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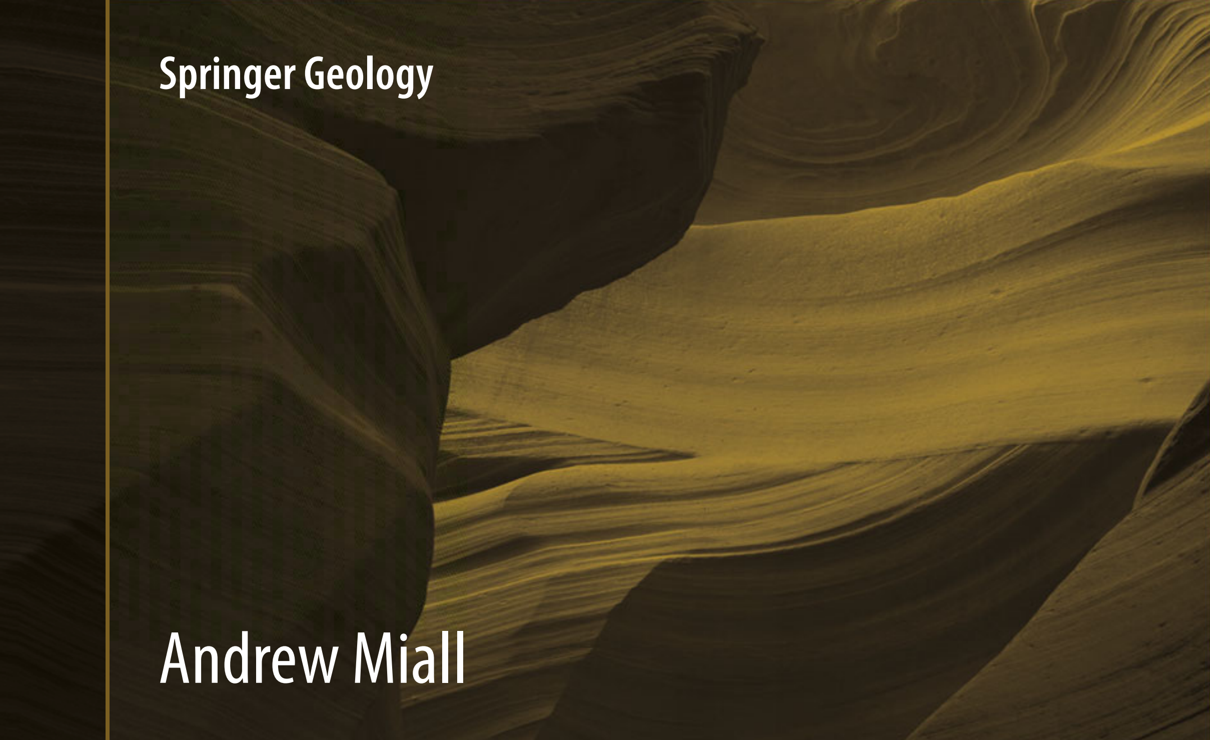

Andrew Miall

Fluvial Depositional Systems

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Fluvial Depositional Systems

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Preface

In an earlier book, *The Geology of Fluvial Deposits* (1996), I set out in detail modern methods of facies and architectural analysis of fluvial deposits, and used numerous case studies to illustrate the architecture of fluvial systems, on scales ranging from that of the outcrop to that of entire basins. Chapters were devoted to the tectonic and climatic controls on fluvial deposition, and an attempt was made to erect a classification of nonmarine oil and gas fields based on the stratigraphy and architecture of the fluvial reservoirs.

In subsequent years, a host of new case studies has provided much material for refining our understanding of allogenic controls, and has substantially improved our ability to apply sequence-stratigraphic methods to fluvial systems. Exploration techniques used for petroleum exploration and development have become much more sophisticated, and in my view, are steadily reducing the need for much of the statistically based modeling work that is carried out during the reservoir development process, in favor of the detailed mapping of what is actually there, using such techniques as three-dimensional seismic reflection, and the careful analysis of production data, such as pressure-depth relationships.

One of the major foundations of sedimentological work has been the analogue method, whereby the processes and products of modern and very recent sedimentary environments form the basis for comparison with the ancient record. However, our increasing ability to develop accurate ages for the rock record has raised an important question about the validity of the analogue method, which forms the basis for one of the fundamental principles of geology, that of uniformitarianism. The fragmentary nature of preserved stratigraphies is increasingly apparent, and it is clear that comparisons to the ancient record based on studies of post-glacial stratigraphy, such as the great deltas and continental margin sedimentary prisms bordering modern oceans, must be carried out with a major caveat regarding questions of preservability. This is particularly the case in the area of sequence stratigraphy, an area that is examined in depth in this book as it relates to the analysis and interpretation of fluvial deposits.

The purpose of this book is to discuss the new methods and the new understanding of fluvial depositional systems, with a particular emphasis on those techniques and results that are most useful for subsurface work.

Toronto, March 2013 Andrew Miall

Acknowledgments

The background to this book has been formed by the numerous presentations of courses on fluvial depositional systems to petroleum geology audiences in Calgary and elsewhere. I have repeatedly asked myself the question, what do these professional people need to hear from me? I am grateful, particularly to the Canadian Society of Petroleum Geologists, for the opportunity to be forced to ask myself this question, and for the expectation that I can respond with relevance.

I am particularly grateful to Robin Bailey and David Smith for their invitation to speak at the *Geology and Time* symposium at the Geological Society of London in September 2012. The preparation for this occasion led me to explore an area that has long troubled me, that of sedimentation rates and stratigraphic completeness. The ideas contained in the chapter on sequence stratigraphy in this book owe much to the rethinking that went into my contribution to that event.

Conversations with many colleagues over the years have helped me to formulate and clarify my ideas, and now being able to access the research literature from even the most remote holiday cabin with Internet access means that, to some extent, the thinking never stops. In recent years I have found the work of Phil Allen, Robin Bailey, Janok Bhattacharya, Nick Eyles, Chris Fielding, Martin Gibling, John Holbrook, Colin North, Chris Paola, Guy Plint and Pete Sadler, particularly illuminating. Paul Heller critically read most of the manuscript and provided many essential comments.

As with all my work, conversations in the field and in the office with my graduate students have added immeasurably to my understanding of geological problems and my abilities to explain them. With regard to fluvial processes and systems I must mention, in particular (in alphabetical order), Tosin Akinpelu, Mike Bromley, Gerald Bryant, Octavian Catuneanu, Jun Cowan, David Eberth, Carolyn Eyles, Phil Fralick, Greg Nadon, Tobi Payenberg, Mark Stephens, Andrew Willis, and Shuji Yoshida.

Finally, I must again thank my wife Charlene for putting up with yet another book. This fluvial enterprise owes much to Charlene's field assistance, companionship, professional advice, support, and love over the years, and the work we did together on the history and methodology of stratigraphy owes much to her educating me about the nature of the scientific method and the sociology of science.

Contents

Chapter 1
The Nature and Purpose of This Book

1.1 Looking Back to 1996

This book is not a revised version of "*The geology of fluvial deposits*" (Miall 1996), but an entirely different product.

Much of the material in the 1996 book was compiled at a time when the methods of facies analysis and architectural element analysis were maturing and were becoming widely used by the sedimentological community. The lithofacies classification which I first proposed in 1977, and the method of architectural-element analysis, set out in major papers published in 1985 and 1988, were thoroughly documented in the 1996 book (Chaps. 5–7), and little has been done since then to require revisions or an upgrade. A recent summation of the methods was provided by Miall (2010a). As expected, indeed, as was recommended, researchers have taken the basic ideas and adapted them to suit the particular needs of their research projects. Field techniques now include the use of LIDAR for the recording of outcrop images, which may substitute for photomosaics, but the methods of outcrop architectural analysis (Chap. 4) remain much the same. New approaches and techniques for mapping the subsurface have been developed for use in the petroleum industry; these are introduced briefly below and discussed at greater length in Chap. 4 of the present book. Three-dimensional reflection-seismic data is increasingly becoming a standard tool for petroleum geologists, and its interpretive arm, seismic geomorphology, is a powerful tool requiring a deep knowledge of sedimentology for maximum usefulness.

The compilation of facies models that constituted Chap. 8 of the 1996 book has largely stood the test of time. Only one new facies model has been formally proposed since that time, a model for rivers in hot, seasonal, semiarid and subhumid environments (Fielding et al. 2009, 2011). Extensive research, such as that by Long (2011) has demonstrated the applicability of the original suite of models to the rock record.

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The tectonic control of fluvial systems was thoroughly described in Chap. 11 of the 1996 book, and the chapters dealing with oil and gas fields in fluvial systems (Chaps. 14 and 15) need little modification.

For a research-level textbook covering all this material, the reader is still referred to the 1996 book.

1.2 New Developments

The area that appeared to require the most extensive revision and renewal is, not surprisingly, the material dealing with sequence stratigraphy (Chap. 13 in the 1996 book). Much has changed since that chapter was written, and indeed, whole new ways of thinking have evolved that require some new approaches. Some of these new ways have thinking have developed from the imaginative and quite revolutionary laboratory work undertaken by Chris Paola at his experimental facility at the University of Minnesota. In this research, fluvial and deltaic processes have been modeled in a large tank that has been constructed to simulate base-level change and differential subsidence. Theoretical arguments and comparisons with modern fluvial-deltaic systems have established that the results of the experiments may be scaled up to that of natural systems, thereby filling an essential observational gap, termed the "mesoscale", between the documentation of modern and historical processes, which essentially only cover about the last 100 years, and geological observations on the rock record, for which the most refined time scale available is that of magnetostratigraphy, in the 10^4-year range. Results and conclusions drawn from the work of Paola and his group have been integrated into the discussion at several places throughout this book.

Another critical development in the last two decades has been the steady accumulation of quantitative data relating to sedimentary and stratigraphic processes. We now know substantially more than we did in the 1990s about the rates of sedimentary processes, and about the nature and rates of an increasingly wide range of allogenic forcing processes. Work by such researchers as Paul Heller, Doug Burbank, David Mohrig and Elizabeth Hajek, amongst others, has aimed to test experimental and theoretical work against observations from the ancient fluvial record, using carefully selected field case studies. Some of these results are discussed in this book, focusing primarily on the larger-scale fluvial systems and those components of which (channels, channel belts and depositional systems) that are the main focus of the subsurface geologist.

However, in one important area, this increasingly detailed and quantitative knowledge of sedimentary processes has led to what, in this writer's view, is the emergence of a serious but hitherto largely unrecognized disconnect between those studying modern processes and the post-glacial record, versus those studying the more ancient record. The increasingly large data base that is now available to researchers on rates and time scales has demonstrated that sedimentation rates, and the rates of processes, as measured in modern environments and in

Pleistocene-Holocene settings, are one to three orders of magnitude more rapid than those normally derived from detailed chronostratigraphic studies of the pre-Neogene record. This is partly a reflection of the high rates and large magnitudes of changes that occurred through the late Cenozoic glacial cycles, but it is also a reflection of the nature of what I have called the “geological preservation machine”, whereby high-frequency, high-rate events are systematically removed from the record as time passes. This is not a new observation; it was an obvious conclusion of the work of Sadler (1981) who published a by-now classic paper on sedimentation rates (Fig. 1.1). What is new is the availability of new theory and much new data to assist in the explanation of this phenomenon. As discussed in Chap. 2, and at greater length elsewhere (Miall, in press), stratigraphic processes over the full spectrum of geological time scales may now be understood with reference to the concept of fractals.

In a widely-quoted remark, the implications of which have been largely ignored in practice, Ager (1973) stated that “the stratigraphic record is more gap than record.” As Miall (in press) argued, we now have to consider the fact that there are, in effect, gaps within the gaps, and that the record is permeated with them,

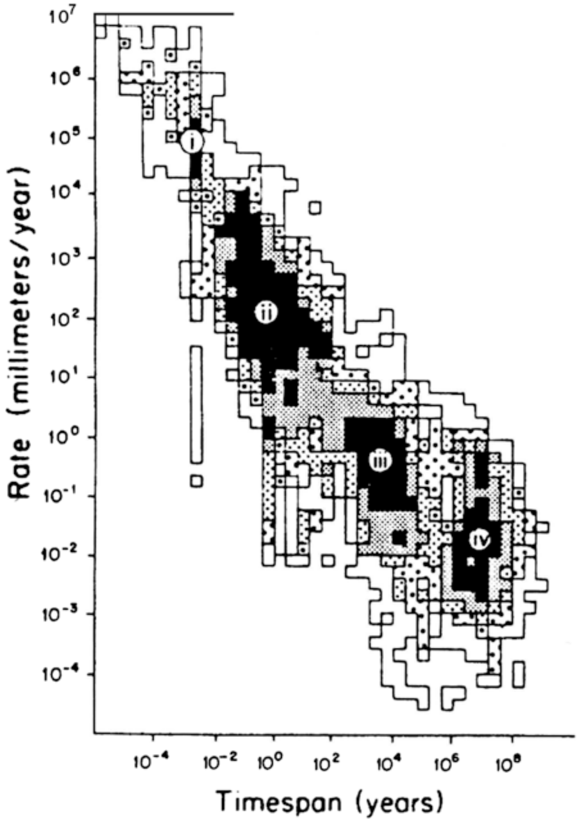

Fig. 1.1 The relationship between sedimentation rate and elapsed time in the stratigraphic record (Sadler 1981)

at every scale. Preserved stratigraphy constitutes a set of fragmentary remnants, that have been called "frozen accidents." (Bailey and Smith 2010, pp. 57–58). These can tell us a great deal, but only if we work within the appropriate time scale. Much of the present book consists of a working through of the implications of these concepts for fluvial systems and the fluvial sedimentary record. This constitutes part of what I have called "*updating uniformitarianism*" (Miall, in press).

We need a new approach to uniformitarianism, because of the disconnect, noted above, between those working on the modern and the ancient record. It could be argued that the analog method on which modern sedimentology is based, is no longer a satisfactory foundation for research into long-term geological processes. It was based on the long-standing, traditional Hutton-Lyell aphorism "the present is the key to the past", and its obverse, "the past is the key to the present". If the geological preservation machine systematically removes much of the modern record before it can become part of the ancient record, we need to be constantly alive to the potential for the bias this introduces into our interpretations.

In the practical world of petroleum geology, the transition that takes place from exploration to production involves a handover from the geologist to the engineer of a model of reservoir architecture to be used as the basis for the design of a production program. There are tensions in this process because of the level of uncertainty inherent in geological prediction (e.g., Martin 1993). Speaking of high-risk and high cost frontier exploration project, Larue and Hovadik (2008, p. 337) said:

> Project appraisal and development may be based on very few wells with or without the benefit of 3D seismic data, but with implications for capital costs of hundreds of millions to billions of dollars.

The qualitative nature of these models may not satisfy the quantitative requirements of the engineer. Typically this is now managed by the use of numerical models that employ probabilistic methods to provide ranges of likely values for engineering purposes. Essential information, such as the dimensions and spacing of reservoir bodies may be calculated as ranges of likely values from the sedimentological and sequence models compiled by the geologist. There are many commercial computer modeling methods that manage this part of the production process. With the exception of the next, concluding paragraph of this section they are not discussed in this book, the main purpose of which is to assist the geologist to understand the fluvial system from which the computer input is assembled.

A specialized area of computer simulation has grown to answer the following problem:

> In industry scenarios, the typical paucity of data relating to sedimentary heterogeneity at a resolution finer than the seismic and interwell-spacing scales, together with the need to undertake uncertainty analysis for the assessment of risk, has resulted in the need for the development and implementation of stochastic methods for modeling reservoir sedimentary architecture by simulating several different equiprobable architectural realizations. Structure-imitating stochastic reservoir modeling aims at simulating sedimentary architecture without considering depositional and/or erosional processes.

This quote, from Colombera et al. (2012, p. 2144) introduces an elaborate new database system from which to sample input parameters relating to depositional systems, architectural elements and lithofacies in order to construct reservoir models for development engineering purposes. This approach appears to be by far the most sophisticated in this category of model building. The purpose is not to simulate fluvial processes, but to construct a practical architectural model for reservoir planning purposes based on the limited input data available from preliminary exploration and interpretation of facies, fluvial style, tectonic and climatic setting, etc. However, as discussed throughout this book, fluvial systems are notoriously difficult to predict. The simple case of trunk rivers having tributaries of variable scales and fluvial styles (Fig. 2.11) may play havoc with a well-thought-out engineering model. It is to be hoped that the contents of this book can assist in the work to understand and constrain the input that needs to be used in models of this type or, as we discuss in Chap. 4 (see below) to try to avoid statistical approaches altogether, as much as possible, by the employment of various new mapping tools.

1.3 Introduction to the Contents of This Book

Chapter 2: Modern fluvial sedimentology began with the development of the point bar model and the fining-upward cycle in the late 1950s and early 1960s (Miall 1996, Chap. 2). The process-response model flourished in the subsequent decades, and has left us with a wealth of information on modern rivers and ancient deposits, much of it categorized under the heading of facies models. In Chap. 2 I take a look at the modern state of fluvial facies studies, and conclude that the facies model approach has long-since reached its limit of usefulness. One of the difficulties is the selective preservation of modern fluvial processes. For example, studies of the shallow deposits of modern rivers using ground-penetrating radar have demonstrated that the surface form is often not reflected by the internal structure, but is superimposed on fragments of earlier channel and bar deposits above recent local erosion surfaces. This is part of the preservability issue that I raised earlier. Another important point is the growing data base that points to the low level of predictability that can be inferred from geological studies of the rock record. Gibling's (2006) survey of dimensional data on fluvial facies units is examined in Chap. 2, where I reproduce some of his data documenting such relationships as the width:depth ratio. These kinds of relationships have been used for a long time as predictive tools for studying the subsurface, but are not, in fact, very discriminatory. Prediction of subsurface dimensions from limited vertical profile, including core, data, is fraught with hazard.

Architectural methods of description and documentation of the rock record are more powerful than traditional vertical-profile methods, because they direct the observer to seek out three-dimensional information, and come with no presumptions regarding fluvial style. However, the methods are difficult if not impossible to use where there is only limited well data, as in the early phases of a subsurface exploration program. In addition, many of the most interesting architectural elements, such as nested channels and incised valleys, are commonly at scales of hundreds of metres to a few kilometres across that commonly are too large to be seen completely in outcrop or sampled reliably by exploration wells, but too small to be seen properly on reflection seismic data. I discuss this problem further in Chap. 6.

Chapter 3: A major concern of the subsurface geologist is the problem of defining and describing the architecture of the various facies, particularly the porous units—typically composed of sandstone or conglomerate, that constitute potential or actual petroleum reservoirs. The size, orientation and connectivity of these bodies are critical to the effective and efficient design of well networks, particularly for the purpose of enhanced recovery projects. Much depends on the ways in which fluvial channels move around on a floodplain, whether by gradual migration or by sudden shifting—the process termed *avulsion*—the major focus of this chapter. Geological work on this problem has consisted of extensive study of the history of avulsion of modern rivers, mapping of ancient avulsions in the rock record, and the numerical and experimental modeling of avulsions. The physical processes of avulsion are complex, and are still not completely understood. Numerical models of the avulsion process, of which there are several, do not attempt to simulate the physics of the process and are essentially exercises in dynamic geometry. The results of laboratory experiments, primarily those of Chris Paola's *experimental stratigraphy* laboratory, are helping to throw light on the issue. Despite decades of activity in this area, a definitive treatment of the issue of avulsion, and the more general topic of the autogenic control of alluvial architecture, is still not possible.

Of key practical importance to the business of reservoir development is the nature of the sand fairway. Sand body connectivity is the key descriptor, and in this chapter we discuss the critical factors on which it depends. It can be demonstrated that fluvial style is NOT a critical element in the determination of reservoir performance.

Chapter 4: Moving on to larger-scale features of fluvial systems, where allogenic processes become predominant, requires the construction of detailed maps and sections of fluvial systems. Modern mapping methods (Table 1.1) include a range of dynamic tools that make use of production measurements, and are more effective than the traditional methods based on the facies model and the vertical profile, in that they are empirical, directed towards systematically revealing what is actually there rather than attempting to predict based on assumed relationships that may have little factual, basis. Some of these methods make use of the dynamic production data that may be collected as a petroleum field is developed.

Chapter 5: Developments in the understanding of tectonic and climatic control of fluvial sedimentation have advanced significantly in the last few decades owing to the accumulation of numerous case studies. The improved understanding of high-frequency tectonism in foreland basins, and a much broader knowledge of the development of paleosoils, including their dependence on climatic controls, are two developments that have significantly improved our range of tools for interpreting the ancient fluvial record. At the same time, experimental and theoretical research have provided essential insight into rates and scales, particularly regarding such issues as the response time of alluvial systems to allogenic forcing.

Table 1.1 Methods for mapping complex fluvial systems in the subsurface

Old/traditional methods largely based on facies-models concepts	
"*The geostatistics of random sandstone encounters*"	*Discussed in Sects.:*
The vertical profile (and its limitations)	2.2.1–2.2.2
Width-depth ratios and other geomorphic relationships	2.2.3
Architectural elements	2.3
Idealized bar models	
Net: gross and sandbody connectivity	3.6
Reservoir models and their limitations	
Newer, empirical methods:	
Ground-Penetrating Radar (GPR)	4.1.2
3-D seismic surveys	4.2.1
Dipmeter and formation microscanner	Miall (1966, Sect. 9.5.8)
Dynamic methods:	
"*Stroking the substrate*" *with directional drilling*	
Pressure testing	4.2.2
Geochemical fingerprinting, tracer testing, etc.	4.2.2
4-D seismic surveys	4.2.2
History matching	4.2.2

Chapter 6: Two important sequence models that were developed for fluvial deposits in the 1990s have been very influential, but in Chap. 6, I suggest that they commonly have been misapplied to the rock record. A number of worked examples are used to illustrate the argument that because these models are largely based on observations from modern rivers and the post-glacial sedimentary record, they cannot be applied directly to the ancient record, because of the issues of sedimentation rates and preservation, that I introduced above.

There has been much interest in fluvial sequence boundaries in the last few years, particularly the way in which erosional boundaries develop through lengthy periods of negative accommodation. The shaping of this surface and the fragmentary deposits that are commonly left behind during this process provide a graphic insight into the succession of vanished landscapes that evolve during these periods—and suggest an illustration based on modern data of the "abyss of time" that was so eloquently described by John Playfair on seeing Hutton's angular Silurian-Devonian unconformity at Siccar Point for the first time. As with other aspects of fluvial processes, the experimental stratigraphy experiments of Paola's group are providing many useful insights.

Lastly, in Chap. 7, I discuss the issue of identifying large rivers and their associated depositional systems in the rock record. There has been a substantial recent literature published on the matter of large rivers (Gupta 2007; Ashworth and Lewin 2012), large-scale depositional systems (Weissmann et al. 2010, 2011; Fielding et al. 2012), and paleovalleys (Gibling et al. 2011; Blum et al. 2013). Much of this is focused on rivers and valleys of the present day and the post-glacial period, but there are limits on how far these data can be applied to the task of reconstructing ancient depositional systems. Modern and recent systems can be interpreted in terms of contemporaneous tectonism and climate, but when studying the ancient record, the problem is the reverse: that of deriving the maximum amount of information from what is often very fragmentary and incomplete evidence—evidence that is commonly quite ambiguous. One of the outstanding issues dealt with, in particular, by Gibling et al. (2011), is the problem of discriminating between paleovalleys and large channel systems.

1.4 Conclusions

The main purpose of this book is to assist those working with the rock record to maximize the information they can obtain from their research. Architectural methods have contributed substantially to the interpretation of preserved fluvial systems at the outcrop scale. In the case of the subsurface—the attempt to map and explain potential reservoir units or to provide more complete descriptions of producing units—many of the same problems remain as they have been for decades: the limitations on interpretation that are imposed by the lack of critical data. However, where available, such new exploration tools as the 3-D seismic-reflection method, and some mapping methods that make use of production data, can add substantially to the depth and reliability of interpretations.

As background to all of this are developments in our understanding of the "geological preservation machine", the means by which allogenic and autogenic processes operate over an enormous range of time scales to create the preserved rock record, with all its recognizable features, such as channel systems and sequences, while also inserting subtle and not so subtle gaps in the record, that make the work of the geologist continually challenging.

Chapter 2
The Facies and Architecture of Fluvial Systems

2.1 Introduction

In Sect. 2.3.1 I pose the question: why do petroleum geologists worry about fluvial style? and provide the answer: it is because it has long been assumed that reservoir architecture is the key to reservoir performance. In this chapter we discuss some of the difficulties in the reconstruction of fluvial style and facies architecture from the ancient rock record. It is important to note, however, that reservoir architecture, as such, may not be the critical key to reservoir performance that it has commonly been thought to be. As Larue and Hovadik (2008) have demonstrated, from their series of numerical experiments, facies variation along the flow paths, and its control on permeability, is of the greatest practical importance. The most important control on reservoir performance is sand body connectivity (the "sand fairway"), which may only be loosely dependent on reservoir architecture. Channel density and stacking pattern, regardless of the style of the channels, are the key controls on connectivity. Sand body connectivity is discussed in Sect. 3.7.

2.2 Depositional Scales

One of the most distinctive features of the earth sciences is the wide range of scales with which we have to deal (Fig. 2.1). The concept of deep time is a concern of earth scientists, theoretical physicists and astronomers. On Earth we deal with 4.5 billion years of time (about one third of the duration of the universe), but we deal with it in different ways on different time scales that vary over sixteen orders of magnitude:

- The formation of continents, basins and basin-fill successions over millions to as much as a billion years;
- The effects of tectonism and climate change on time scales of 10^4–10^7 years;

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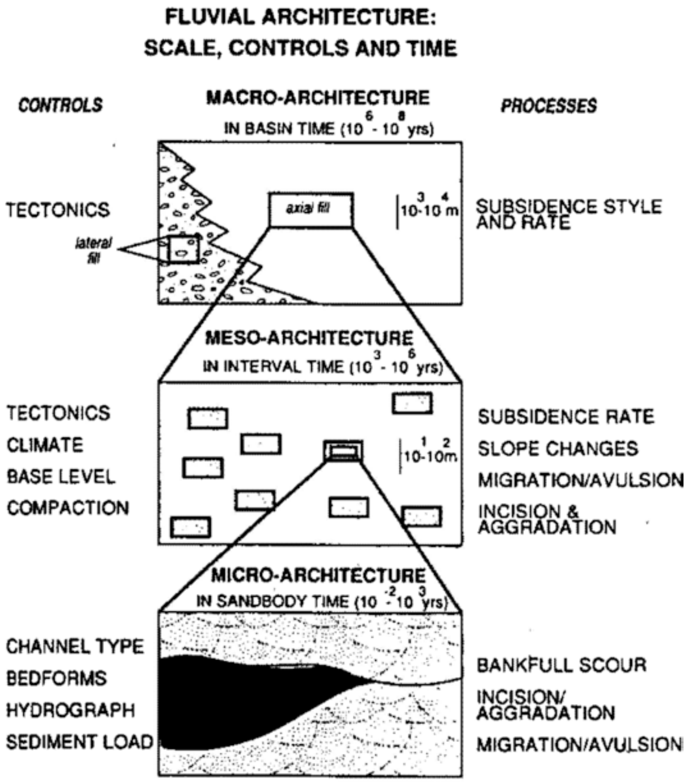

Fig. 2.1 Hierarchies of scale and time in fluvial deposits (Leeder 1993)

- The evolution of depositional systems, a geomorphic process that addresses processes over a time scale of tens to hundreds of thousands of years;
- The formation of bedforms and local aggradational cycles in response to daily and seasonal processes and to dynamic events (e.g., the 100-year flood). These processes are observable in present-day depositional systems, but for the purpose of understanding the ancient record we need to be aware that most of what we observe is geologically ephemeral.

It has become a geological truism that many sedimentary units accumulate as a result of short intervals of rapid sedimentation separated by long intervals of time when little or no sediment is deposited (Ager 1981, 1993). It is also now widely realized that rates of sedimentation measured in modern depositional environments or the ancient record vary in proportion to the time scale over which they are measured. Sadler (1981) documented this in detail, and showed that measured sedimentation rates vary by eleven orders of magnitude, from 10^{-4} to 10^{7} m/ka (Fig. 1.1). This wide variation reflects the increasing number and length of intervals of nondeposition or erosion factored into the measurements as the length of the measured stratigraphic record increases. Breaks in the record include such events as the nondeposition or erosion that takes place in front of an advancing bedform (a few seconds to minutes), the nondeposition due to drying out at ebb tide (a few hours), up to the major regional unconformity generated by orogeny (millions of years).

The variation in sedimentation rate also reflects the variation in actual rates of continuous accumulation (fifteen orders of magnitude in total), from the rapid sandflow or grainfall accumulation of a cross-bed foreset lamina (time measured in seconds, or 10^{-6} years), and the dumping of graded beds from a turbidity current (time measured in hours to days), to the slow pelagic fill of an oceanic abyssal plain (undisturbed in places for hundreds or thousands of years, or more), to the development of a major structural-stratigraphic province, which could represent hundreds of millions of years. There clearly exists a wide variety of time scales of sedimentary processes (Figs. 2.1, 2.2, 2.3).

There also exists a hierarchy of physical scales, which the same two examples illustrate—the cross-bed foreset at one extreme to the basin-fill at the other extreme (Fig. 2.1). At least fifteen orders of magnitude are represented, from the few square centimeters in area of the smallest scale of ripple foreset, to the tens of thousands of square kilometers of a major sedimentary basin. At the scale of the bedform, physical scales are constant, because they reflect invariant processes of

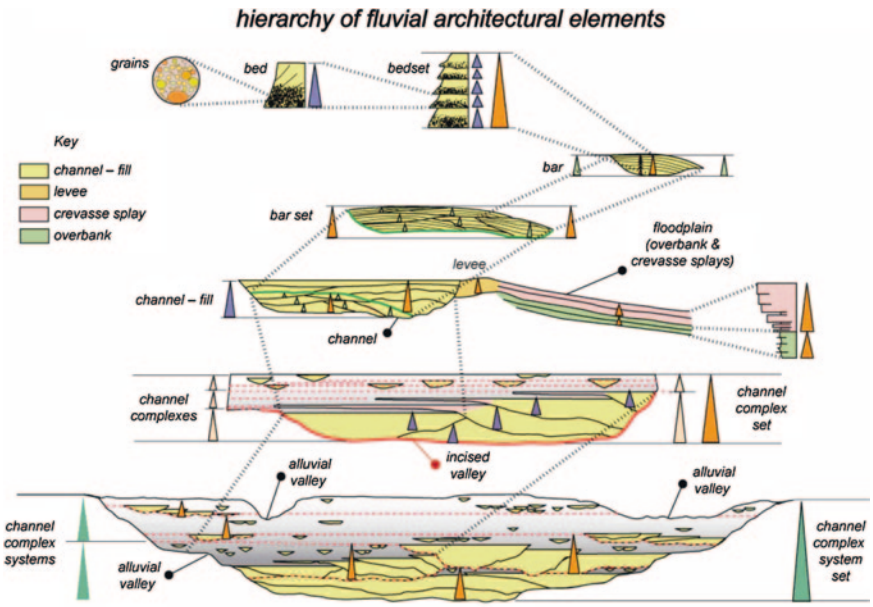

Fig. 2.2 The hierarchy of depositional units in a fluvial complex. This diagram was developed primarily to assist in the explanation of sequence-stratigraphic terms and concepts (Kendall 2008; sepmstrata.org)

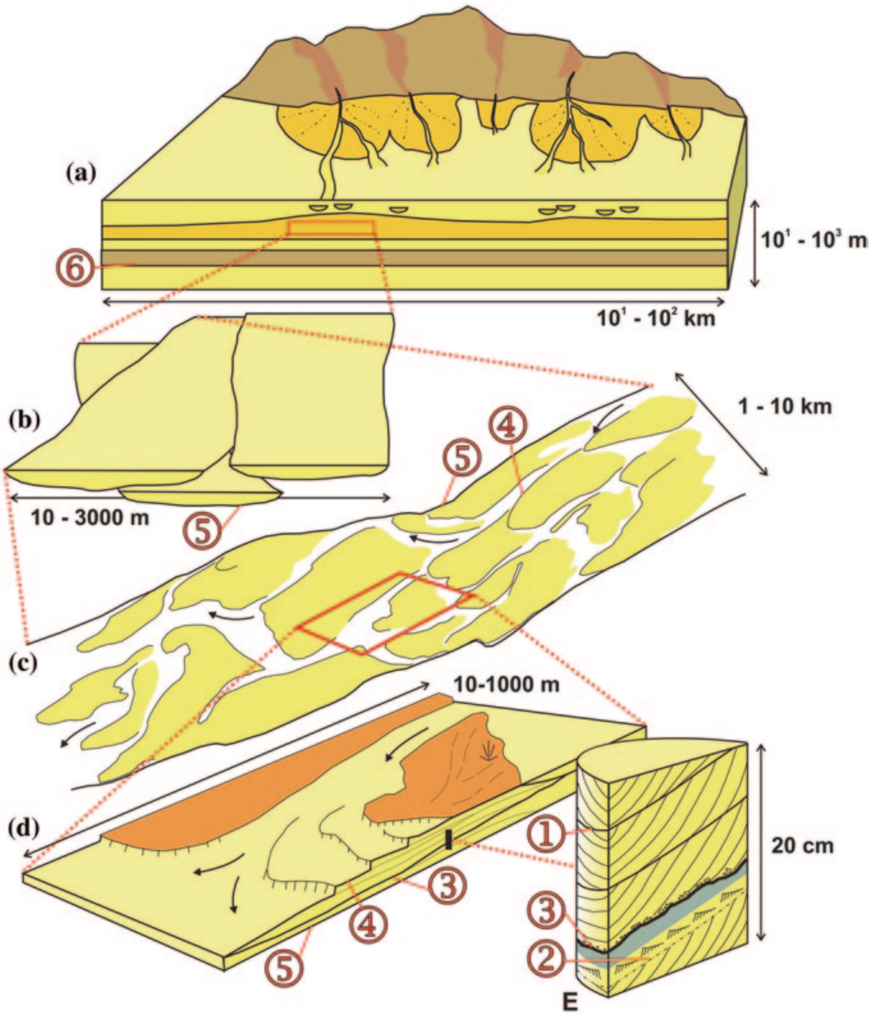

Fig. 2.3 The hierarchy of depositional units in a fluvial system. *Circled numbers* indicate the ranks of bounding surfaces, using the classification of Miall (1996)

the physics of sedimentation. However, at other levels of the hierarchy the scales may show wide variation, such as the scales of fluvial channels (Fig. 2.4).

The ways by which earth scientists study sedimentary processes and the resultant depositional products vary according to the scale of interest (Table 2.1). Bedforms in flumes are studied during experimental runs of, at most, few days duration. Nonmarine and marginal-marine sediments and processes have been much analyzed in modern environments, using studies of surface processes, and by sampling the sediments themselves in trenches and shallow cores. The use of old maps and aerial photographs extends the record as far back as about 100 years.

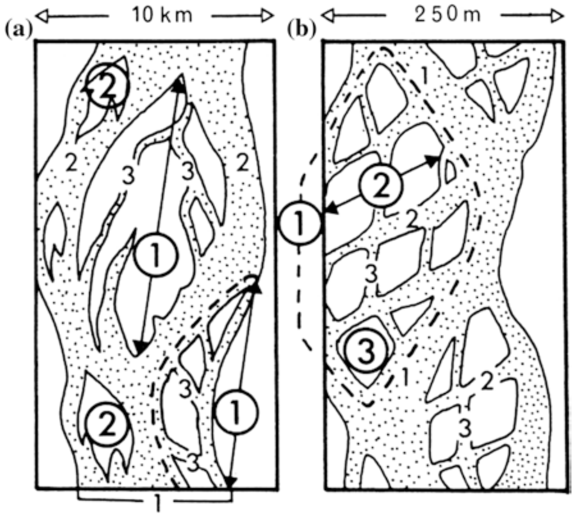

Fig. 2.4 Channel hierarchies in the Brahmaputra River, (**a**), and the Donjek River, (**b**) (after Williams and Rust 1969). *Numbers in circles* refer to bars, *other numbers* refer to channels. The first-order channel comprises the whole river, which includes several second-order channels. Bars scale within the channels in which they occur. In the Brahmaputra River third-order channels modify higher-order bars but still have bars within them, which cannot be shown at this scale (Bristow 1987)

Optically stimulated luminescence (OSL) can provide age information for the 300-100,000-BP time span. ^{14}C dates may enable stratigraphic records of the last few tens of thousands of years to be calibrated. Many sedimentological studies draw on geomorphological work on landforms and Recent sediments. However, such work is hampered by the specific, and possibly non-generalizable nature of the Recent record, such as the Holocene deglaciation, climatic change, and rapid rise of global sea levels. Stratigraphic studies typically deal with much longer time periods, as represented by the deposits of basin fills, which may have taken hundreds of thousands to millions of years to accumulate. Intermediate scales, represented by such major depositional elements as large channels and bars, delta lobes, draas, coastal barriers and shelf sand ridges, which may represent thousands to tens of thousands of years of accumulation, are particularly difficult to document in the ancient record and to analyze in modern environments. The time scales of the relevant sedimentary processes are difficult to resolve, and the physical scale of the deposits falls between the normal size of large outcrops and the well spacing or the scale of geophysical resolution in the subsurface. Yet it is this scale of deposit that is of particular interest to economic geologists, representing as it does the scale of many stratigraphic petroleum reservoirs and their internal heterogeneities (Table 2.2).

Figures 2.2 and 2.3 represent two different ways of illustrating the hierarchical nature of stratigraphic accumulations. Most of the problems faced by geologists attempting to wrestle with field-scale heterogeneities relate to the intermediate scales shown on these diagrams, the channel fill and channel complex of Fig. 2.2, and the units shown in diagrams B, C, and D of Fig. 2.3. We return to these scale issues in a discussion of reservoir problems, in the next section.

Geomorphologists have devoted considerable attention to the problem of time scales and their effects on analysis and prediction (Cullingford et al. 1980;

Table 2.1 Hierarchies of architectural units in fluvial deposits

SRS	Time scale	Inst. sed. rate	Examples of processes	Depositional unit	Type of process	Interpretive significance	Investigative technique
1	10^{-6}	10^{6}	Burst-sweep cycle	Lamination	Autogenic	Trivial	Thin-section hand specimen
2	10^{-6} – 10^{4}	10^{5}	Ephemeral flow events	Ripple (microform)	Autogenic	Superficial hydraulic fluctuations	Hand specimen core
3	10^{-3}	10^{5}	Diurnal dune increment, reactivation surface	Diurnal	Autogenic	Daily variability small outcrop	Core
4	10^{-2} – 10^{1}	10^{4}	Storms (mesoform)	Dune	Autogenic	Dynamic events	Core, small outcrop
5	10^{0}–10^{1}	10^{2}–10^{3}	Seasonal to 10 year flood	Macroform growth increment	Autogenic	Major dynamic events	Large outcrop GPR on modern river
6	10^{2}–10^{3}	10^{2}–10^{3}	100 year flood levee, splay	Macroform, e.g. point bar	Autogenic	Major dynamic events	Large outcrop GPR on modern river
7	10^{3}–10^{4}	10^{0}–10^{1}	Avulsion	Channel	Autogenic	Behavior of river system	Large outcrop horizontal 3-D seismic section
8	10^{4}–10^{5}	10^{-1}	5th order (Milankovitch) cycles	Channel belt	Autogenic or allogenic	Geomorphic response to regional change	Regional outcrop network horizontal 3-D seismic section
9	10^{5} – 10^{6}	10^{-2} – 10^{-1}	4th order (Milankovitch) cycles	Depositional system, alluvial fan, major delta	Allogenic	Tectonism, climate change, base-level change	Regional 2-D seismic or well network
10	10^{6}–10^{7}	10^{-1} – 10^{0}	2nd–3rd order cycles	Basin-fill complex	Allogenic	Rapid tectonism	Regional 2-D seismic or well network
11	10^{6}–10^{7}	10^{-2}–10^{-1}	2nd–3rd order cycles	Basin-fill complex	Allogenic	Tectonism	Regional 2-D seismic or well network
12	10^{6}–10^{7}	10^{-3}–10^{-2}	2nd–3rd order cycles	Basin-fill complex	Allogenic	v. slow cratonic subsidence	Regional 2-D seismic or well network

Adapted from Miall (1996, in press), with ideas from Brierley (1996). GPR = ground penetrating radar

Table 2.2 Classification of fluvial-channel bodies and fluvial-valley fills according to size and form (Gibling 2006)

Width (m)		Thickness (m)		Width/Thickness		Area (km^2)	
Very wide >	10,000	Very thick >	50	Very broad Sheets >	1,000	Very large >	10,000
Wide >	1,000	Thick >	15	Broad sheets >	100	Large >	1,000
Medium >	100	Thick >	15	Narrow sheets >	15	Medium >	100
Narrow >	10	Thin >	1	Broad ribbons >	5	Small >	10
Very narrow <	10	Very thin <	1	Narrow ribbons <	5	Very small <	10

Hickin 1983; Schumm 1985a). As Hickin (1983, p. 61) has stated, "time-scale selection largely determines the questions that we can ask." Schumm (1985a) showed that the significance of an event diminishes as the time-scale increases. Thus, an individual volcanic eruption, a spectacular geological event at the time of its occurence (a "megaevent", to use Schumm's term), diminishes in geological importance as the millenia go by and other eruptions take place, until eventually, after perhaps millions of years, all evidence of the eruption is lost (it becomes a "nonevent") as a result of erosion or burial of the rocks and landforms formed by the eruption. Events that seem random in the short term (such as turbidity-current events) may assume a regular episodicity, or even cylicity, with definable recurrence intervals, if studied over a long enough time scale. Many events occur only when some critical threshold has been passed, such as the buildup of deposits on a depositional slope leading to gravitational instability and failure. In several essays, Schumm (1977, 1979, 1985a, 1988; Schumm and Brakenridge, 1987) has discussed the concept of "geomorphic thresholds" and their impact on sedimentary processes. Such thresholds reflect both autogenic and allogenic processes, and are characterized by a wide range of time scales (Fig. 2.5) and scales of cyclicity (Fig. 2.6).

The accumulation of information relating to sedimentation rates and its interpretation based on fractal theory has led to two important developments: (1) The realization that the stratigraphic record is far more fragmentary than has hitherto been appreciated (Miall, in press); and (2) The realization that many processes are scale independent. This has been argued from the perspective of sequence stratigraphy (Posamentier et al. 1992; Catuneanu 2006). It has also been argued from the basis of experimental and theoretical considerations that small-scale experiments, such as those carried out in the Experimental Earthscape Facility (XES) at University of Minnesota can be used to explore full-scale sedimentological processes that take place over geologically significant periods of time (Paola et al. 2009).

Miall (in press) proposed the definition of a suite of *Sedimentation Rate Scales* to encompass the range of time scales and processes that can now be recognized from modern studies of the stratigraphic record (Table 2.1, Fig. 2.7). Assignment of stratigraphic units to the appropriate scale should help to initiate a potentially rich new form of debate in which tectonic and geomorphic setting, sedimentary processes and preservation mechanisms can be evaluated against each other,

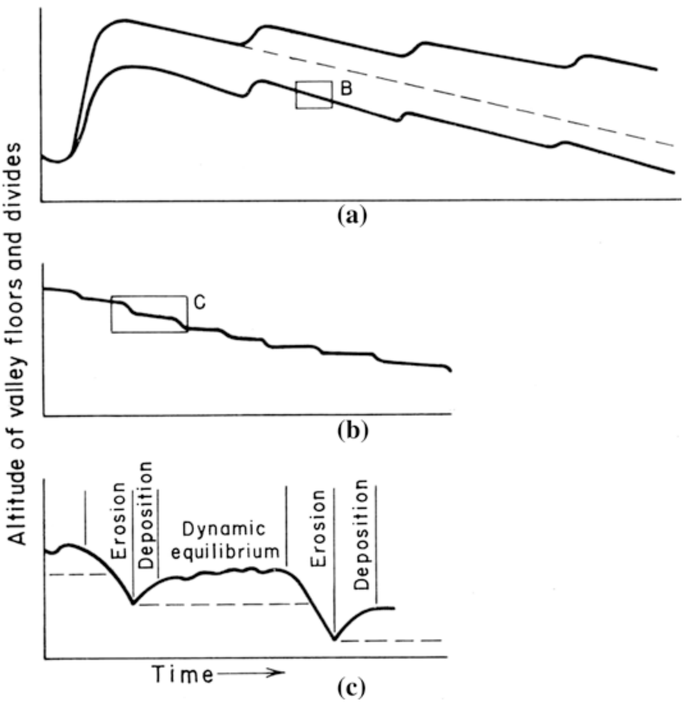

Fig. 2.5 The various time scales of geomorphic processes. **a** The erosion cycle, as envisioned by W. M. Davis in the nineteenth century. The *lower line* indicates the elevation of the valley floor, the *upper line* that of drainage divides. Initial uplift is followed by degradational lowering and episodic pulses of isostatic uplift in response to erosional unroofing. Total elapsed time is in the order of $10^{7–8}$ years for a major drainage basin, with minor uplift events occurring on the scale of $10^{6–7}$ years (corresponding to the tectonic cyclothems of Blair and Bilodeau (1988)). Box labelled B is enlarged in diagram (**b**). In detail the valley floor shows an episodicity on a smaller time scale (in the range of $10^{2–3}$ years) as a result of the periodic storage and flushing of sediment from bars and floodplain deposits, for example by avulsion events. Box labelled C is shown enlarged in (**c**), in which the episodicity of diagram (**b**) is shown in greater detail (diagram from Schumm 1977)

leading to more complete quantitative understanding of the geological preservation machine, and a more grounded approach than earlier treatments of "stratigraphic completeness".

The incorporation of hierarchical scale concepts into fluvial studies requires an architectural approach. Early approaches to the architectural study of fluvial deposits, notably, the work of J. R. L. Allen and of A. Ramos and his colleagues, is described elsewhere (Miall 1996, Chap. 2). The main classification used in this book is briefly described in Sect. 2.3. The current explosion of interest in sequence stratigraphy represents an increasing interest in large-scale stratigraphic architecture, and its dependence on such allogenic controls as tectonics and sea-level change, which topics form one of the major focuses of the present book (Chap. 6).

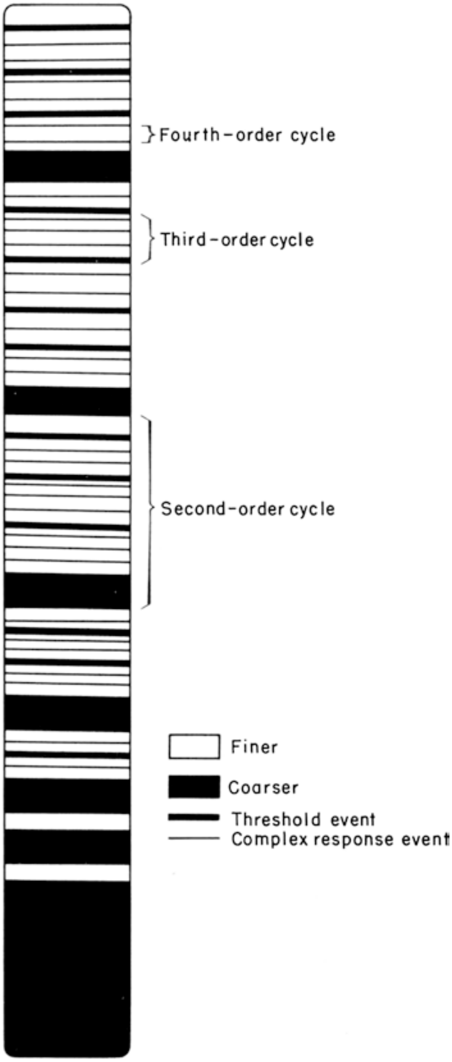

Fig. 2.6 The hierarchy of cycles of sedimentation, based on geomorphic concepts of the complex and episodic response of fluvial systems to autogenic and allogenic forcing. Schumm's cycle terminology does not correspond to that which emerged with sequences stratigraphy (Vail et al. 1977), and is explained here with reference to the *Sedimentation Rate Scales* of Table 2.1. The primary cycle is the entire succession, reflecting the gradual diminution of sediment grade following initial uplift (corresponding to the "erosion cycle" curve of Fig. 2.5a; *SRS 10* of Table 2.1). Second-order geomorphic cycles reflect isostatic adjustments (tectonic cyclothems) or major climate change (the kinks in the curves of Fig. 2.5a; corresponding to *SRS8-10* of Table 2.1). Third-order geomorphic cycles are those relating to the exceeding of geomorphic thresholds, leading to periods of "metastable equilibrium" and periods of rapid change and adjustment (The events shown in Fig. 2.5b). These processes occur over various time scales (groups 6–8). Fourth-order cycles are related to episodic erosion, and to the complex response of the fluvial system to any of the above changes (*SRS 5–8*). Fifth-order cycles are related to seasonal and other major hydrological events, such as the "hundred-year flood" (*SRS 5, 6*) (Schumm 1977)

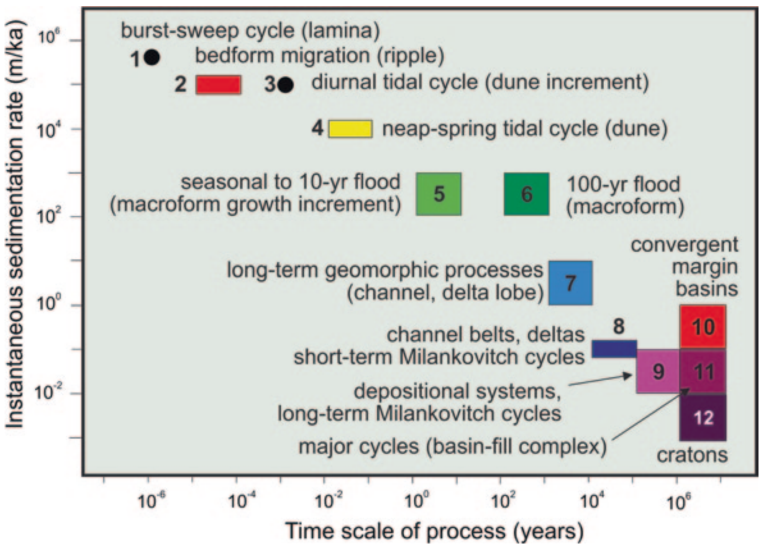

Fig. 2.7 Rates and durations of sedimentary processes. Numerals refer to the *Sedimentation Rate Scale* (see also Table 2.1)

2.3 Fluvial Style

2.3.1 Statement of the Problem

A great deal of sweat and much ink has been spent on worrying about fluvial style, that is, the shape and arrangement of channels on the valley floor of a fluvial system. Why? Because it has long been thought that fluvial style is the key to reservoir architecture. Until the advent of three-dimensional seismic, and the emergence of seismic geomorphology as practical tools for exploration and development of stratigraphic traps, geologists had very little data and only very unreliable tools to reconstruct reservoir geometry in the subsurface.

Development geologists and engineers employ models to assist in the characterization of their reservoirs. These models take many forms, including the use of modern analogues of the reservoir's interpreted depositional system, outcrop analogues of a unit assumed to have formed under similar conditions, physical scale models of the depositional system, and numerical simulations of the reservoir built using mathematical short-cuts to simulate the physics of reservoir construction. Many published studies attest to the usefulness of such models, at least as providing first approximations of reservoir character, although it is almost always the case that discrepancies develop between the predicted character of the reservoir and the actual performance of the reservoir, as development proceeds (the issue of "history matching"). Several general studies of the modeling process have appeared in recent years, that have provided excellent introductions to the strengths and limitations of the various approaches (e.g., Alexander 1993; Bryant and Flint 1993; Geehan 1993; North 1996).

In a lengthy and thorough review of the area of modeling and prediction of subsurface fluvial reservoirs, North (1996) emphasized the complexity and variability of fluvial successions and the difficulties in predicting fluvial architecture in the subsurface. He discussed the various conceptual approaches that have been used to systematize our understanding of fluvial systems, including vertical-profile-based facies modeling, architectural-element analysis and sequence stratigraphy. He noted the problems caused by the simultaneous actions of the various autogenic and allogenic sedimentary controls. He demonstrated that limits of vertical seismic resolution and the limits imposed by a borehole network, even within a mature basin, may limit the ability of the geologist to accurately define and predict fluvial architecture with the quantitative rigour required by development engineers. Ethridge (2011) likewise, in an appraisal of the methods of sedimentological interpretation of ancient fluvial systems, reviewed the many attempts to classify fluvial channels and channel systems, pointing out the inconsistencies in terminology and the fact that such classifications have not, in fact, assisted greatly with the interpretation of the ancient record.

North (1996, p. 451) suggested that the computer models of flow in channels (as recently summarized by Bridge, 2003), which provide predictions of vertical profile and paleocurrent variations, are valuable, as providing the basis for more reliable reconstructions of channel form and style than earlier, descriptive models, but acknowledged that sufficient data would rarely be available from the subsurface to make this a practical tool. These numerical models are based on geomorphic data bases of channel dimensions, from which sets of equations have been derived that express the relationships between such parameters as channel width, depth, meander wavelength, discharge, etc. (e.g., Ethridge and Schumm 1978; Bridge and Mackey 1993b). North (1996, p. 452) noted the inadequacy of the data base on which paleohydraulic reconstructions have been based, the large errors inherent in the standard equations, and the procedural errors involved in using the output from one equation as the input for another. Many studies, including that of Bridge and Mackey (1993b), have addressed the issue of the paucity of data, but the conceptual question discussed by Alexander (1993) and Geehan (1993) remains: how do we know we are using the right analogue?

Weissmann et al. (2011) offered an even more fundamental criticism of the data base of fluvial studies on which modern fluvial sedimentology rests: they argued that most of the modern river systems, the descriptive features of which have been used to construct modern facies models, are located in degradational settings. They asserted that these studies are of limited relevance in the interpretation of ancient successions which, by their very existence, indicate the long-term persistence of aggradational environments. They stated (p. 330):

> We believe that these studies of fluvial systems in degradational settings have validity in terms of channel processes and products at the scale of bar forms, macroforms, and channel belts. However, they do not inform us about the way the macroform-scale deposits stack into overall 3D basin-fill architecture.

I address this argument in Sect. 7.3.2.

A theme throughout the discussions by North (1996) and the concluding remarks in the book of which that paper is a part (Carling and Dawson 1996) is the lack of information about modern rivers, a refrain expressed many times by J. S. Bridge, as well. For example, Mackey and Bridge (1995, p. 28) concluded that "There is a critical need for more comprehensive architectural data from modern fluvial systems, especially data related to processes controlling floodplain geometry and channel pattern over periods of thousands of years." They called for more comprehensive physical models of flow, sediment transport, channel geometry and the effects of tectonism and base level change. However, the usefulness of such models would still be questionable, for the reasons discussed below. North (1996, p. 399) noted that:

> The geological emphasis needed is often determined by the economic and engineering parameters of the project. So in a hydrocarbon reservoir analysis, for example, while the geologist may be fretting over the sinuosity of the ancient river, the engineer may be much more concerned by the impact on channel-sand permeability and porosity of the variations in diagenesis.

Tye (2004) argued that the documentation of surface form, without the need for subsurface analysis, could provide an invaluable input into reservoir studies by providing constraints on the scale, orientation and interrelationships between reservoir components, such as channels and bars, so long as the appropriate modern analogue had been selected from which modeling input data was derived. He illustrated his argument with examples of the use of measurements on selected modern rivers and deltas as input into an object-based three-dimensional reservoir model. He acknowledged, however, that his "geomorphology" approach could not take account of the erosional relationships between successive channel-belt units. This is where knowledge of the subsurface architecture must be added in.

The problem of documenting fluvial architectures from modern river systems has largely been solved by the development of ground-penetrating radar (GPR). This geophysical technique is superbly adapted to documenting the shallow subsurface, providing high-resolution architectural data that can be related precisely to the surface channel and bar morphology (e.g., excellent case studies were provided by Best et al. (2003), Lunt and Bridge (2004)). Both the value and the limitations of modern architectural studies using GPR are well illustrated by the detailed study of the Sagavanirktok gravelly braided river in Alaska by Lunt and Bridge (2004) and Lunt et al. (2004). These papers contain detailed documentation of the channel and bar architecture, documented with numerous GPR profiles. From the GPR data the authors extracted a set of "vertical logs of typical sequences through different parts of compound bar deposits and channel fills" (Lunt et al. 2004, Fig. 24d). They also developed a table relating "stratal thicknesses measured in boreholes" to the "widths of different scales of stratasets" (Lunt et al. 2004, p. 410 and Table 2.3). They stated that this "quantitative three-dimensional depositional model … will allow prediction of the dimensions and spatial distributions of different scales of stratification …" However, they then go on to say that "reconstructing the origin and evolution of compound bar deposits from only recent aerial photographs or cores is impossible. It is also impossible to determine from core whether a compound bar was a point bar or a braid bar." They also assembled some modern data relating to the width-depth relationships for the channel belt deposits of recent braided and meandering rivers and concluded that this ratio is widely variable and that there may be very little difference between the two river styles in terms of the channel-belt deposits currently accumulating.

Here, then, is the first of the two major problems with modern analogues for interpreting the ancient record: snapshots of a modern river (surface maps, aerial photographs) do not necessarily reveal the internal structure of the bars and channel deposits beneath the surface. For example, an apparently simple point bar in a braided system may, upon dissection or GPR surveying, reveal an internal structure partly composed of the remnants of a different type of bar, or of an earlier point bar with a different orientation, upon which the modern bar form has been superimposed by the latest configuration of the adjacent active meander bend. Best et al. (2003) documented the evolution of a single large braid bar in the Jamuna (Brahmaputra) River in Bangladesh. This bar, 1.5 km long in a downstream direction, migrated downstream a distance equal to its own length in a little over a year, and temporarily doubled in downstream length. How relevant to the study of the ancient record is the detailed documentation of such an ephemeral feature, other than to illustrate short-term bar-forming processes? How much of this bar is likely to make it into the preserved record?

In its simplest condition, the evolution of a braided channel can be considered as the development of opposite-facing low-sinuosity meanders migrating away from a central (mid-channel) bar (Bridge 1993). The work of Ashworth et al. (2000) explicitly ruled out this mode of evolution in the case of the bar they studied, although they made a comparison with the small bar in the Calamus River, Nebraska, analyzed by Bridge et al. (1998), which the latter demonstrated to have grown by a comparable pattern of lateral and downstream accretion from an upstream nucleus. Where bar migration is symmetrical, as proposed by Bridge (1993), channel scour would be expected to sweep out an erosional channel form approximating the width of two channels plus the intervening bar. Assuming two channels of second-order Brahmaputra scale (in the terminology of Bristow (1987)), each 2 km wide, and a mid-channel bar also 2 km wide, if both channels were filled prior to abandonment this could theoretically generate a second-order sand body bounded by a fifth-order surface (the numbering refers to the channel-scale bounding surface classification of Miall (1988, 1996, 2010a)) in the order of 6 km wide. With an average depth of 12 m such a sand body would have a W/D ratio of 500. However, this scenario is quite speculative. Several groups of researchers have demonstrated patterns of active anabranch migration and bar growth and erosion in the Brahmaputra/Jamuna River (Thorne et al. 1993; Ashworth et al. 2000), which indicate that sand bodies of the full theoretical width estimated here may never develop. Sand bodies bounded by surfaces of fifth-order rank are likely to be substantially less than 6 km wide. The final preserved architecture of sand bodies of the type described by Ashworth et al. (2000) would depend on the balance between (1) lateral growth of the bar under conditions of anabranch migration, and (2A) erosional incision brought about by events of avulsive anabranch switching, or (2B) migration and lateral erosion of an anabranch from another location within the channel belt. Final preserved sand body widths are presumably somewhere between the hypothetical maximum of 6 km and the width of individual bars—a minimum of 1 km. How useful are estimates with such wide error margins? I return to this question in Sect. 7.4, where the Brahmaputra/Jamuna River is discussed as a possible analog for the interpretation of the Hawkesbury Sandstone, Australia.

The second of the major problems is that well data (including core logs) relating to the internal architecture may be as poor a guide as surface form as a diagnostic tool for reservoir body evaluation. Lunt et al. (2004) reconfirmed the point argued many years ago (e.g., see Miall 1980; Collinson 1986) that vertical profiles are not reliably diagnostic of fluvial style, let alone of bar character within a river of known style. Even with a detailed core record it may be difficult to impossible to determine whether a particular vertical profile relates to a single channel-fill record or to superimposed fragments of several or many channel and bar deposits, such as the one documented by Best et al. (2003). Interpretations derived from core should therefore include the development of several alternative scenarios for further testing.

The demonstration of statistical relationships between channel thickness and width may be useful for characterizing individual rivers, but such relationships should be used with great caution in examining the ancient record. The problem is that even detailed GPR documentation of a modern river system relates only to the present-day snapshot of the deposits. On the short term (decades to hundreds of years) the architecture relates to the preservation of fragments of bars and channels formed, modified and eroded under the existing channel pattern. But none of this present-day deposit has yet made it into the geological record (this is, in part, what Weissmann et al. objected to, as noted above). On the longer term (from thousands of years up to geological time scales) the pattern of preservation is influenced by subsidence rates and climate change. In addition to the fragmenting of channels and bars within the short-term time frame of channel migration and avulsion there may be erosional incision caused by channel systems at much later time periods, which may partially or completely remove the earlier deposits and which may demonstrate different styles because of changes in long-term allogenic controls. Given slow subsidence rates it is quite conceivable that a given stratigraphic unit could contain the amalgamated, mutually incised fragmentary deposits of different river styles that were active tens to hundreds of thousands of years apart and which could have generated channel and bar deposits with significantly different internal character and thickness-depth relationships (e.g., see Blum and Törnqvist 2000; Ethridge and Schumm 2007; Sheets et al. 2008). In Chap. 6 we address the issue of the relationship between alluvial architecture and accommodation generation.

Shanley (2004, pp. 171–172) argued that although much geomorphic information is available from studies of modern rivers, "the interplay of subsidence, base level, and magnitude of sediment supply exerts a far greater control on the degree to which fluvial [channel] deposits are amalgamated or isolated than the many short-term processes commonly viewed in the study of modern analogs." Gibling (2006) has documented with a thoroughness not previously attempted the