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Long-term trends in clay deposition in the ocean

Clay
Paleoenvironment
Meso/Cenozoic
Sediments
Terrigenous supply

Argile
Paléoenvironnement
Méso/Cénozoïque
Sédiments
Héritage

H. Chamley
Sédimentologie et Géochimie, Équipe de Recherche Associée 764, Université de Lille 1, 59655 Villeneuve d'Ascq Cedex, France.

ABSTRACT

Results are presented on recent investigations about the paleoenvironmental signification of Mesozoic and Cenozoic clay successions, recovered in marginal areas of Atlantic and North-West Pacific Oceans and in the Mediterranean Sea. Chiefly derived from adjacent land-masses, clay assemblages represent useful indicators of major tectonical, climatical, hydrodynamical and morphological events which occurred through time. Examples are chosen in different sedimentary basins, and at different geological periods from late Jurassic to late Quaternary. Results are compared with previous work, in order to emphasize the advantages and limitations of using clay materials to reconstruct the patterns of paleosedimentation.

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RÉSUMÉ

Grandes tendances de la sédimentation argileuse marine.

On présente le point des recherches récentes sur la signification des successions argileuses mésozoïques et cénozoïques déposées dans les milieux détritiques des océans Atlantique et Nord-Ouest Pacifique, ainsi que de la Méditerranée. Les assemblages argileux, principalement terrigènes, représentent des témoins utiles en domaine géodynamique externe des grandes modifications tectoniques, climatiques, courantologiques et morphologiques, survenues notamment sous l'effet des événements majeurs de la géodynamique interne. Des exemples pris dans divers bassins sédimentaires, depuis le Jurassique jusqu'aux époques récentes, permettent de mesurer le chemin parcouru et d'apprécier les limites d'utilisation des argiles dans le cadre général de la sédimentologie dynamique.

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INTRODUCTION

The aim of this paper is to present a short review of one approach to the study of clay minerals deposition, with emphasis on the significance of Mesozoic-Cenozoic clay deposits, in various marine environments where terrigenous supply and low diagenesis predominate. Illustrated by numerous examples, the long-term trends in clay deposition here suggested are based on thousands of mineralogical analyses, as well as complementary lithological and geochemical studies of DSDP material, from the Mediterranean (late Cenozoic), the North and South Atlantic (Mesozoic and Cenozoic), and the North-Western Pacific (Cenozoic). The investigations concern drill sites of Legs 3, 11, 13, 14, 39, 40, 41, 42 A, 44, 47 A and B, 48, 50, 57 and 58, to which the reader may refer for documentation. The references listed in this review are restricted to papers published outside of the Initial Reports of the DSDP.

MAIN FEATURES OF CLAY DEPOSITION

Clay assemblages of recent deep-sea deposits stem largely from terrigenous supply of rock and soil materials (Biscaye, 1965 ; Griffin *et al.*, 1968). This is especially the case in the more narrow oceans and sea-ways, those influenced by large rivers, wind or ice discharge, and/or devoid of deep trenches which form sediment traps. Relevant arguments are given by comparing the average latitudinal zonation of clay minerals abundance in continental soils and in marine sediments, and by showing the relationships existing between main geological provinces and main clay sedimentary provinces (see discussions in Berger, 1974 and Chamley, 1971 ; 1979). Examples are the Atlantic ocean and adjacent seas, North-East Pacific and North Indian Oceans, marginal and back-arc basins in the North-West Pacific, and high latitude seas.

Numerous mineralogical and geochemical studies point to the existence of similar conditions during past geological times in the same areas, especially those where oceans were even narrower or included much more emerged structures than today (e.g. newly rifted Atlantic, aseismic ridges, former island arcs, volcanic archepelagoes : Chamley, 1979 ; Debrabant, Foulon, 1979 ; Maillot, Robert, 1980). A dominance of terrigenous components in most of Mesozoic and Cenozoic deep-sea clays is suggested by the following facts : 1) absence, along most of drill cores, of quasi-continuous clay mineralogical change related to diagenetic modifications with the depth of burial ; 2) occurrence at many drill levels, even very old ones, of diversified clay assemblages similar to the present ones, including typical species from surficial and thermodynamically immature environments (badly crystallized illite and chlorite, irregular mixed-layers, smectite, kaolinite, scattered fibrous clays), and not genetically associated with diagenetic minerals such as opal CT lepispheres or clinoptilolite ; 3) general independence of clay mineralogy and lithology (i.e. calcareous, siliceous, organic facies) ; 4) absence of relationships between smectite and volcanic activity or remains, except in oceanic basalts themselves, and in volcaniclastic sediments whose smectite often results from subaerial alteration and erosion of igneous rocks (Rockall Plateau, Iceland and Norway Seas, Philippine Sea, Afar) ; 5) presence of abundant fragile minerals, such as fibrous clays, in typically reworked sediments (slumps, turbidites, mass-flows : African and European Atlantic margins) (i.e. Weaver, Beck, 1977 ; Chamley, 1979).

As a consequence, the long-term mineralogical trends recorded in DSDP sediments, as well as in offshore and onshore series, do not reflect predominantly *in situ* changes, but largely geochemical changes which primarily occurred on land-masses adjacent to sedimentary basins. The *in situ* changes mostly concern non-clay components of sediments (carbonates, organic matter, siliceous minerals, zeolites, Fe and Mn oxides), or are restricted to local and minor events (Debrabant, Foulon, 1979 ; Maillot, Robert, 1980). Thus it appears that marine clay successions are potential tools in deciphering paleoenvironmental events on land, as expressed by changing pedogenesis, marginal sedimentation, erosion, transport and sedimentation. The main events are of a tectonic, climatic or hydrodynamic nature, and all are linked to morphologic conditions.

TECTONIC EVENTS

The Earth crust movements, and inferred major morphological changes, are expressed by marine clay assemblages in various ways.

— *In a general way* a strong mineralogical contrast exists between periods of tectonic stability and those of tectonic activity. Tectonically quiet periods allow deep weathering and the development of continental soils in equilibrium with local climate. We may assume that during late Mesozoic and part of early Cenozoic, the dominance of pre-alpine low relief favored the pedogenic formation of well-crystallized smectite, as it is the case today in flat and hot downstream areas (Paquet, 1969). In the same way relaxation stages during Cenozoic stages are characterized by moderately altered illite and chlorite, irregular mixed-layers and locally supplied kaolinite. Tectonically active periods cause morphological rejuvenation and hence the erosion of diversified minerals, chiefly issued from rocks and/or upstream soils (i.e. Chamley *et al.*, 1980 ; see Fig. 1).

— *Rifting and ocean opening stages* induce major tectonic activity on continental margins. They are reflected by strong supplies of primary minerals in an environment of continental crust (illite, chlorite, quartz, feldspars, amphiboles : North American basins, Cape Verde (Fig. 1) and other African basins), and by the development of highly crystallized smectite where oceanic volcanic crust predominates (Rockall Plateau, North Philippine Sea, Afar area). Associated minerals point to the instability of marginal land-masses : they consist either of immature pedogenic species such as vermiculite, several types of irregular mixed-layers, degraded smectite (i.e. Cape Hatteras basin during late Jurassic), or species reworked from marginal deposits such as palygorskite (Cat Gap area, East of Florida, at the same time). Just after the basin initiation and above basalt flows, a short period of pelagic clay deposition occurs sometimes, and the distinction between an *in situ* genesis and a tenuous detrital supply is difficult (Shikoku basin, NW Pacific, Leg 58).

— *Main spreading and ocean widening stages* also induce tectonic reactions of continental margins, but generally not as strongly marked by clay assemblages as opening stages. Amounts of primary minerals and associated species (quartz, feldspars) increase temporarily, sometimes together with various pedogenic species according to the paleolatitudes (kaolinite, fibrous clays, mixed-layers). Many examples occur all around the Atlantic Ocean during Cretaceous stages (ex. Fig. 1), North and South basins showing a phase shift due to their independent evolution. The final separation of African and America in late Cretaceous time also produce tectonic activity on the margins of Central Atlantic, reflected by both chemical and mineralogical sedimentary components (Site 367, Cape Verde Basin ; Site 114, Demerara Rise). The high latitude parts of Atlantic Ocean being largely opened a long time before the low latitude ones, the tectonic rejuvenation expressed by detrital minerals shows progressive delays towards the tropical-equatorial zones (from Aptian in Cape Basin to Cenomanian in Nigeria Basin : Chamley, 1979 ; Robert *et al.*, 1979 ; Chamley *et al.*, 1980).

— *Plate movements* responsible for the formation of new marine basins also caused changes in the continental morphology. One of the most characteristic consequence is the formation and the progressive hierarchization of terrestrial river basins linked to the new sedimentary basin. Kaolinite, a mineral chiefly formed in upstream zones of continental landscapes, can espress the morphological development of river basin systems, when it appears for the first time in open marine sediments : if epicontinental barriers such as carbonate platforms do not prevent the transport of this mineral to open sea, the delay existing between the ocean

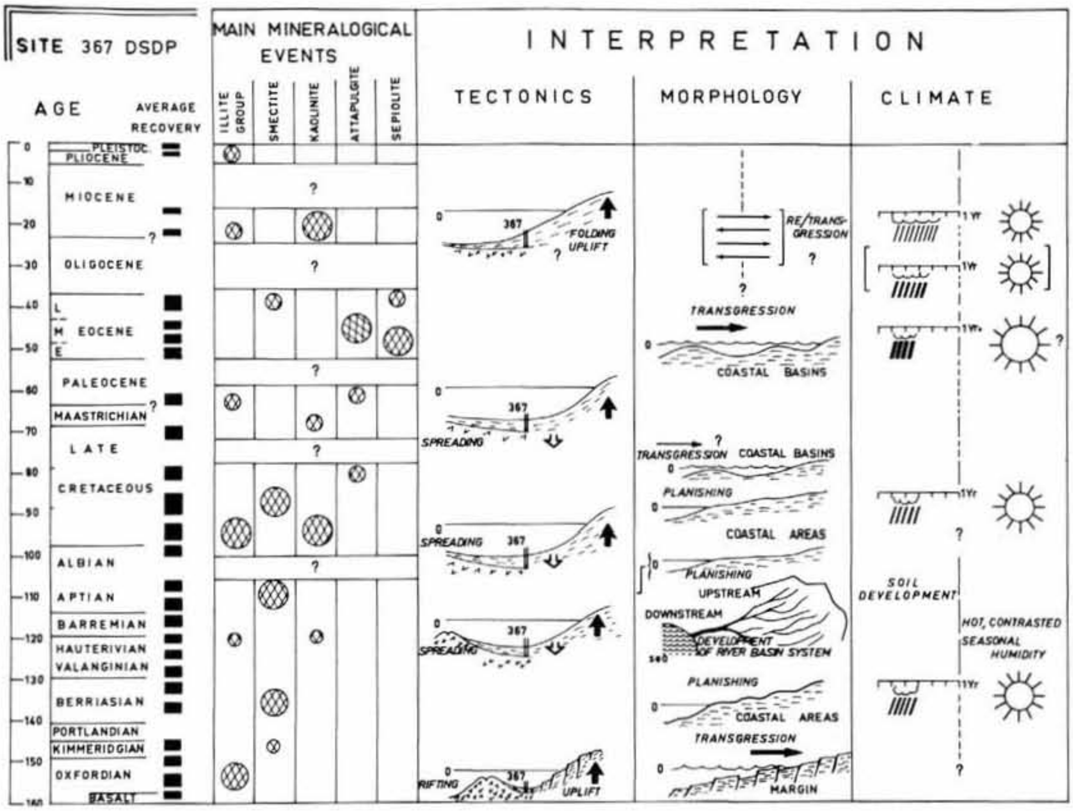

Figure 1

Meso-Cenozoic major mineralogical events in Cape Verde Basin (Site 367, Leg 41 DSDP), and paleoenvironmental implications.
Principaux événements minéralogiques au Méso-Cénozoïque dans le Bassin du Cap-Vert (site 367, Leg 41 DSDP). Implications paléoenvironnementales.

initiation and the first kaolinite occurrence may represent the time requested for shaping a new upstream-downstream morphology on land, linked to the new sedimentary basin (i.e. Sites 367 and 105, Cape Verde and Cape Hatteras Basins ; Chamley *et al.*, 1980 ; see Fig. 1).

— *Uplift and subsidence movements* of aseismic ridges and other submarine barriers control the importance of erosion and of water exchanges, by often reflected detrital clay assemblages. Widely emerged ridges favor strong local erosion and local supply, as for instance in the latest Cretaceous on Rio Grande Rise (Thiede, 1977 ; Robert, 1980 ; see Fig. 2), in the Eocene on Daito Ridge, in the Mio-Pliocene on Kyushu-Palau Ridge (Fig. 3) and on the Eastern Mediterranean Ridge (Fig. 2). The subsidence causes large water exchange and allows transport over long distances, leading to a mineralogical diversification ; examples are in the late Cretaceous of the South Atlantic (Robert *et al.*, 1979), Paleogene of the Rio Grande Rise area (Robert, 1980) late Cenozoic of the Philippine Sea (Fig. 3) and of the Eastern Mediterranean (Fig. 2).

— *Other tectonic events* can be recognized by major changes observed in detrital clay assemblages. On the inner slope bordering the Japan Trench, the abundance of primary minerals during the latest Cretaceous time suggests the existence of an ancient land-mass in the North-West Pacific (Oyashio land-mass ; von Huene *et al.*, 1980). The mineralogical diversification occurring since the latest Oligocene indicates a fast subsidence of this ancient land-mass, with drastic changes in submarine topography (unpubl. data). The strong Plio-Pleistocene movements in the Mediterranean area (rapid subsidence of several western and eastern basins at earlier Pliocene time, uplift of Sicily in Middle Pliocene increasing towards the Pleistocene, uplift of Mediterranean ridge, Hellenids and Taurids close to the Plio-Pleistocene boundary, Pleistocene movements in Peloponnesus and Cyprus), are clearly reflected by mineralogical changes, which appear much more important than those caused by climatic events (Chamley *et al.*, 1977). The relative stabilization of Atlantic margins at several Mesozoic and Cenozoic stages (late Jurassic, Albian, late Cretaceous, Paleocene, Eocene) favored marine transgressions and the development of marginal basins where fibrous clays (palygorskite, sepiolite) formed under warm and alkaline restricted conditions. The reworking of these peculiar deposits was favored by the subsidence along the marginal faults linked to the subcontinuous oceanic spreading (see Chamley, 1971 and Fig. 1). The best large-scale period for the formation of fibrous clays and associated minerals (opal CT, clinoptilolite) seems to have been the Early Paleogene, where the most suitable tectonic, eustatic, morphologic and climatic conditions were combined (see Millot, 1964 ; Nathan, Flexer, 1977 ; Chamley, 1979).

CLIMATIC EVOLUTION

Numerous examples of continental climates expressed by pedogenic detrital clays exist in the world literature. Only a very general summary can be given here :

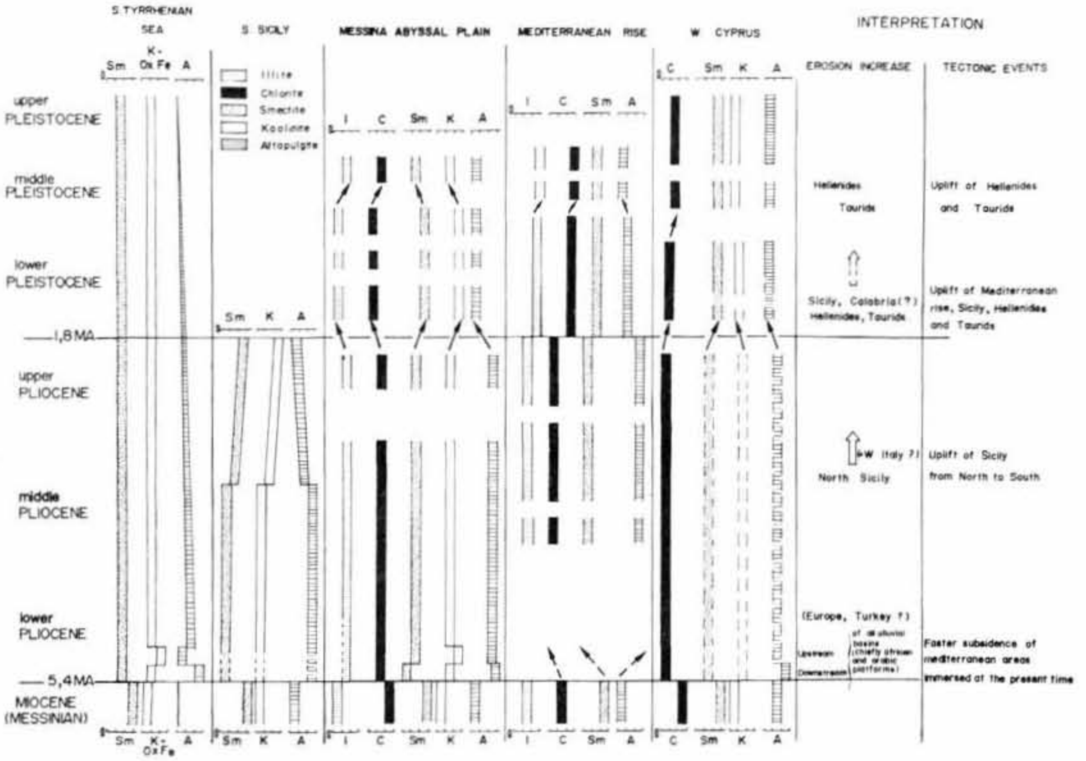

Figure 2

Plio-Pleistocene tectonic evolution of the Mediterranean area, from clay sedimentary successions.

Évolution tectonique de la zone méditerranéenne au Plio-Pléistocène, à partir des successions d'argiles sédimentaires.

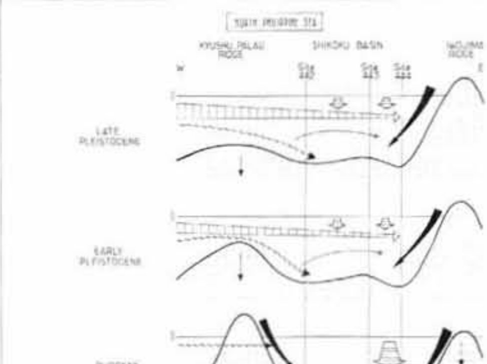

Figure 3

Late Cenozoic tectonics and currents in North Philippine Sea from data on detrital clays (Leg 58 DSDP).

Tectonique et courants au Cénozoïque supérieur dans le nord de la Mer des Philippines, d'après les données des argiles détritiques (Leg 58 DSDP).

— *At the present time* a general relationship exists between the latitudinal distribution of clays in continental soils and in surficial marine sediments (Millot, 1964 ; Biscaye, 1965 ; Griffin *et al.*, 1968 ; Pédro, 1968), pointing to the main climatic dependence of terrigenous minerals. *During the Quaternary* the climate fluctuations influencing soils genesis in a given area, combined with the lack of diagenetic influence, lead some workers to propose climatic curves in terms of continental temperature and humidity, complementary of the successions obtained from other methods based on pollen, foraminifera, nannofossils, pteropods and oxygen isotopes (Chamley, 1971 ; Cita *et al.*, 1977 ; Pastouret *et al.*, 1978). In a general way, the climatic signal of sedimentary clays improves when moving away from coastal zones where hydrodynamical sorting occurs (Chamley, 1971).

— *From latest Eocene to Pleistocene* the long-term trend consists of an irregular cooling, especially well documented in the oxygen isotope data (i.e. Shackleton, Kennett, 1975), and also seen in the clay record (Chamley, 1979). Detrital minerals express this cooling by a transition from pedogenically evolved species (well crystallized smectite, kaolinite) to species characteristic of rocks and moderate alteration (primary minerals, irregular mixed-layers, degraded smectite). The decrease of weathering and pedogenesis, due to the world cooling, is also favored by strong sea-level changes during glacial/interglacial alternations and locally by alpine tectonical movements, both events determining an increase of continental erosion. The following climatic evolution is proposed from mineralogical data : the main cooling stages appear at the Eocene/Oligocene boundary, early-middle Miocene, late Miocene and in the Pleistocene, due to ice-caps developments and regional glaciations ; the average rainfall regime becomes progressively more regular in the course of the year, and the latitudinal climatic zonation more distinct ; climatic differenciations show progressive increase towards high latitudes compared to low latitudes ; in desert zones there appear aridity/humidity alternations ; a peri-mediterranean climate crisis occurs during latest Miocene, marked by temperate-warm conditions and seasonal contrasts in humidity (pedogenic smectite, lacustrine palygorskite and sepiolite), which is due to the Mediterranean Messinian isolation from open ocean and to the repeated sea water evaporation (Hsü, Cita, 1973, and references in Chamley, 1979 ; Chamley, Robert, 1980 ; Diester-Haass, Chamley, 1980).

— *From late Jurassic to late Eocene* warm conditions prevail in most latitudinal zones, as suggested by the predominance of smectite, probably reworked from poorly-drained soils (Chamley, 1979). Strong contrasts in seasonal or pluri-annual humidity, also necessary for the massive pedogenic growth of smectite (Paquet, 1969), favor the periodical formation of fibrous clays in peri-marine environments (see above). Climate fluctuations occur as in subsequent periods, but they appear to be of lesser amplitudes.

General relationships arise between climate and global tectonics, due to the migration of lithospheric plates under different latitudinal zones. The most relevant interactions of this kind concern the North Atlantic area, from late Cretaceous to late Cenozoic (Chamley *et al.*, 1980). The North American plate tends to move northwards compared to the Equator position, and terrigenous clays express progressively cooler continental conditions along the time (primary minerals ; i.e. Site 105, Cape Hatteras Basin). During the same period, the African plate moves across the equatorial zone, leading to the production and erosion of kaolinite, smectite and fibrous clays (Site 367, Cape Verde Basin). Deciphering the paleoclimatical and geographical evolution of such clay associations leads one to participate in reconstructing past lithospheric movements.

HYDRODYNAMIC EVENTS

Clay minerals deposited in the open sea commonly have various origins and depend on the local current regime. The comparison of synchronous clay assemblages recorded at different bathymetric and topographic levels, under similar paleolatitudes, contributes to the identification of past oceanographic conditions and their evolution.

Differential settling processes occur frequently on a general scale when moving from near-shore areas toward the high sea : minerals of small size, easily floatable and little flocculable (smectite often associated with mixed-layers and fibrous clays), remain in suspension a longer time and settle farther out than other species (illite, chlorite, kaolinite). The result is a general increase of smectite and associated species in sediments distant from the coast. Numerous examples exist in most seas and at many periods, related or not to deltaic fans : Quaternary in Mediterranean and Atlantic provinces, late Cretaceous and early Tertiary of the Armorican and African margins, etc. (i.e. Porrenga, 1966 ; Chamley, 1971 ; Gibbs, 1977). In arid zones, eolian input contributes in a significant way to terrigenous supply, with changing conditions along time and space (i.e. Chester *et al.*, 1972 ; Sarnthein *et al.*, 1979).

Mineral supply by large marine currents generally replaces the differential settling processes when going away from epicontinental zones. Latitudinal and meridional currents, as well as surficial, intermediate and deep water masses intervene in a complementary and changing way. Their respective influence, often linked to main morphologic and climatic changes (i.e. Berggren, Hollister, 1977 ; Thiede, 1979), is frequently expressed by the small-sized and easily scattered clay minerals : dispersal patterns of Eastern-Mediterranean recent suspensions, implications of Quaternary glacial/interglacial alternations on deep water extension, velocity and exchanges in North-East and South-West Atlantic and in Eastern Indian Ocean, late Mesozoic and Cenozoic North-South movements related to Atlantic widening and deepening, Cretaceous and Cenozoic circulation events determined by the subsidence of different ridges and the communication between different sedimentary basins (Atlantic, North-West Pacific) (see references in Venkatarathnam, Ryan, 1971 ; Venkatarathnam, Biscaye, 1973 ; Moyes *et al.*, 1974 ; Melguen *et al.*, 1978 ; Chamley, 1979 ; see also Fig. 3).

CONCLUSION

Extended studies on clay mineralogical stratigraphy of late Jurassic to Recent DSDP sediments from Atlantic, North-West Pacific and Mediterranean reveal various long-term trends, interpreted in terms of paleoenvironment.

In most marine environments, clay sedimentation expresses less the autochthonous chemical conditions than allochthonous events linked to external and internal geodynamics. Events are chiefly of a tectonic, climatic, hydrodynamic and/or morphologic nature, and intervene on clay assemblage by the way of surficial alteration, pedogenesis, erosion, transport and deposit processes. Little or not changed by diagenesis, terrigenous materials can be used in deciphering the nature, amplitude and relative chronology of geodynamical events. One major problem consists in the possible superimposition of different causes ; the consequent confusion can be alleviated by combining various sedimentological methods.

In a general way, the tectonic influence and local supply predominate in Atlantic ocean during late Mesozoic time, in Mediterranean and North-West Pacific during Cenozoic time, the cause of the shifting being a different chronology in structural history. Climatic and hydrodynamic influences prevail in the Atlantic realm during Cenozoic time. In both other basins they distinctly determine minor but significant fluctuations, independently of major structural changes. Morphological changes are generally connected to one or two of precedent influences.

In each basin, the long-term trends in clay sedimentation contribute to the determination, by means of surficial effects, of the dominant changes concerning the evolution of the earth crust. As a consequence, they represent one of the meeting points of geophysics, structural geology and environmental geology. Terrigenous sedimentation reacts to the major events of internal geodynamics in a parallel way as do biogenous and chemical marine sedimentations. Each main external process reflects in its own way the internal changes : growing of new minerals in areas of volcanic and hydrothermal activity ; production and dissolution of calcareous and siliceous tests partly related to ocean widening, deepening and plate motion ; changing modalities of detrital supply, largely depending on global tectonics and inferred paleogeographic modifications. The last topic is one that needs more intense investigation, in order to progress in dynamical sedimentology.

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