# Clay Sedimentology

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With 243 Figures and 65 Tables

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*To Marie, my wife,*
*and to Camille, Noëlle and Vincent, my children,*
*who shared much more than expected the efforts*
*linked to the redaction of this book*

# Preface

## 1. Purpose

Clay is the dust of the Earth. Clay sedimentology deals with the composition, properties and significance of the argillaceous fraction of recent and ancient sediments. Clay minerals represent the most ubiquitous components of all sediments, from desert or beach sands and sandstones to deep-sea oozes and muds. Clays constitute a dominant percentage of some of the most common sedimentary rocks such as mudstones, shales, and marls, from Proterozoic to Cenozoic age.

Surprisingly, textbooks devoted to clay minerals in natural environments are rare. The most known work is "Géologie des Argiles" translated as "Geology of Clays" by G. Millot (1964, 1970). Millot's book constitutes an invaluable reference that is still largely used and quoted. One may envisage various explanations to the scarcity of geologic books about clays: the relatively small number of clay mineral families, that can hardly be thought of as reflecting the very diverse natural environments, the difficulty for geologists to easily memorize the complex clay structures and to handle devices which usually belong to physicists and chemists, or the fact that clay just looks like a dirty, earthy, and unattractive stuff. Whatever the reason, here is a book that tries to present some information on "Clay Sedimentology" to the patient reader.

One of the main points of interest in writing a textbook is to summarize data that are published in various research papers on a given subject, and therefore to tend toward a relatively objective and dispassionate document. As far as clays in sediments are concerned, it is in addition particularly exciting to put together information arising from European, North-American, and other laboratories, whose respective ways of reasoning sometimes differ.

## 2. Bibliographic Data

The literature on sedimentary clays is immense. The development during the few past decades of new geochemical and microscopic devices, applied problems on the argillaceous fractions from soils and rocks, and mineralogical sections in numerous geological departments, has determined a staggering increase of publications. For example, Volume 50 of "Bibliography and Index of Geology", compiled for the year 1986 by the American Geological Institute Compilation, reports a total of 1110 references under the topic "Clay Mineralogy", covering areal and experimental studies, mineral data and theoretical studies. Under the same title 117 references are quoted in the issue of June 1987. It is, of course, very difficult and tiresome to read and synthetize such a huge bibliography, which itself is necessarily incomplete. In addition, to summarize such an extensive literature would result in an indigestible catalog. For this reason I have tried to present selected examples of the available data, by combining classical and most recent studies. G. Millot's book (1964, 1970) is considered as a basic document, to which the reader is often referred.

One should add that the different topics covering the sedimentology of clay sometimes correlate to a very uneven number of references. Bibliographic data on well-debated subjects like clays in soils and in estuaries, or on applied problems such as the clay evolution in sandstones are countless; by contrast, accurate references on less-common subjects such as the early to middle diagenetic evolution, or the transition from detrital supply to authigenesis are fairly rare. "Clay Sedimentology" attempts to give a basic idea on most topics dealing with sedimentary clays, and to present the uncertainties due to the frontiers of knowledge.

## 3. Contents

"Clay Sedimentology" is divided into six parts, each of them containing two to five chapters. The successive topics considered are the following:

- Part I. Clay minerals and weathering, covering a short recall on the main natural minerals, and a summary of clay formation during land- alteration processes.
- Part II. Clay sedimentation on land, from deserts, glaciers, and rivers, to lakes of various chemical types.
- Part III. Origin and behavior of clay minerals and associated minerals in transitional environments such as estuaries and deltas, influence of sorting in sea water and of aeolian supply, and importance of the recent terrigenous input within the sea.
- Part IV. Genesis of clay in the marine environment, before appreciable burial of sediment has taken place: alkaline-evaporative deposits, ferriferous clay granules, organic sediments, metalliferous deep-sea clays and volcano-hydrothermal deposits.
- Part V. Post-sedimentary processes intervening during early and late diagenesis, or controlled by tectonic, lithologic or hydrothermal factors.
- Part VI. Use of clay stratigraphic data for the reconstruction of past climate, marine circulation, tectonics, and other paleogeographical characters, supplemented by an overview on the transition from the paleoenvironmental to diagenetic expression of clay associations considered from a geodynamical viewpoint.

It is sometimes difficult to make a choice between different methodological or scientific approaches. For instance, I have chosen to generally follow a classical distinction between single clay minerals and random mixed-layers, rather than to apply a statistical classification based on continuously transitional terms between smectite and illite (calculation of the mixed- layering rate); in fact, the former classification seems often more convenient for designating clay associations devoid of burial modifications, is more widely used and quoted, and often allows better characterization and understanding of complex natural assemblages. The term diagenesis is employed in its most frequent European meaning, and designates processes occurring after the sediment is appreciably buried and protected from exchanges with the open-sea water (Part Four). As some very different environments, such as terrigenous deposits and deeply buried sediments, may contain the same clay minerals (e.g., illite and chlorite), and symmetrically as a given environment may include very distinct clay minerals (e.g., metalliferous clays with either terrigenous, hydrogenous, volcanogenic, or hydrothermal species), it is sometimes necessary to choose a type of presentation, and to make some cross-references or repetitions. In a didactic aim, I have deliberately chosen to put in distinct chapters some data on allochthonous and autochthonous processes, although they may jointly occur in the same sediments; the last chapter provides some indications on combined processes, and the conclusion of each chapter tries to integrate a summary of results as well as general, somewhat critical considerations. Finally, some topics are only briefly considered, since they belong to disciplines adjacent to clay sedimentology, or are extensively covered by high-quality books; this is the case with the structure and classification of clay minerals, the weathering processes and associated clay formation, and the diagenesis due to depth of burial. I apologize for the disagreements induced by these drawbacks in the presentation and contents. "Clay Sedimentology" is a textbook written by a geologist for geologists or for people interested in clay, and could severely disappoint some mineralogists, crystallographers, and geochemists.

## 4. A Few Lessons

Some general considerations arise from the present state of research on the sedimentology of clays. First, the understanding of the significance of clay-mineral successions greatly benefits from data on the geological and sedimentological context, on the detailed chemical and morphological nature of individual particles, and on logging and modeling experiments.

Much progress is expected from the systematic analysis of the clay fraction from the diverse lithologic types that constitute a sedimentary pile. To concentrate the investigations only on the clay-rich facies greatly diminishes the interest of clay stratigraphic investigations.

A great deal of new information results from investigations on the materials sampled during the Deep Sea Drilling Project and the Ocean Drilling Program. The clay sedimentology of submarine series is frequently better known than that of exposed or land-borehole sections. A continuous effort of research has to be pursued on exposed series from Proterozoic to Cenozoic ages, as well as on transects extending from continental to deep- sea sedimentary facies.

Some common mistakes or improper conclusions should be fought patiently and replaced by up-to-date information, knowing humbly that today's evidence can change tomorrow into crude errors due to technical or scientific improvements. For instance, smectite is not systematically of volcanic origin in marine sediments and may have various sources, including geologic and pedogenic continental sources. Palygorskite and sepiolite do not systematically form in sediments where they are identified, and can be reworked by wind or water from distant soils or chemical sediments. Kaolinite does not exclusively derive from laterite-type soils, and may issue from various other weathering profiles or ancient sediments. The formation of iron-rich granules of the glaucony type does not necessitate a hot climate. The deep-sea red clays do not automatically comprise only hydrogenous or volcano-hydrothermal minerals and may include noticeable land-derived components. The diagenesis linked to depth of burial does not systematically show intermediate mixed-layered terms, and appears to depend noticeably on high temperatures of fairly short duration rather than on moderate pressure over a long time. Numerous transitional situations occur between exclusively detrital series and solely authigenic series, as far as the sedimentary clay fraction is concerned. The time is over to passionately discuss and fight about the either allochthonous or autochthonous character of clay fractions in sediments. It is time to better understand the boundary situations and the kinetic control by pedologic, sedimentary, and diagenetic environments.

Some genetic processes responsible for the formation of clay minerals in past sediments obviously do not exist any longer today; this is the case of the sedimentary precipitation of most fibrous clays and probably of some smectite-rich deposits. By contrast, it is likely that some present-day kinds of clay genesis were very restricted or even lacking during some ancient periods; this is probably the case with illite- and chlorite-rich sediments that abundantly form climatically in peri-glacial regions, and were hardly deposited during warm Mesozoic times. One should therefore be cautious in applying some present-day data to ancient sediments.

Finally clay-stratigraphy data appear to represent a useful tool in understanding the control of successive internal and surficial geodynamical factors on the large-scale history of a sedimentary basin subject to plate-tectonic constraints.

## 5. Acknowledgements

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Clay families are approximately as numerous as the notes of the musical scale. The mixed-layers and other transitional minerals may be compared to accidentals in music. There is a huge diversity of clay mineral assemblages in natural environments. Knowing the great variety of musical works of art that man has produced in a few thousand years, it is easy to understand the extraordinary variety and the numerous sequences of argillaceous environments that nature has built in the sedimentary record over a few billion years.

Villeneuve d'Ascq, April 1989 Hervé Chamley

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# Part I

# Clay Minerals and Weathering

## Chapter 1

# Clay Minerals

## 1.1 Introduction

Clay minerals consist of *hydrous layer silicates* that constitute a large part of the family of phyllosilicates. Clay minerals are particularly abundant in clayey oozes, claystones, mud, mudstones, shales, and argillites, a group of fine-grained rocks called physil rocks by Weaver (1980). Clay minerals also occur in virtually all other types of soft and hard sedimentary rocks, including coarse silicoclastites and saline evaporites. This explains the increased interest on the part of sedimentologists in studying these minerals.

We begin with a short summary of the structure, composition, and classification of clay minerals. This will allow the inclusion of some basic data, and the definition of the technical terms used in the following chapters.

Detailed information on clay mineralogy and chemistry is provided notably by Grim (1968), Weaver and Pollard (1973), Dixon and Weed (1977), Van Olphen and Fripiat (1979), Brindley and Brown (1980), Caillère et al. (1982), Velde (1985), whose data are extensively used in this chapter.

## 1.2 Clay Structure

Clay crystals fundamentally consist of silicon, aluminum or magnesium, oxygen, and hydroxyl (OH), with various associate cations according to the species. These ions and OH groups are organized into two-dimensional structures of two types, called *sheets*. (1) *The tetrahedral sheets* have a general composition $T_2O_5$ ($T$ = tetrahedral cation; mainly Si, with varying Al or $Fe^{3+}$ content). Silicon is located at the center of the tetrahedra, oxygen anions form the four corners. The individual tetrahedra are connected with adjacent tetrahedra by sharing three corners (the three basal oxygens), constituting a hexagonal mesh arrangement (Fig. 1.1A). The fourth tetrahedral corner points in a direction normal to the sheet. Its oxygen (the apical oxygen) forms part of the *octahedral sheet*. (2).*The octahedral sheets* comprise medium-sized cations at their center (usually Al, Mg, $Fe^{2+}$, or $Fe^{3+}$), and oxygens at the eight corners. The individual octahedra are linked laterally with the neighboring octahedra (Fig. 1.1B), and vertically with the tetrahedra,by sharing oxygens. The smallest structural unit of the octahedral sheet contains three octahedra. If all three octahedra have octahedral cations at