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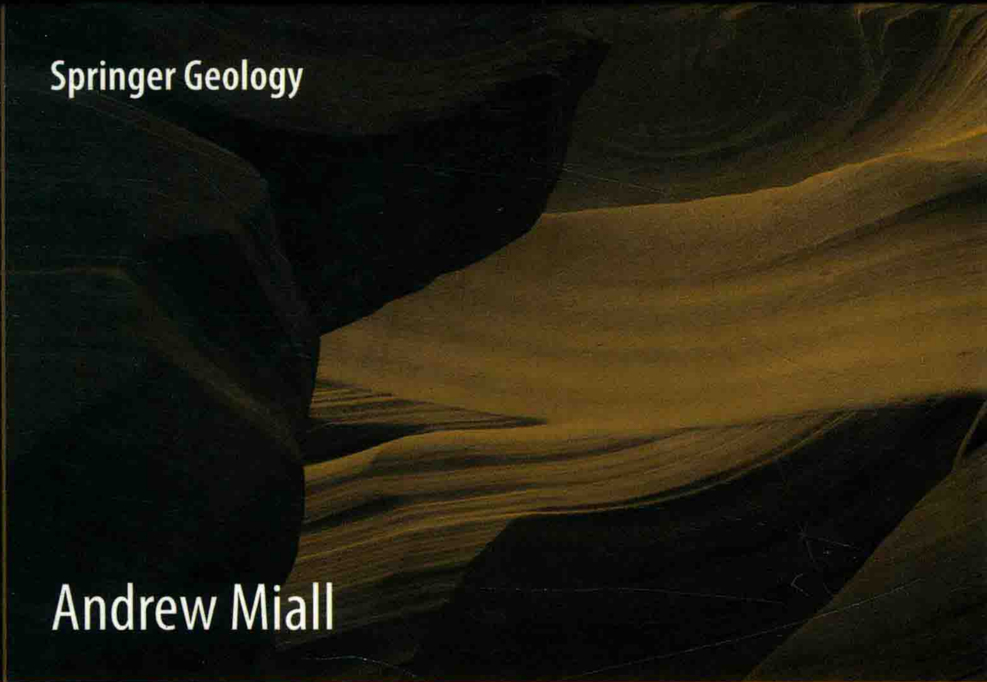

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Preface

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,

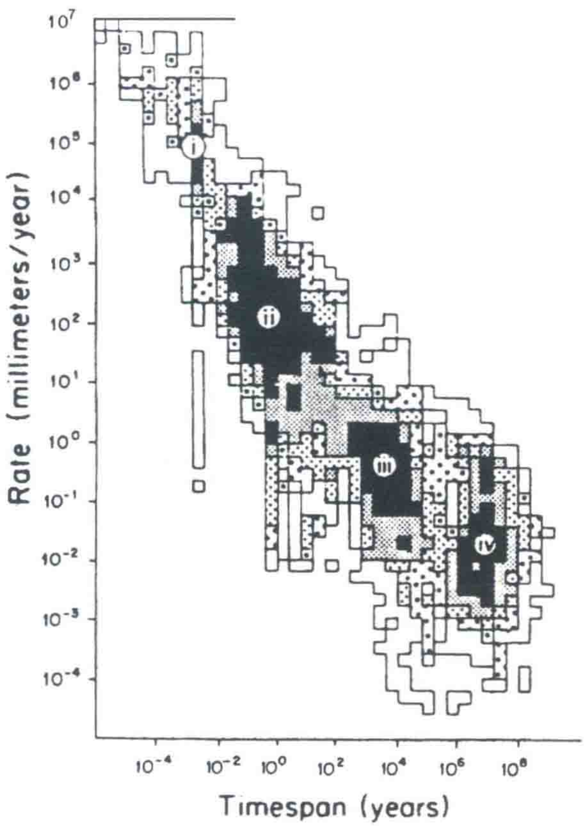

Fig. 1.1 The relationship between sedimentation rate and elapsed time in the stratigraphic record (Sadler 1981)

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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