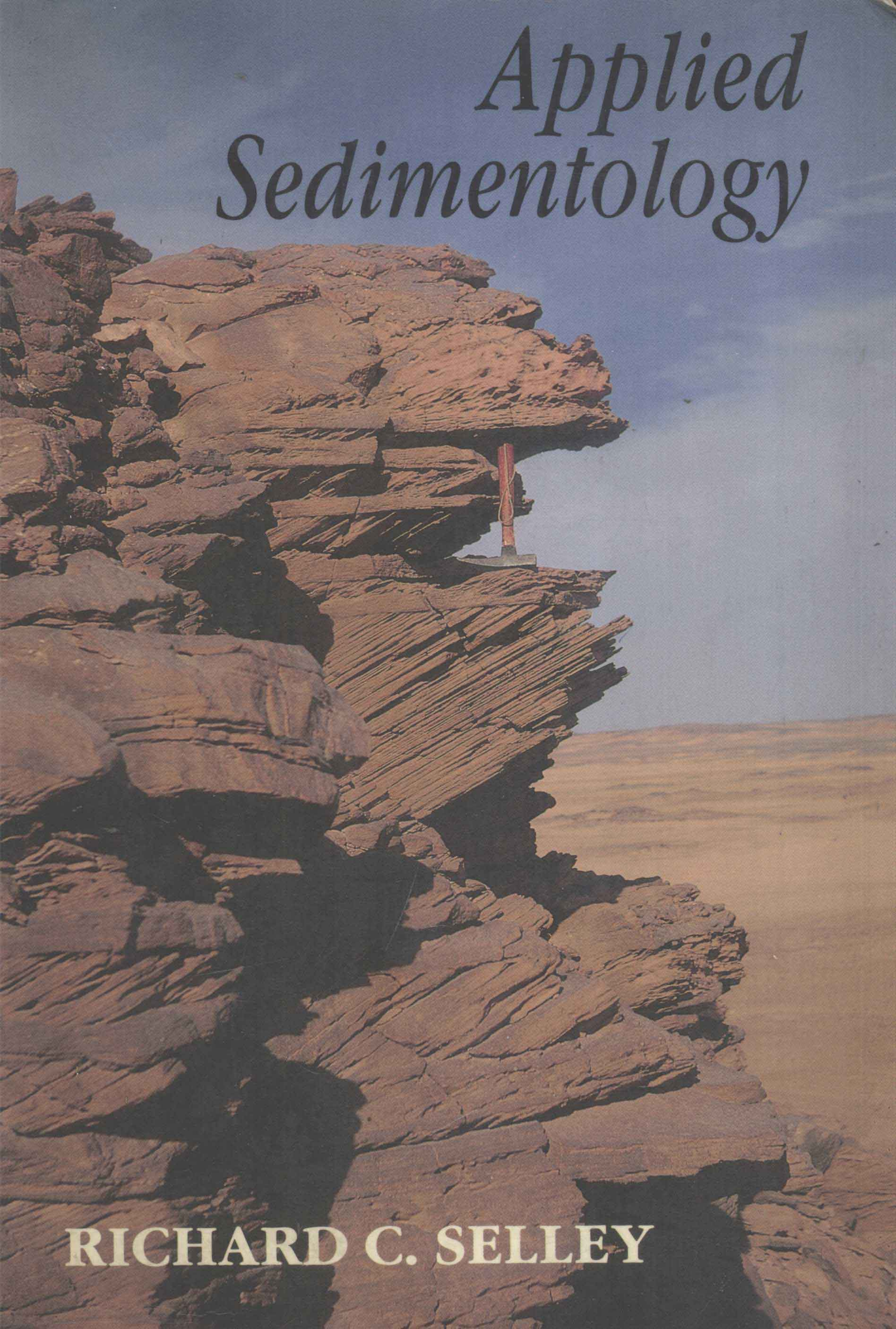
# Applied Sedimentology



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# Preface

This book was conceived as the third edition of "Introduction to Sedimentology", first published in 1976 and the second edition in 1982. Books have a curious habit of writing themselves, however, irrespective of the author's original intentions. As revision progressed, and the modifications became so extensive, it became apparent that a new book was struggling to be born. "Applied Sedimentology" is the result.

This book is divided into three parts: Rock to Sediment, Sediment Sedimented and Sediment to Rock, reflecting the closed nature of the sedimentary cycle. Each part is introduced with an appropriate quotation from Sir Charles Lyell's seminal "Elements of Geology", which first appeared in 1838.

The book begins with an introductory chapter that outlines the field of sedimentology, relates it to the fundamental sciences, and discusses its applications. Part I, Rock to Sediment, consists of two chapters. Chapter 2 outlines the processes of weathering, and shows not only how these give rise to the terrigenous sediments, but also how they mobilize and concentrate diverse residual mineral deposits. Chapter 3, Particles, Pores and Permeability, describes the textural properties of unconsolidated sediments, and shows how these are related to porosity and permeability.

Part II, Sediment Sedimented, takes the story a stage further. Chapters 4 and 5 describe sedimentary processes and sedimentary structures respectively. Chapter 6 outlines the major sedimentary environments, and discusses how their deposits may serve as petroleum reservoirs and hosts for mineralization.

Part III, Sediment to Rock, completes the cycle. Chapter 7 describes the temperatures, pressures and fluids of the subsurface environment within which sediment is turned into rock. Chapter 8 describes the clays, sands and gravels, and details their diagenesis and porosity evolution during burial. Chapter 9 does the same for the chemical rocks, describing the mineralogy, composition and diagenesis of limestones, dolomites, evaporites, sedimentary ironstones, coal, phosphates and chert.

The book concludes with a chapter on sedimentary basins. This describes the various types of basin, and their sedimentary fill, and also details their petroleum and mineral potential. It also describes the evolution of basin fluids through time.

The applications of sedimentology are many and varied. My own experience is principally in the field of petroleum exploration, with minor excursions into hydrogeology and coal exploitation. In writing this book I have been torn between the wisdom of writing only from personal knowledge, and the desire to display the wide applications of sedimentology.

Formerly the only source of sedimentary data was the collection and analysis of the rocks themselves. Nowadays, however, sediments may be remotely sensed by geophysical means, such as seismic surveying and well-logging. The composition, porosity and fluid content of rocks may be measured, and their depositional environments interpreted, without actually seeing or touching them. Indeed, there is at least one oil company in which geologists are strictly forbidden to bring rock into the office. This book is restricted to "real rock" sedimentology. There are other excellent texts on seismic stratigraphy and on the subsurface diagnosis of ancient sedimentary environments.

"Applied Sedimentology" is written principally for postgraduate and senior undergraduate students of geology, mining and petroleum engineering. I also hope, however, that it may prove useful to more mature geologists who explore and exploit the sedimentary rocks for fossil fuels and mineral deposits.

*Imperial College* R. C. Selley
*January 1988*

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My colleagues in the petroleum, mining and sedimentology sections of the Geology Department of Imperial College aided the production of this book in many ways. They supplied photographs and specimens for photography, read sections of the manuscript and, for many years, discussed with me the applications of sedimentology to petroleum and mineral exploration.

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# 1 Introduction

## 1. INTRODUCTION AND HISTORICAL REVIEW

The term *sedimentology* was defined by Wadell (1932) as "the study of sediments". *Sediments* have been defined as "what settles at the bottom of a liquid: dregs: a deposit" (Chambers Dictionary, 1972 edition). Neither definition is wholly satisfactory. Sedimentology is generally deemed to embrace chemical precipitates, like salt, as well as true detrital deposits. Sedimentation takes place not only in liquids, but also in gaseous fluids, such as eolian environments. The boundaries of sedimentology are thus pleasantly diffuse.

The purpose of this chapter is twofold. It begins by introducing the field of sedimentology and placing it within its geological context, and within the broader fields of physics, chemistry and biology. The second part of the chapter introduces the applications of sedimentology in the service of mankind; showing in particular how it may be applied in the quest for fossil fuels and strata-bound minerals.

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 B.C. (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 what were then called 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 are thick sequences of flysch facies deposited in geosynclines?". It was modern oceanography which provided the turbidity current as a possible mechanism (see p. 89). 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 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. 246).

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

Through the 1960s the main focus of research was directed towards an understanding of sedimentary processes. By studying the bedforms and depositional structures of recent sediments, either in laboratory flumes or in the wild, it became possible to interpret accurately the environment of ancient sedimentary rocks (Laporte, 1979; Selley, 1985a; Reading, 1978).

Through the 1970s the emphasis of sedimentological research gradually changed from the macroscopic and physical to the microscopic and chemical. Improved analytical techniques and the application of cathodoluminescence and scanning electron microscopy gathered new data which could be interpreted with a better understanding of geochemistry.

This renaissance of petrography has enhanced our understanding of the relationship between diagenesis, pore fluids and their effects on the evolution of porosity and permeability in sandstones and carbonates. Similarly, we are now beginning to understand the relationships between clay mineral diagenesis and the maturation of organic matter in hydrocarbon source beds.

Today a distinction is often made between macrosedimentology and microsedimentology. Macrosedimentology ranges from the study of sedimentary facies down to sedimentary structures. Microsedimentology covers the study of sedimentary rocks on a microscopic scale, what was often termed petrography.

## II. SEDIMENTOLOGY AND THE EARTH SCIENCES

Figure 1.1 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.

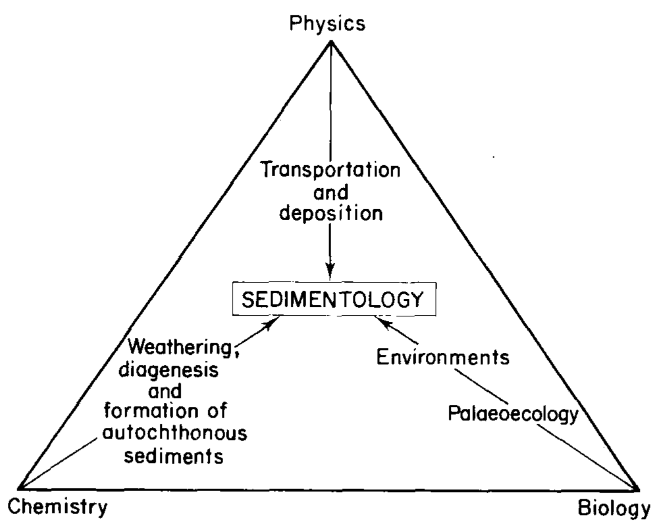


Fig. 1.1. Triangular diagram to show the relationship between sedimentology and the fundamental sciences.

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.

Environmental analysis is the determination of the depositional environment of a sediment (Selley, 1985a).

Our review of sedimentology has now moved from the biological aspect to those facets which involve biological, physical and chemical properties of sedimentary rocks. To determine the depositional environment of a rock it is obviously important to identify correctly 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 predepositional 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 of 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.

Referring again to Fig. 1.1 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 demonstrate continuously how much sedimentology is based on the fundamental sciences of biology, physics and chemistry.

## III. APPLIED SEDIMENTOLOGY

Sedimentology may be studied as a subject in its own right, arcane and academic; an end in itself. On the other hand, sedimentology has a contribution to make to the exploitation of natural resources and to the way in which man manipulates the environment. This book has been written primarily for the reader who is, or intends to be, an industrial geologist. It is not designed for the aspiring academic. It is relevant, therefore, to consider the applications of sedimentology. Table 1.1 documents some of the applications of sedimentology. Specific instances and applications will be discussed throughout the book.

Most of the intellectual and financial stimulus to sedimentology has come from the oil industry, and, to a lesser extent, the mining industry. The applications of sedimentology in these fields will be examined in some detail to indicate the reasons for this fact.

First, however, some of the other uses of sedimentology will briefly be reviewed.

The emphasis throughout this book is on sedimentology and its relationship to ancient lithified sedimentary rocks. It is important to note, however, that a large part of sedimentology is concerned with modern sediments and depositional processes. This is not just to better interpret ancient sedimentary rocks. These studies are of vital importance in the manipulation of our environment (Knill, 1970). For example, the construction of modern coastal erosion defences, quays, harbours and submarine pipelines all require detailed site investigation. These investigations include the study of the regime of wind, waves and tides and of the physical properties of the bedrock. Such studies also include an analysis of the present path and rate of movement of sediment across the site and the prediction of how these will alter when the construction work is completed. It is well known how the construction of a single pier may act as a trap for longshore drifting sediment, causing coastal erosion on one side and beach accretion on the other.

Table 1.1
Illustrative of some of the applications of sedimentology

| | | Application | Related fields |
|---|---|---|---|
| I. Environmental | | Sea-bed structures<br>Pipelines<br>Coastal erosion defences<br>Quays, jetties and harbours | Oceanography |
| | | Opencast excavations and tunnelling | Identification of nuclear waste sites<br>Engineering geology |
| | | Foundations for motorways<br>Airstrips and tower blocks | Soil mechanics and rock mechanics |
| II. Extractive | A. Whole rock removed | Sand and gravel aggregates<br>Clays<br>Limestones | Quarrying |
| | | Coal<br>Phosphate<br>Evaporites<br>Sedimentary ores | Mining geology |
| | B. Pore fluid removed | Water | Hydrology |
| | | Oil<br>Gas | Petroleum geology |

Turning inland, studies of modern fluvial processes have many important applications. The work of the US Army Corps of Engineers in attempting to prevent the Mississippi from meandering is an example. Studies of fluvial channel stability, flood frequency and flood control are an integral part of any land utilization plan or town development scheme.

Engineering geology is another field in which sedimentology may be applied. In this case, however, most of the applications are concerned with the physical properties of sediments once they have been deposited and their response to drainage or to the stresses of foundations for dams, motorways or large buildings. These topics fall under the disciplines of soil mechanics and rock mechanics.

Thus before proceeding to examine the applications of sedimentology to the study of ancient sedimentary rocks, the previous section demonstrates some of its many applications in environmental problems concerning recent sediments and sedimentary processes.

Most applications of sedimentology to ancient sedimentary rocks are concerned with the extraction of raw materials. These fall into two main groups: the extraction of certain strata of sediment, and the extraction of fluids or gases from pores, leaving the strata intact.

There are many different kinds of sedimentary rock which are of economic value.

These include recent unconsolidated sands and gravels which are useful in the construction industry. Their effective and economic exploitation requires accurate definition of their physical properties such as size, shape and sorting, as well as the volume and geometry of individual bodies of potentially valuable sediment. Thus in the extraction of river gravels it is necessary to map the distribution of the body to be worked, be it a palaeochannel or an old terrace, and to locate any ox-bow lake clay plugs which may diminish the calculated reserves of the whole deposit.

Similarly, consolidated sandstones have many uses as aggregate and building stones. Clays have diverse applications and according to their composition may be used for bricks, pottery, drilling mud and so forth. Limestones are important in the manufacture of cement, fertilizer and as a flux in the smelting of iron. The use of all these sedimentary rocks involves two basic problems. The first is to determine whether or not the rock conforms to the physical and chemical specifications required for a particular purpose. This involves petrography and geochemistry. The second problem is to predict the geometry and hence calculate the bulk reserves of the economic rock body. This involves sedimentology and stratigraphy. Here geology mingles with problems of quarrying, engineering and transportation. Geology is nevertheless of extreme importance. It is no use building a brand new cement works next to a limestone crag if, when quarrying commences, it is discovered that the limestone is not a continuous formation, but a reef of local extent.

Coal is another sedimentary rock of vital importance to the energy budget of most modern industrial countries. Coal technology is itself a major field of study with its own text books (cited on p. 369). Like the other economic sedimentary rocks coal mining hinges on two basic geological problems: quality and quantity. The quality of the coal is determined by specialized petrographic and chemical techniques. The quantitative aspects of coal mining involves both problems of structural geology and mining engineering as well as careful facies analysis. Classic examples of ancient coal-bearing deltaic rocks have been documented in the literature (e.g. the Circulars of the Illinois State Geological Survey). These studies have been made possible by a combination of closely spaced core holes and data from modern deltaic sediments.

Using this information, facies analysis can delineate the optimum stratigraphic and geographic extent of coal-bearing facies. Detailed environmental studies can then be used to map the distribution of individual coal seams. Coal can form in various deltaic subenvironments, such as interdistributary bays, within, or on the crests of channel sands, as well as regionally uniform beds. The coals which form in these various subenvironments may be different both in composition and areal geometry.

Evaporite deposits are another sedimentary rock of great economic importance, forming the basis for chemical industries in many parts of the world. The main evaporite minerals, by bulk, are gypsum ($CaSO_4.2H_2O$) and halite (NaCl). Many other salts are rarer but of equal or greater economic importance. These include carbonates, chlorides and sulphates. The genesis of evaporite deposits has been extensively studied both in nature and experimentally in the laboratory. The study of evaporites is important, not just because of the economic value of the minerals, but because of the close relationship between evaporites and petroleum deposits (Buzzalini *et al.*, 1969).

Turning now from the applications of sedimentology in the extraction of rock *en masse*, let us consider those uses where only the pore fluids are sought and removed.

The world shortage of potable water may soon become as important as the energy