates of sediment input, sediment transport pathways and the composition of the accumulating sedimentary materials. Clear links between anthropogenic activity and sedimentary

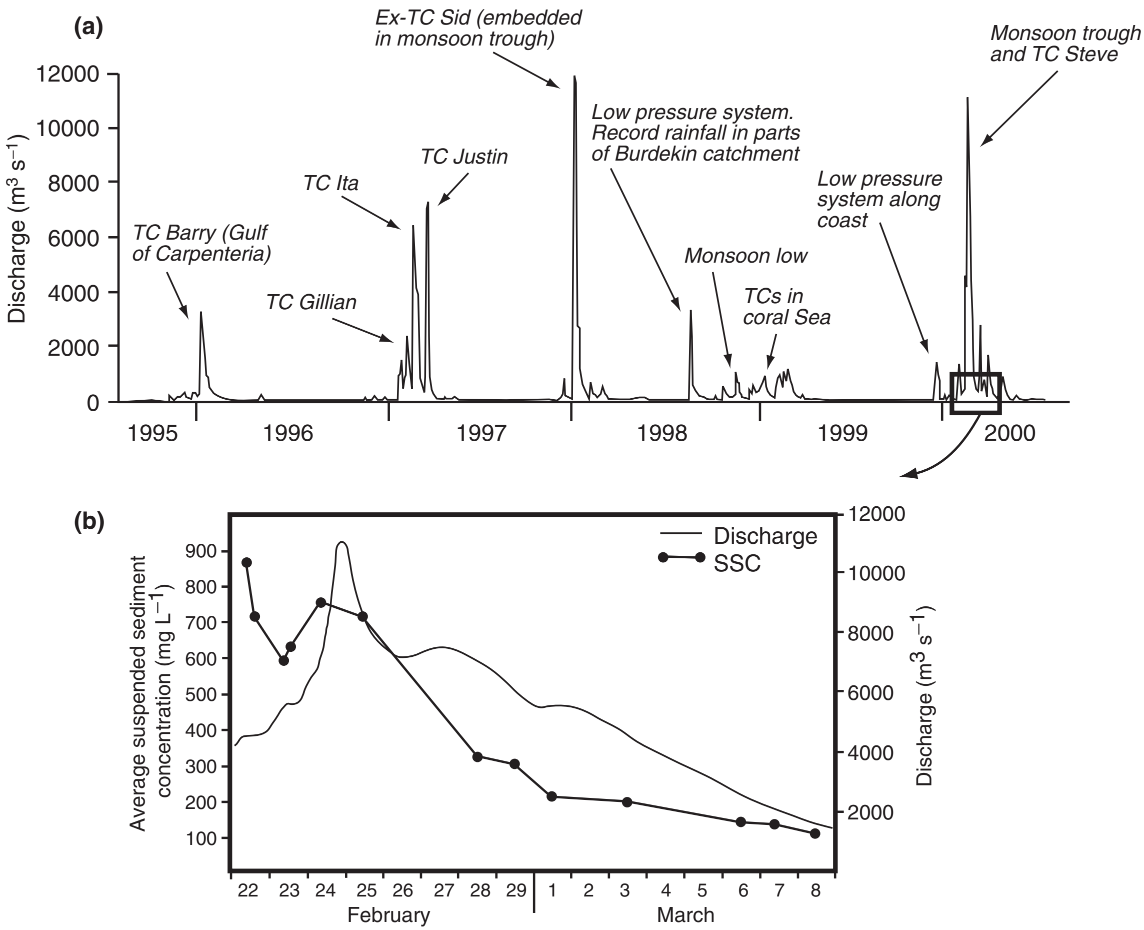


Fig. 1.12 (a) Data from hydrographs recording fluvial discharge between 1995 and 2000 in the lower part of the Burdekin River catchment. (b) Detail of discharge and suspended sediment concentrations (SSC) between February and March 2000. Note that SSC generally decreased through the discharge event and that, in this catchment, SSC levels appear to be supply limited. (Adapted from Amos et al. 2004.)

system response occur, for example, in areas where construction or resource extraction activities in the upstream sectors of catchments result in downstream sediment starvation and/or erosion. At a global scale, the transport of sediment through river systems represents a major pathway of sediment movement from upland 'source' to marine 'sink'. The transport of such sedimentary material is, however, highly sensitive to a range of anthropogenic influences, including reservoir construction, land-use change, soil and water conservation activities, and sediment control programmes (Walling & Fang 2003). Some of these activities lead to increased sediment loads but others, and in particular reservoir construction, lead to reduced sediment transport. The impacts vary between catchments, but in some regions reduced sediment supply has resulted in marked changes in the behaviour and geomorphology of fluvial systems (see Chapters 2 and 3). In the Alpine region of Europe, for example, sediment deficits have been recorded in many rivers over the past 30–40 years. Such reductions have resulted from excessive gravel extraction from rivers and the retention of sediment behind dams. The result, on many upland rivers, has been widespread erosion and entrenchment (Descroix & Gautier 2002).

Similar links between sediment sources and sinks are evident along many coastlines where sediment is supplied either from fluvial sources or from one area of coastline to another, often via longshore transport. Reductions in sediment supply often lead to increased rates of erosion along the coastal sectors that are deprived of sediment. This occurs, for example, where sediments are trapped behind dams located on the rivers that feed the coastal sector. In California, reduced fluvial sediment supply due to damming has led to increased rates of cliff erosion (see Chapter 8), and extensive subsidence and shoreline erosion of the Nile delta is attributed to significantly reduced sediment supply to the delta front (see Chapter 7). In the northern Gulf of California fundamental changes in the sources and rates of sediment supply, and in the composition of accumulating sediment, have also been directly linked to the effects of dam construction and have resulted in a 95% reduction in sediment supply from the Colorado River (see Case Study 1.1). Coastal retreat may also occur where 'upstream' sediment supply has been restricted by sea-defence construction. In such cases, seawall or groyne systems either prevent or restrict sediment throughput, leading to increased rates of downstream beach erosion and shoreline change (see Chapter 8). The recognition of these important sedimentary links has been a key driver in the development of integrated catchment and coastal management schemes.

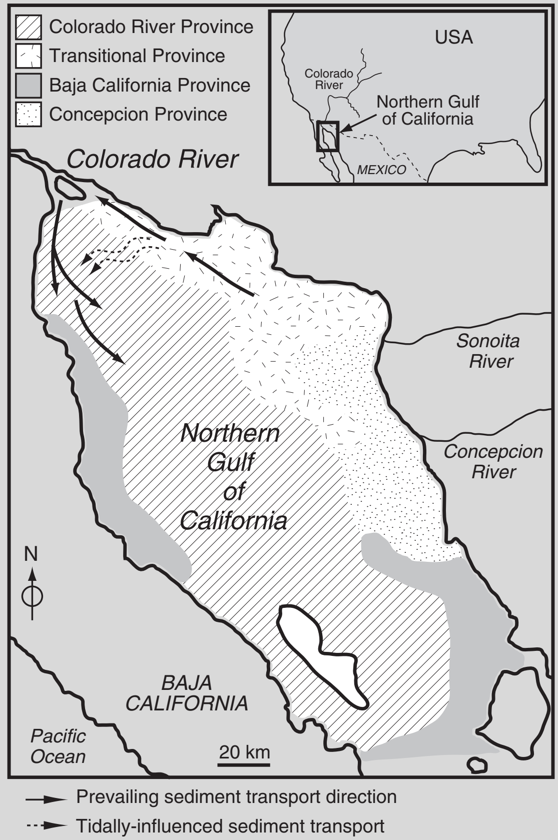
Anthropogenic-related modifications to sediment source and transport pathways may be significantly exacerbated by the effects of urbanization. In relation to sedimentary systems, the most important influence occurs where constructional activities occur within the sedimentologically active zone. Problems arise either because of construction in areas where episodic sedimentological and geomorphological changes can be expected, or where deliberate constructional activities have a consequent effect upon pathways of sediment transport and zones of sediment accumulation. Coastal dune and barrier island sequences, for example, form part of active sedimentary systems that will respond to high-energy storm events. Hence, roads and houses built in such zones become susceptible to storm damage (see Chapters 8 and 9). Similarly, construction of seawalls or other landward constraints may lead to 'coastal squeeze' as landward migration

Case study 1.1 Anthropogenic modifications to sediment supply, northern Gulf of California

The Gulf of California is a narrow epicontinental sea, 1500 km long, that has formed from tectonic activity along the Californian coast (Case Fig. 1.1). The Northern Gulf of California (NGC) receives sediment from four areas, the Colorado River, the batholith of the Baja California, the Sierra Madre Occidental, and the deserts of north-west Mexico. Each of these source areas has a distinctive mineralogical signature enabling the provenance of accumulating marine sediments in the NGC to be determined. On this basis four distinct sediment provinces have been identified, these being, (i) the Colorado River Delta Province, (ii) the Concepción River Province, (iii) the Transitional Province and (iv) the Baja-Sonora Province (Case Fig. 1.1).

Historically, the Colorado River has been the primary source of sediment into the NGC, with an estimated annual sediment discharge of 160×10^6 t. Fluvial sediment supply has, however, been dramatically reduced over the past 100 years following the construction of a series of dams along the river. Of particular significance have been the Hoover Dam (built in 1934) and the Glenn Canyon Dam (built in 1952). The result of this extensive water flow regulation has been to reduce fluvial sediment supply by around 95%, resulting in sediment starvation to both estuarine and deltaic environments of the Colorado River mouth, and in the northern areas of the Gulf.

In the vicinity of the Colorado River, major changes in sediment supply and transport have been identified and, as a result, oceanic (rather than fluvial) hydrodynamic forces now exert the major influence on sediment dynamics within the estuary and delta (Carriquiry & Sánchez 1999). Rather than a predominant north to south (fluvial to basinal) transfer of sediment, sediment is now transported from south-east to north-west along the eastern side of the NGC into the estuarine basin, and then reworked southwards along the western sides of the NGC (Case Fig. 1.1). Despite significant reductions in fluvial sediment input from the Colorado River, however, average sedimentation rates in this NGC are reported to have remained relatively constant over the past 100 years. This is attributed to a transition in the source areas that supply sediment to the Gulf (Carriquiry et al. 2001). In particular, a high proportion of sediment is now supplied from resuspension and reworking of the Colorado Delta sediments and from the shallower part of the NGC shelf. These sediments form the Colorado River Delta Province and dominate the central areas of the NGC marine basin (Case Fig. 1.1). Additional sources of sediment are derived from the desert areas of north-west Mexico and south-west USA. These form the Concepción River Province and feed into the basin via the Sonoita and Concepción Rivers (Case Fig. 1.1). In addition, intense desert winds from the Sonora Desert represent an important transport medium for aeolian sediment transport into the Gulf. These sediments are rich in zircon and garnet, and contribute primarily to the Transitional Sediment Province. The area therefore emphasizes the effects of anthropogenically influenced reductions in sediment supply through fluvial systems, and the consequent 'downstream' impacts on both sediment transport pathways and on the composition of the accumulating marine sediments.



Case Fig. 1.1 Distribution of the main sediment provinces in the Northern Gulf of California. The main sediment transport pathways in the vicinity of the Colorado River Delta are also shown. (Adapted from Carriquiry & Sánchez 1999; Carriquiry et al. 2001.)

Relevant reading

Carriquiry, J.D. & Sánchez, A. (1999) Sedimentation in the Colorado River delta and Upper Gulf of California after nearly a century of discharge loss. *Marine Geology* **158**, 125–45.

Carriquiry, J.D., Sánchez, A. & Camacho-Ibar, V.F. (2001) Sedimentation in the northern Gulf of California after cessation of the Colorado River discharge. *Sedimentary Geology* **144**, 37–62.

of coastal sedimentary environments is restricted. Such interactions with sedimentary systems or a restriction in the way sediment systems respond to increased energy levels often brings with it a management or remediation 'cost'. Hence in many cases, the need for management is often driven not so much by the actual event, but as a result of (increasing) human occupation and modification of the environment, i.e. urbanization of environments that will naturally respond to changes in the energy inputs associated with storm or flood events. The influence of urbanization of the coastal fringe is seen particularly clearly in relation to estuarine environments where large areas of intertidal land have been claimed over a period of several centuries (see Chapter 7). The result is often a fundamental change in the character and extent of intertidal land, and a suppression of an estuary's ability to respond to changes in nearshore energy regimes or sea-level state.

Urbanization also has major impacts upon the hydrology of catchments and river basins, which in turn influences the nature of sediment movement and accumulation (see Chapter 6). The increase in runoff rate in urban systems leads to enhanced flooding pressures in river systems, and this is often exacerbated by the past removal of floodplains and river culverting, which inhibits the accumulation of sediment. These increases in runoff rate also have marked impacts upon sediment transport in urbanized river basins, with large storm events accounting for the majority of suspended sediment transport flux over short periods of time (Goodwin et al. 2003; Old et al. 2003).

Another highly significant anthropogenic impact on sediments is that of sediment composition and quality. The increase in contaminant loading in sediments has been extensively documented for virtually all sedimentary systems globally, including those that are generally assumed to be pristine. These have been documented both through monitoring programmes on sediment composition, and sedimentary archives of contaminant accumulation, such as salt marshes, lakes, reservoirs and floodplains. The former approach allows for short-term data sets only, as monitoring programmes on sediment composition have not been in place for long. Longer temporal records of sediment composition may be recorded by sediments accumulating in depositional environments (see Case Study 1.2). The nature and length of the sediment record will depend on a number of factors, including sediment accumulation rates, extent of sediment disturbance and post-depositional changes. Examples of temporal records of sediment compositional change for lakes and river basins can be found in Chapter 4 and in Smol (2002). Such compositional changes, and associated records of environmental pollution have also been clearly documented for saltmarsh sediments (see Chapter 7).

1.6.3 Response of sedimentary systems to climatic and environmental change

Given the influence that climate exerts on the development of sedimentary environments, ongoing and projected climatic and environmental changes are potentially significant in relation to the dynamics and functioning of most sediment systems. Climate exerts, for example, an important influence on weathering regimes, the hydrological cycle (including seasonality of rainfall) and the frequency and magnitude of high-energy (storm) events, all of which are important in determining rates of sediment supply and transport (e.g. Chapters 2–4). In the marine environment, climatic conditions also influence environmental factors such as levels of dissolved CO_2 and sea-surface temperatures. These are primary controls on the distribution and development of biogenic sedimentary deposits (Chapter 9). Sea-level itself is a major control both on the distribution and extent of coastal sedimentary environments (Chapters 7 and 8) and, because it influences base level, a major forcing factor with fluvial systems (Chapter 3). Hence many of the predicted changes in global climatic conditions need brief consideration here. These include changes in atmospheric CO_2 concentrations, increased atmospheric and sea-surface temperatures, increased UV radiation, changes to patterns of storm frequency and