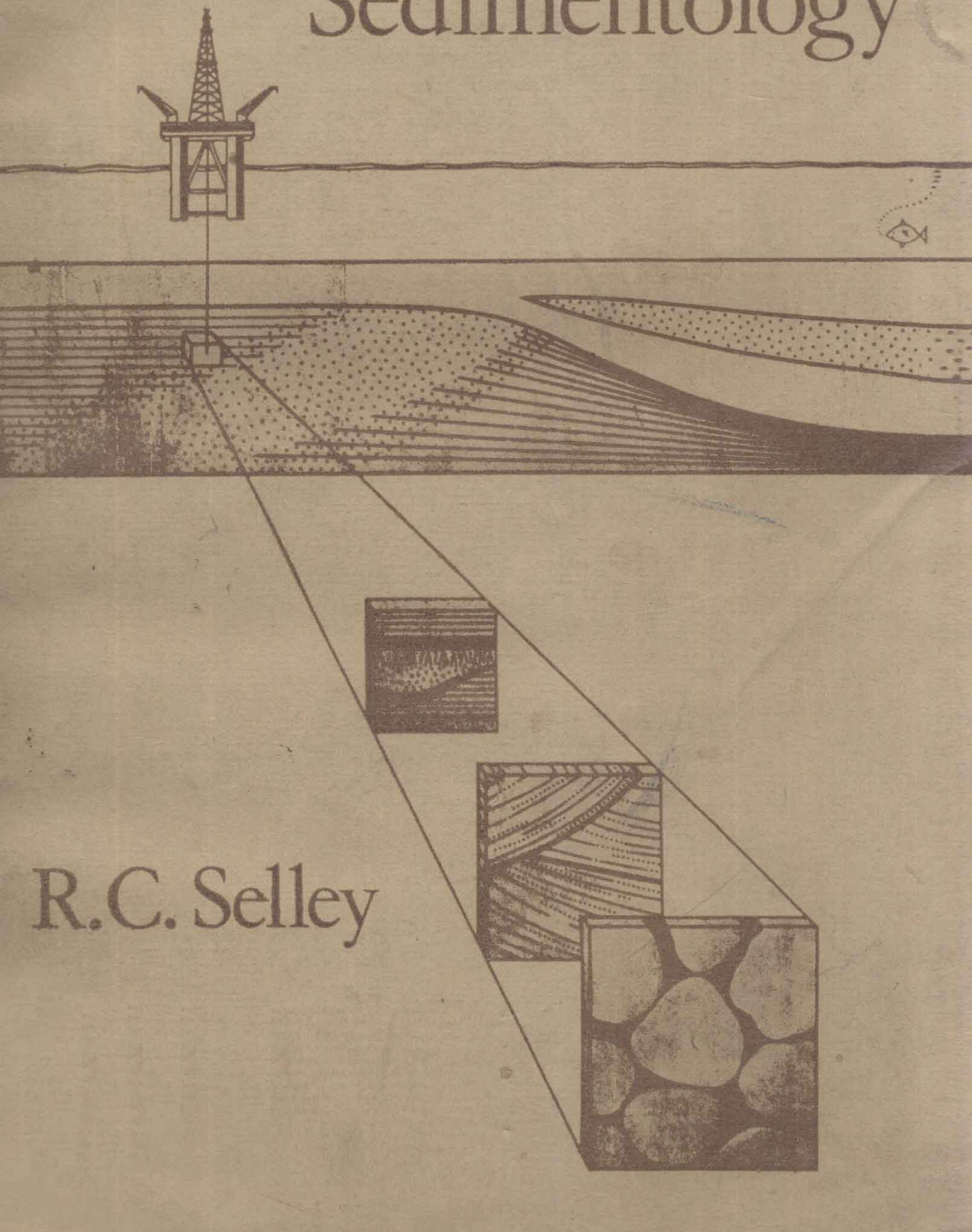
An Introduction to Sedimentology



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An Introduction to Sedimentology

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Preface

Sedimentology, the study of sediments, has grown rapidly within the last quarter century. Initially the impetus for this development came from the oil industry. More recently sedimentology has been carried on the crest of the oceanography wave.

There are many excellent books which synthesize various aspects of the field of sedimentology; few, perhaps wisely, have attempted an overview of the subject. "An Introduction to Sedimentology" attempts such an overview, but within certain specific and limited objectives. I assume the reader to have attended an introductory course in geology, but hope that this book will also be of use to qualified geologists whose main interest is in other fields, particularly petroleum geology.

This book is written for geologists whose principal interest is ancient sediments. Modern depositional processes and products are discussed, not as an end in themselves, but only in so far as they aid our understanding of their ancient counterparts.

There are few full-time sedimentologists in the world; yet many professional geologists require a working knowledge of sedimentology as part of their stock in trade. I have written this text for students and practising geologists who wish to acquire such a background.

The book opens with an introductory chapter which places sedimentology within the context of the physical, chemical and biological sciences and discusses its relationship with the other branches of geology.

Chapter 2 discusses the physical properties of sediments. Attention is given not only to particles, but also to the porosity and permeability of sediments in bulk.

Chapter 3 reviews the processes of weathering which form sediments and the sedimentary cycle.

Chapters 4 and 5 describe the petrography and diagenesis of sediments. These are no substitute for a course of study in practical petrography aided by one of several excellent texts now available. The objective of these two chapters is to show the relationship between diagenesis and porosity development and to provide a minimal background to the subsequent chapters.

Chapter 6 gives a brief qualitative review of the processes of sediment transport and deposition. Chapter 7 describes the resultant sedimentary structures and shows how they may be used in facies analysis.

Chapter 8 is concerned with facies analysis and environmental interpretation. It shows how studies of modern sediments may be used to define a series of depositional models which have occurred repeatedly through geological time.

This leads on logically to Chapter 9, a discussion of sedimentary basins. Various types of basin are defined, described and illustrated. Basin topology and evolution are integrated with the concepts of plate tectonics.

The book ends with a selective review of some of the applications of sedimentology. Particular emphasis is placed on the search for oil and gas and for sedimentary metalliferous deposits.

In conclusion, then, I have tried to write a book which, while not spanning the whole field of sedimentology, covers those aspects which are of particular importance to practising geologists.

R. C. Selley
August 1975

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Similarly I am grateful to my colleagues in industry and in universities who critically reviewed chapters from their several viewpoints. Dr H. Reading in particular shouldered much of this burden on the academic side.

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1

Introduction

I. INTRODUCTION AND HISTORICAL REVIEW

A sediment is "what settles at the bottom of a liquid: dregs: a deposit" (Chambers Dictionary, 1972 edition). Sedimentology is the study of sediments. Few sedimentologists would accept the preceding definition because we like to include both eolian deposits and chemical precipitates as sedimentary rocks. The limits of the field of sedimentology are, therefore, pleasantly ill-defined.

The purpose of this chapter is to introduce the field of sedimentology and to place it in the scheme of science, both the basic sciences of chemistry, physics and biology and, more parochially, within the field of geology.

It is hard to trace the historical evolution of sedimentology. Arguably among the first practitioners must have been the Stone Age flint miners of Norfolk who, as seen in Grimes cave, mined the stratified chert bands to make flint artifacts (Shotton, 1968). Subsequently civilized man must have noticed that other useful economic rocks, such as coal, building stone and so on, occurred in planar surfaces in the earth's crust that cropped out in a predictable manner. It has been argued that the legend of the "Golden Fleece" suggests that sophisticated flotation methods were used for alluvial gold mining in the fifth century BC (Barnes, 1973).

From the Renaissance to the Industrial Revolution the foundations of modern sedimentary geology were laid by men such as Leonardo da Vinci, Hutton and Smith. By the end of the nineteenth century the doctrine of uniformitarianism was firmly established in geological thought. The writings of Sorby (1853–1908) and Lyell

(1865) showed how modern processes could be used to interpret ancient sedimentary textures and structures.

Throughout the first half of the twentieth century, however, the discipline of sedimentology, as we now understand it, lay moribund. The sedimentary rocks were either considered fit only for microscopic study or as homes for fossils. During this period heavy mineral analysis and point counting were extensively developed by sedimentary petrographers. Simultaneously, stratigraphers gathered fossils; wherever possible erecting more and more refined zones until they were too thin to contain the key fossils.

Curiously enough modern sedimentology was not born from the union of petrography and stratigraphy. It seems to have evolved from a union between structural geology and oceanography. This strange evolution deserves an explanation.

Structural geologists have always searched for criteria for distinguishing whether strata in areas of tectonism were overturned or in normal sequence. This is essential if regional mapping is to delineate recumbent folds and nappes. Many sedimentary structures are ideal for this purpose, particularly desiccation cracks, ripples and graded bedding. This approach reached its apotheosis in Shrock's volume "Sequence in Layered Rocks", written in 1948.

On a broader scale, structural geologists were concerned with the vast prisms of sediments which occur in geosynclinal furrows. A valid stratigraphy is a prerequisite for a valid structural analysis. Thus it is interesting to see that it was not a stratigrapher, but Sir Edward Bailey, doyen of structural geologists, who wrote the paper "New light on sedimentation and tectonics" in 1930. This defined the fundamental distinction between the sedimentary textures and structures of shelves and those of deep basins. It was this paper which also contained the germ of the turbidity current hypothesis.

The concept of the turbidity flow rejuvenated the study of sediments in the 1950s and early 1960s. While petrographers counted zircon grains and stratigraphers collected more fossils, it was the structural geologists who asked "how do thick sequences of flysch facies get deposited in geosynclines?". It was modern oceanography which provided the turbidity current as a possible mechanism (see p. 178). It is true to say that this concept rejuvenated the study of sedimentary rocks. Though in their enthusiasm geologists identified turbidites in every kind of facies, from the Viking sand bars of Canada to the alluvial Nubian sandstones of the Sahara (Anon).

Another stimulus to sedimentology came from the oil industry.

The search for stratigraphically-trapped oil led to a boom in the study of modern sediments. One of the first fruits of this approach was the American Petroleum Institute's "Project 51"; a multidisciplinary study of the modern sediments of the north-west Gulf of Mexico (Shepard *et al.*, 1960).

This was followed by many other studies of modern sediments both by oil companies, universities and oceanographic institutes. At last, hard data became available so that ancient sedimentary rocks could be interpreted by comparison with their modern analogues. The concept of the sedimentary model was born as it became apparent that there are, and always have been, a finite number of sedimentary environments which deposit characteristic sedimentary facies (see p. 256).

By the end of the 1960s sedimentology was firmly established as a discrete discipline of the earth sciences.

II. SEDIMENTOLOGY AND EARTH SCIENCES

Table I shows the relationship between sedimentology and the basic sciences of biology, physics and chemistry.

The application of one or more of these fundamental sciences to the study of sediments gives rise to various lines of research in the earth sciences. These will now be reviewed as a means of setting sedimentology within its context of geology.

Biology, the study of animals and plants, can be applied to fossils in ancient sediments. Palaeontology may be studied as a pure subject which concerns the evolution, morphology and taxonomy of fossils. In these pursuits the fossils are essentially removed from their sedimentological context.

The study of fossils within their sediments is a fruitful pursuit in two ways. Stratigraphy is based on the definition of biostratigraphic zones and the study of their relationship to lithostratigraphic units (Shaw, 1964; Mathews, 1974). Sound biostratigraphy is essential for regional structural and sedimentological analysis.

The second main field of fossil study is to deduce their behaviour when they were alive, their habitats and mutual relationships. This study is termed palaeoecology (Ager, 1963). Where it can be demonstrated that fossils are preserved *in situ* they are an important line of evidence in environmental analysis.

Table I

The various branches of sedimentology and their relationship to the fundamental sciences

BIOLOGY	Palaeontology	
⇅	Biostratigraphy	
	Palaeoecology	
	Environmental analysis	
	Facies analysis	
PHYSICS	Basin analysis	
⇅	Petrography	Petrophysics
		Diagenesis
CHEMISTRY	Geochemistry	

Environmental analysis is the determination of the depositional environment of a sediment (Selley, 1970).

Our review of sedimentology has now moved from the biological aspect to those facets which involve both biological, physical and chemical properties of sedimentary rocks. To determine the depositional environment of a rock it is obviously important to correctly identify and interpret the fossils which it contains. At a very simple level a root bed indicates a terrestrial environment, a coral reef a marine environment. Most applied sedimentology, however, is based on the study of rock chips from bore holes. In such subsurface projects it is micropalaeontology that holds the key to both stratigraphy and environment. The two aspects of palaeontology which are most important to sedimentology, therefore, are the study of fossils as rock builders (as in limestones) and micropalaeontology.

Aside from biology, environmental analysis is based also on the interpretation of the physical properties of a rock. These include grain size and texture as well as sedimentary structures. Hydraulics is the study of fluid movement. Loose boundary hydraulics is concerned with the relationship between fluids flowing over granular solids. These physical disciplines can be studied by theoretical mathematics, experimentally in laboratories, or in the field in modern sedimentary environments. Such lines of analysis can be applied to the physical parameters of an ancient sediment to determine the fluid processes which controlled its deposition (Allen, 1970).

Environmental analysis also necessitates applying chemistry to the study of sediments. The detrital minerals of terrigenous rocks indicate their source and pre-depositional history. Authigenic minerals can provide clues both of the depositional environment of a rock as well as its subsequent diagenetic history.

Environmental analysis thus involves the application of biology, physics and chemistry to sedimentary rocks.

Facies analysis is a branch of regional sedimentology which involves three exercises. The sediments of an area must be grouped into various natural types or facies, defined by their lithology, sedimentary structures and fossils. The environment of each facies is deduced and the facies are placed within a time-framework using biostratigraphy.

Like environmental analysis, facies analysis utilizes biology, chemistry and physics. On a regional scale, however, facies analysis involves the study of whole basins of sediment. Here geophysics becomes important, not just to study the sedimentary cover, but to understand the physical properties and processes of the crust in which sedimentary basins form.

Moving along the spectrum of Table I we come to the chemical aspects of sediments. It has already been shown how both environmental and facies analysis utilize knowledge of the chemistry of sediments. Petrology, or petrography, are terms which are now more or less synonymously applied to the microscopic study of rocks (Carozzi, 1960; Folk, 1968). These studies include petrophysics, which is concerned with such physical properties as porosity and permeability. More generally, however, they are taken to mean the study of the mineralogy of rocks.

Sedimentary petrology is useful for a number of reasons. As already pointed out, it can be used to discover the provenance of terrigenous rocks and the environment of many carbonates. Petrography also throws light on diagenesis: the post-depositional changes in a sediment. Diagenetic studies elucidate the chemical reactions which took place between a rock and the fluids which flowed through it. Diagenesis is of great interest because of the way in which it can destroy or increase the porosity and permeability of a rock. This is relevant in the study of aquifers and hydrocarbon reservoirs. Chemical studies are also useful in understanding the diagenetic processes which form the epigenetic mineral deposits, such as the lead-zinc sulphide and carnotite ores.

Lastly, at the end of the spectrum the pure application of chemistry to sedimentary rocks is termed sedimentary geochemistry (Degens, 1965). This is a vast field in itself. It is of particular use in the study of the chemical sediments, naturally, and of microcrystalline sediments which are hard to study by microscopic techniques. Thus the main contributions of sedimentary geochemistry lie in the study of clay minerals, phosphates and the evaporite rocks.

Organic geochemistry is primarily concerned with the generation and maturation of coal, crude oil and natural gas. Organic geochemistry combining biology and chemistry brings this discussion back to its point of origin.

The preceding analysis has attempted to show how sedimentology is integrated with the other geological disciplines. The succeeding chapters will continuously demonstrate how much sedimentology is based on the fundamental sciences of biology, physics and chemistry.

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2

Particles and Pores

A sediment is, by definition, a collection of particles, loose or indurated. Any sedimentological study commences with a description of the physical properties of the deposit in question. This may be no more than the terse description "sandstones", if the study concerns regional tectonic problems. On the other hand, it may consist of a multipage report, if the study is concerned with the physical properties of a specific sedimentary unit in a small area. It must be remembered that the analysis of the physical properties of a sedimentary rock should be adapted to suit the objectives of the project as a whole.

The study of the physical properties of sediments is an extensive field of analysis in its own right, and is of wide concern not only to geologists. In its broadest sense of particle analysis, it is of importance to the managers of sewage farms, manufacturers of leadshot, plastic beads and to egg graders.

Enthusiasts for this field of study are directed to the writings of Herdan (1953), Chayes (1956), Tickell (1965), Mueller (1967) and Carver (1971).

The following account is a summary of this topic which attempts only to give sufficient background knowledge needed for the study of sedimentary rocks in their broader setting. This is in two parts. The first describes individual particles and sediment aggregates; the second describes the properties of pores – the voids between sediment particles.

I. PHYSICAL PROPERTIES OF PARTICLES

A. Surface Texture of Particles

The surface texture of sediment particles has often been studied, and attempts have been made to relate texture to depositional process.

In the case of pebbles, macroscopic striations are generally accepted as evidence of glacial action. Pebbles in arid eolian environments sometimes show a shiny surface, termed "desert varnish". This is conventionally attributed to capillary fluid movement within the pebbles and evaporation of the silica residue on the pebble surface. The folk-lore of geology records that wind-blown sand grains have opaque frosted surfaces, while water-laid sands have clear translucent surfaces. Kuenen and Perdok (1962) attributed frosting not to the abrasive action of wind and water but to alternate solution and precipitation under subaerial conditions. Electron microscope studies by Margolis and Krinsley (1971) show that wind-induced grain to grain impacts generate minute fractures which split the grain surface into upturned plates.

Krinsley and his co-workers have also described a variety of different types of quartz grain surface textures, using electron microscopes (Krinsley and Funnell, 1965; Krinsley and Cavallero, 1970; Krinsley and Doornkamp, 1973). They identified a number of different abrasion patterns which are characteristic of glacial, eolian and aqueous processes. At subcrop, and at outcrop in the tropics, these abrasional features are modified by solution and by secondary quartz cementation. The surface texture of ancient quartz grains thus reveals little or nothing of its depositional history.

B. Particle Shape, Sphericity and Roundness

Numerous attempts have been made to define the shape of sediment particles and to study the controlling factors of grain shape.

Pebble shapes have conventionally been described according to a scheme devised by Zingg (1935). Measurements of the ratios between length, breadth and thickness are used to define four classes: spherical (equant), oblate (disc or tabular), blade and prolate (roller), shown in Fig. 1. A more sophisticated scheme has been developed by Sneed and Folk (1958).

The shape of pebbles is controlled both by their parent rock type and by their subsequent history. Pebbles from slate and schistose rocks will tend to commence life in tabular or bladed shapes, whereas