

Clay Sedimentology

Hervé Chamley





Hervé Chamley

Clay Sedimentology

With 243 Figures and 65 Tables

Springer-Verlag Berlin Heidelberg GmbH

Prof. Dr. Hervé Chamley

University of Lille I
F-59655 Villeneuve d'Ascq

University of Paris VI
F-75252 Paris cedex 05

ISBN 978-3-642-85918-2 ISBN 978-3-642-85916-8 (eBook)
DOI 10.1007/978-3-642-85916-8

Library of Congress Cataloging-in-Publication Data

Chamley, Hervé. Clay sedimentology/Hervé Chamley. p. cm. Bibliography: p. Includes index.
1. Clay minerals. I. Title. QE389.625.C47 1989 549'.6-dc20

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, re-use of illustrations, recitation, broadcasting, reproduction on microfilms or in other ways, and storage in data banks. Duplication of this publication or parts thereof is only permitted under the provisions of the German Copyright Law of September 9, 1965, in its version of June 24, 1985, and a copyright fee must always be paid. Violations fall under the prosecution act of the German Copyright Law.

© Springer-Verlag Berlin Heidelberg 1989

Originally published by Springer-Verlag Berlin Heidelberg New York in 1989.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Product Liability: The publisher can give no guarantee for information about drug dosage and application thereof contained in this book. In every individual case the respective user must check its accuracy by consulting other pharmaceutical literature.

2132/3145-543210 Printed on acid-free paper

*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 synthesize 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

I have benefited by fruitful scientific discussions with numerous colleagues during my search on clay sedimentology the last 20 years, as well as during the writing of this book. I would especially like to mention, among others, Pierre E. Biscaye, Jean Blanc and Laure Blanc-Vernet, Chantal Bonnot-Courtois, Anne Bouquillon, Jean-Paul Cadet, Norbert Clauer, Pierre Debrabant, Jean-François

Deconinck, Alain Desprairies, Liselotte Diester-Haass, Gilbert Dunoyer de Segonzac, Claude Froget, Michel Hoffert, Thierry Holtzapffel, Glenn A. Jones, James P. Kennett, Claude Latouche, Margaret Leinen, Jacques Lucas, Frédéric Mélières, Georges Millot, André Monaco, Gilles S. Odin, Hélène Paquet, Léo Pastouret, Christian Robert, Michel Steinberg, François Thiébault, Norbert Trauth, Colette Vergnaud-Grazzini. Efficient and high-level technical support was provided at Lille University for the achievement of the book, notably by Martyne Bocquet, Jean Carpentier, Jean-Claude Deremaux, Françoise Dujardin and Philippe Récourt. "Clay Sedimentology" is dedicated to Professor Georges Millot, who was my first teacher in geology, and an exceptional specialist in the geology of clays.

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

Table of Contents

PART I Clay Minerals and Weathering

Chapter 1 Clay Minerals	
1.1	Introduction 3
1.2	Clay Structure 3
1.3	Main Clay Minerals 6
1.3.1	Main Divisions 6
1.3.2	Kaolin-Serpentine Group 7
1.3.3	Pyrophyllite-Talc Group 8
1.3.4	Mica Group 8
1.3.5	Brittle Mica Group 12
1.3.6	Vermiculite Group 13
1.3.7	Smectite Group 13
1.3.8	Chlorite Group 14
1.3.9	Palygorskite-Sepiolite Group 15
1.3.10	Mixed Layers 16
1.4	Main Associated Non-Clay Species 18
1.5	Conclusion 19
Chapter 2 Clay Formation through Weathering	
2.1	Main Weathering Processes 21
2.1.1	Introduction 21
2.1.2	Hydrolysis 22
2.2	Main Soils and Clay Content 26
2.2.1	Zonal Soils 26
	Parallel Change of Temperature and Humidity 26
	Antagonistic Change of Temperature and Humidity 32
	General Distribution of Zonal Soil Clays 37
2.2.2	Azonal Soils 37
	Halomorphic Soils 37
	Hydromorphic Soils 38
	Volcanic Environments 38
	Epeirogenic Environments 41
2.2.3	Paleosols and Clay Content 41
	Quaternary 42
	Tertiary 43

	Mesozoic	46
	Paleozoic, Precambrian	48
2.3	Conclusion	49
<hr/>		
	PART II Clay Sedimentation on Land	
<hr/>		
	Chapter 3 Deserts, Glaciers, Rivers	
3.1	Deserts	53
	3.1.1 Desert Dusts	53
	3.1.2 Aeolian Sediments	56
3.2	Glaciers	58
	3.2.1 Origin of Glacial Clays	58
	3.2.2 Paleoenvironmental Applications	59
3.3	Rivers	61
	3.3.1 Origin of River Clays	61
	3.3.2 River suspended minerals	64
	3.3.3 Environmental Applications	66
3.4	Conclusion	72
<hr/>		
	Chapter 4 Lacustrine Clay Sedimentation	
4.1	Freshwater Lakes	75
	4.1.1 Detrital Supply	75
	4.1.2 Authigenic Clays	79
	Biosiliceous Environment	79
	Iron-Clay Granules	79
	Volcanic Environment	79
4.2	Saline Lakes	80
	4.2.1 General Data	80
	Introduction	80
	Saline Minerals	81
	Volcanic Environment	83
	Detrital Clays in Saline Nonvolcanic Lakes	84
	4.2.2 Authigenic Clay in Recent Saline Lakes	86
	Ferriferous and Magnesian Environment	86
	Volcanic Environment	89
	Biosiliceous Environment	92
	4.2.3 Fibrous Clays in Lacustrine Environment	92
4.3	Conclusion	93
<hr/>		
	PART III From Land to Sea	
<hr/>		
	Chapter 5 Estuaries and Deltas	
5.1	First Studies on Estuarine Clays	97
5.2	Estuarine Clays and Continental Sources	101
5.3	Mechanisms of Clay Distribution	103

5.3.1	Differential Settling and Flocculation	103
5.3.2	Mixing of Water Masses	107
5.3.3	Marine Transgression	111
5.3.4	Cation Exchange and Chemical Modification	114
5.4	Conclusion	115

Chapter 6 Clay Sorting and Settling in the Ocean

6.1	Introduction	117
6.2	Differential Settling	118
6.2.1	Recent Sediments	118
6.2.2	Ancient Sediments	122
6.2.3	Mechanisms	124
6.3	Particle Aggregation and Advection	127
6.4	Conclusion	130

Chapter 7 Aeolian Input

7.1	Wind Transport over the Ocean	133
7.1.1	Evidence of Dust Supply	133
7.1.2	Characterization of Aeolian Dust	134
7.1.3	Importance of Aeolian Input	136
7.2	Identification of Aeolian Minerals in the Oceans	139
7.2.1	Mineral Composition of Aeolian Dust	139
7.2.2	Comparison of Aeolian Dust and Surface Sediments	142
7.3	Distribution of Aeolian Sediments	146
7.4	Aeolian Influence in Past Marine Sedimentation	152
7.4.1	Quaternary	152
7.4.2	Pre-Quaternary	155
7.5	Conclusion	159

Chapter 8 Terrigenous Supply in the Ocean

8.1	Climatic Control	163
8.1.1	Distribution of Kaolinite and Chlorite	163
8.1.2	Other Clay Minerals	167
8.2	Petrographic Control	171
8.2.1	Polar Regions	171
8.2.2	Arid Regions	173
8.2.3	Recognition of Volcanic Sources	174
8.2.4	Mixed Geologic and Pedologic Sources	176
8.3	Hydrodynamic Control	180
8.3.1	Offshore Currents	181
8.3.2	Resedimentation Processes	183
8.4	Combination of Terrigenous Supply and Transportation Agents	185
8.5	Conclusion	190

PART IV Clay Genesis in the Sea

Chapter 9 Alkaline, Evaporative Environment

9.1	General Features	195
9.2	Evaporative Clay Sedimentation, Paleogene in France	197
9.2.1	Basin of Paris	197
9.2.2	Southeastern France	200
9.2.3	Geochemical Implications	204
9.3	Other Marine Environments	205
9.3.1	Early Miocene in Southeastern United States	205
9.3.2	Uppermost Miocene, Mediterranean Sea	208
9.3.3	Illitization by Wetting and Drying	209
9.4	Conclusion	211

Chapter 10 Ferriferous Clay Granules and Facies

10.1	General Features	213
10.2	Nature and Distribution of Recent Green Clay Granules	216
10.2.1	Habits	216
10.2.2	Zonal and Bathymetric Distribution	218
10.3	Genesis of Green Clay Granules	222
10.4	Greensands, Ironstones	227
10.5	Celadonite Facies	230
10.6	Conclusion	232

Chapter 11 Organic Environment

11.1	Influence of Organic Activity on Clay	235
11.2	Late Cenozoic Sapropels, Mediterranean Sea	238
11.2.1	Sapropel Characters and Environment	238
11.2.2	Clay Evolution	242
11.3	Cretaceous Black Shales, Atlantic Domain	251
11.3.1	Black Shale Environment	251
11.3.2	Clay Sedimentation	255
11.4	Conclusion	257

Chapter 12 Metalliferous Clay in Deep Sea

12.1	Deep-sea Clay Environment	259
12.1.1	Introduction	259
12.1.2	Metalliferous Nodules	261
12.1.3	Allochthonous Versus Autochthonous Origin	262
12.2	Smectite Formation	265
12.2.1	Preliminary Data	265
12.2.2	Domes Area, Northeast Pacific	266
12.2.3	Central South-Equatorial Pacific	267
12.2.4	Nazca Plate	270
	Geochemistry of Surface Sediments	270
	Clay Mineralogy of Surface Sediments	272
	Mineralogy and Geochemistry, Northeast Nazca basin	273

	Mineralogy and Geochemistry, Bauer Deep	274
12.3	Fibrous Clay in Deep-Sea Sediments	276
12.4	Transitional Environments	279
	12.4.1 Pacific Ocean	279
	12.4.2 Indian Ocean	282
12.5	Ancient Deep-Sea Metalliferous Clays	284
12.6	Conclusion	287

Chapter 13 Hydrothermal Environment

13.1	Submarine Alteration of Volcanic Rocks	291
	13.1.1 Low-Temperature Alteration	291
	Basaltic Glass	292
	Crystalline Basalts	293
	Silicic Glass	296
	13.1.2 High-Temperature Alteration	297
13.2	Basalt Intrusion in Sediment	299
13.3	Hydrothermal Deposits	302
	13.3.1 Main Precipitates	302
	13.3.2 Pacific Ocean	304
	East Pacific Ridge	304
	Galapagos Rift Mounds	305
	Southwest Pacific	308
	13.3.3 Mid-Atlantic Ridge	310
	13.3.4 Red Sea	312
	13.3.5 Old Hydrothermal Deposits	316
13.4	Palygorskite and Sepiolite Deposits	317
13.5	Sedimentary Impact of Volcano-Hydrothermalism	320
	13.5.1 Lateral Extension	320
	13.5.2 Vertical Extension	323
	13.5.3 Authigenic Formation and reworking	325
13.6	Conclusion	325

PART V Clay Diagenesis

Chapter 14 Early Processes

14.1	Introduction	333
14.2	Smectite and Early Diagenesis	336
	14.2.1 General Features	336
	14.2.2 Lathed Smectites, Clay Mineral Overgrowths	343
	Atlantic Ocean	345
	Indian Ocean	349
14.3	Specific Environment	350
	Early Effects of Burial	350
	Chlorite, Palygorskite Formation	351
	Diagenesis in Slightly Buried Volcaniclastic Sediments	352
14.4	Conclusion	357

Chapter 15 Depth of Burial	
15.1	Basic Evolution 359
15.1.1	Introduction 359
15.1.2	An Example: Gulf of Mexico Coast Sediments 361
15.1.3	Other Cases 364
15.2	Mechanisms of Evolution 370
15.2.1	Open Versus Closed Systems 370
15.2.2	Transformation Versus Dissolution – Precipitation . . . 372
	Illitization 372
	Chloritization, Kaolinization 379
15.3	Modification of Physical Properties 380
15.3.1	Compaction 380
15.3.2	Application to Oil Exploration 382
15.4	Conclusion 386

Chapter 16 Tectonic, Lithologic and Hydrothermal Constraints	
16.1	Diagenesis through Tectonics 391
16.1.1	Lateral Effects 391
16.1.2	Tectonic Overburden 394
16.2	Chemically-Restricted Environment 395
	Deeply Buried Smectite 395
	Limestone – Marl Alternations 397
16.3	Highly-Porous Rocks 398
16.3.1	Introduction 398
16.3.2	Diagenetic Clay Minerals in Sandstones 399
16.3.3	Diagenetic Processes and History 402
16.3.4	Clay Diagenesis and Reservoir Properties 408
16.4	Volcanic Environment 409
16.4.1	Igneous Rock Accumulations 409
16.4.2	Bentonites, Tonsteins 411
16.5	Hydrothermal Environment 414
	Introduction 414
	Vein-Filling and Wall-Rock Minerals 415
	Vein-Filling Clay Sequences 416
	Massive Alteration 418
16.6	Conclusion 420

PART VI Clay Stratigraphy and Paleoenvironment

Chapter 17 Paleoclimate Expression	
17.1	Bases and Conditions 425
17.1.1	Fundamentals 425
17.1.2	Conditions of Application 429
17.2	Late Quaternary 432
17.2.1	Direct Climatic Expression 432
17.2.2	Indirect Effects 436

17.3	Cenozoic	441
17.3.1	Atlantic Ocean	441
17.3.2	Other Oceans	445
17.3.3	Mediterranean Sea	448
	Pliocene, Pleistocene	448
	Messinian	450
17.4	Pre-Cenozoic	452
	Middle-Late Mesozoic	452
	Limestone-Marl Alternations	453
	Pre-Jurassic	454
17.5	Conclusion	455

Chapter 18 Paleocirculation and Tectonics

18.1	Identification of Sources	459
18.2	Paleocurrents and Resedimentation	462
	18.2.1 Introduction	462
	18.2.2 Mediterranean Sea	464
	18.2.3 Southern Ocean	467
18.3	Tectonic Control	470
	18.3.1 An Example: The Pliocene of South Sicily	470
	18.3.2 Applications	473
	Mediterranean Range, Late Cenozoic	473
	New-Zealand Region, Cenozoic	474
	North Atlantic Domain, Late Mesozoic	476
	Other Regions	477
	18.3.3 General Expression of Tectonic Activity by Clay	478
18.4	Conclusion	483

Chapter 19 Paleoenvironmental Reconstruction

19.1	Chronological Evolution of Hatteras and Cape Verde basins	487
	19.1.1 Introduction	487
	19.1.2 Major Similarities	490
	19.1.3 Major Differences	493
19.2	Paleogeographic Evolution of Atlantic Regions	496
	19.2.1 North Atlantic Basins at Albian Time	496
	19.2.2 North Atlantic Ocean, Cretaceous Times	500
	19.2.3 South Atlantic Ocean	502
	19.2.4 Adjacent Regions	505
19.3	Specific Paleoenvironmental Successions	507
	19.3.1 Intraplate Volcanic Environment, Late Cretaceous of the Mariana Basin	507
	19.3.2 Tectono-Eustatic Environment, Late Miocene of Sicily	513
	19.3.3 Cretaceous-Tertiary Transition	518
	Large-Scale Studies	518
	Cretaceous-Tertiary Boundary Layer	521
19.4	Conclusion	524

Chapter 20 Clay and Geodynamics	
20.1	Diverse Significance of Sedimentary Clay Assemblages 527
20.2	Cenozoic Clay Sedimentation in the North Pacific Ocean 530
20.3	Late Mesozoic Clay Sedimentation in the Eastern Atlantic and Western Tethyan Domains 533
20.3.1	Comparison between Cape Verde and Senegal Basins 533
20.3.2	Generalization to Atlantic and Tethyan Domains 543
20.4	Late Tertiary Clay Sedimentation in the Tyrrhenian Domain, Western Mediterranean Basin 545
20.4.1	Western Tyrrhenian Sea 545
20.4.2	Comparison with the Senegal Basin 550
20.4.3	Regional Comparisons 553
	Clay Sedimentation on the Sardinian Margin 553
	Comparison with Sicily 555
	Significance of Chloritic Minerals in the Tyrrhenian Sea 558
20.5	Conclusion 560
References 563	
Subject Index 621	

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