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Clay mineralogy in southeast Spain during the late Miocene: climatic, paleoceanographic and tectonic events in the Eastern Betic seaway

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Abstract

X-ray diffraction and electron microscope investigations were performed on late Miocene sediments of the Fortuna Basin. Results were compared to available paleogeographic data and were interpreted in terms of terrigenous sources, climate, tectonics and sea level changes. Biostratigraphic and chronologic data allow the use of clay stratigraphy in providing paleoenvironmental information. The Western Mediterranean domain was subject to periods of strong aridification as early as late Tortonian. On the land climate was dominated by subarid conditions, favouring the development of pedogenic smectites and probably palygorskite. Tectonic activity rejuvenated the region episodically, especially after the Tortonian-Messinian boundary (lower Sanel marls), at the beginning of upper evaporites deposition (marine marl/gypsum alternations of the Rambla Salada Formation), and probably when the intra-Messinian inundation started. The sea level changes appear to have been of little importance in controlling the clay sedimentation patterns in the Eastern Betic seaway during late Miocene times.

Introduction

During the late Miocene the Atlantic Ocean and the Mediterranean Sea were connected by two seaways, the Rifian Corridor in northern Morocco and the Betic Straits in southeastern Spain. The collision of the African and European plates narrowed and shoaled both marine connections during early and middle Miocene time (Weijermars 1988). Late Miocene tectonics, eustatic regression and a water deficit in the Mediterranean Sea restricted circulation in these seaways and led to a change in circulation after the Tortonian-Messinian boundary (Van Couvering et al. 1976, Müller & Hsü 1987, Benson et al. 1989, Hodell et at. 1989). These events probably siphoned cooler, nutrient-rich intermediate water from the Atlantic Ocean, as a result of the negative water balance (Hodell et al. 1989). Subsequent upwelling of the nutrients in the Mediterranean Sea led to the deposition of the Tripoli Formation (McKenzie et al. 1979, Gersonde & Schrader 1984). The isolation of the Mediterranean Sea from the Atlantic Ocean during the Messinian found also its expression in a specific peri-Mediterranean climatic crisis (Chamley & Robert 1980, Chamley 1983).

The late Miocene tectonics in southeastern Spain affected mainly the northeast-southwest trending external units of the Betic Cordilleras (De Smet 1984, Montenat et al. 1987). The Jaen-Granada-

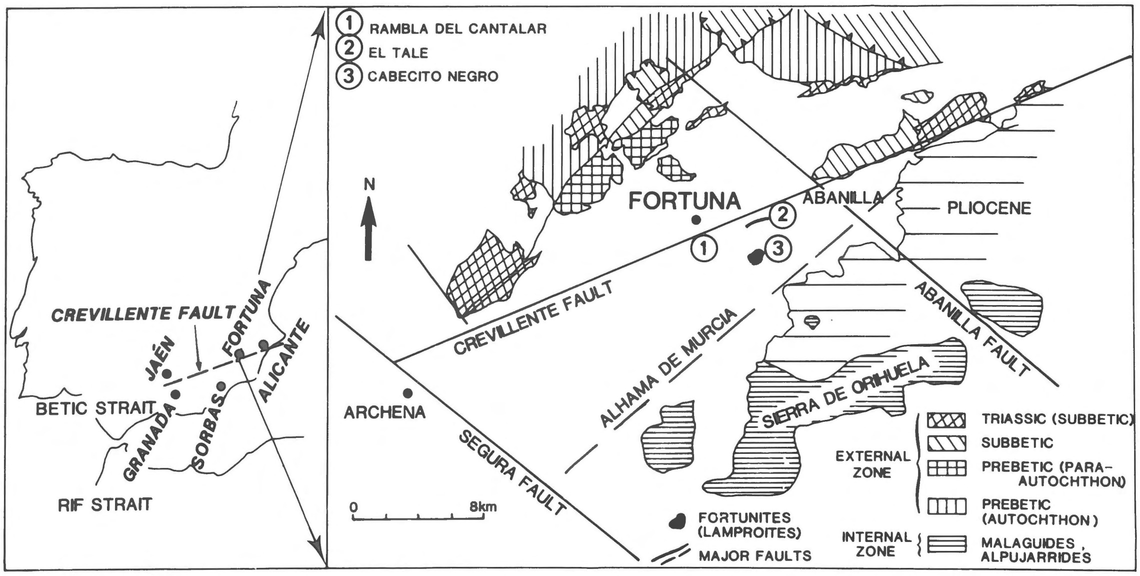

Fig. 1. Geographic and geological situation of the Fortuna Basin in Southeastern Spain. Late Miocene deposits are in white.

Alicante triangle (Fig. 1) most likely formed a sill which further helped restrict the circulation. The Sorbas and Fortuna Basins in Southeast Spain were located within or to the east of the sill (Fig. 1) and therefore, the circulation changes between the Atlantic Ocean and the Mediterranean Sea (Müller & Hsü 1987, Müller & Schrader 1989) and the climatic variations in the peri-Mediterranean domain are documented in these basins. Stable isotopes from the open ocean reveal no evidence for a noticeable glacioeustatic sea level drop in the late Tortonian and early Messinian (Müller et al., in press). Short-term paleoceanographic fluctuations in the Betic and Rif Straits due to glacioeustatic sea level changes which amplified the special circulation conditions, were superimposed on the tectonically and climatically induced long-term events.

In this paper we try to outline major tectonic, paleoceanographic and climatic events with the help of clay mineralogy, correlated to major statigraphic events, previously reported from the same area (Chamley 1983, Chamley et al. 1986, Müller & Hsü 1987), and climatic variations in the peri-Mediterranean domain. The region chosen is the Fortuna Basin, located on the southeastern side of the Iberian peninsula (Fig. 1). The Fortuna Basin represents one of the numerous intramontane Neogene basins in the Betic Cordilleras.

Lithologic, stratigraphic and tectonic settings

Lithostratigraphy

During the late Neogene thick series of interbedded marine and continental sediments was deposited in the Fortuna Basin (Müller 1986). The lowest part consists of gray to yellow hemipelagic marls (Mamoya Marl. Fig. 2), several hundred metres thick. These marls were eroded during a drop in sea level, close to the Tortonian-Messinian boundary, which caused the disconformable deposition of the Fenazar Member, a conglomerate 10 to 15 m thick. During Tortonian time coral debris in the conglomerates were removed from reefs developed on the borders of the Fortuna Basin (Desastre Limestone). Above the Fenazar the Sanel Member comprises: (1) a marine lower unit of light gray to brownish gray bioturbated marls interbedded with turbidites and charcoals; (2) a middle unit, a turbidite series poor in benthic foraminifera, accumulated in an oxygen-deficient environment, and made up of interbedded dark, well-laminated marls and purplish gypsum-arenites; (3) an upper unit deposited in saline to fresh water and consisting of light gray, carbonate-rich marls grading upward into diatomite-like deposits. The Sanel marls are overlain by the Tale Gypsum, which comprises cyclic sequences of gypsum/dolomite layers, sediments with halite pseudomorphs, and marls, suggesting repeated desiccation phases. The overlying Rio Chicamo Diatomite consists of five cycles of marl/diatomite/gypsum sediments, deposited in an oxygen-depleted marine environment. Finally the Rambla Salada Formation lies unconformably upon the Rio Chicamo Formation by means of a basal conglomeratic unit (Wichmann bed). Marine near the base, grading upward into continental deposits, this formation is characterized by cyclic units of marl and either gypsum or red conglomerate. Lacustrine sediments of the Rambla Salada Formation are blanketed by terrestrial conglomerates of Pliocene age, not investigated in the present study.

Biostratigraphy and absolute ages

The Tortonian-Messinian boundary in the Mediterranean domain is marked by the appearance of new species of planktonic foraminifera such as Globorotalia conomiozea, G. mediterranea, and G. saphoae (D'Onofrio et al. 1975). The coiling shift from sinistral to dextral of G. menardii and that of N. acostaensis bracket Tortonian-Messinian boundary. Therefore these two coiling changes, or the replacement of the G. menardii group by that of G. miotumida, also permit to recognize the Tortonian-Messinian boundary (Sierro 1985, Iaccarino & Salvatorini 1982). In the Fortuna Basin, the Tortonian-Messinian boundary is not exactly defined. The biostratigraphy in this basin was studied particularly by Montenat (1973), Santisteban (1981), Müller (1986), and Lukowski (1988). The stratigraphic boundaries presented here (see Fig. 8), as well as the absolute ages, are based on two assumptions: one, that Müller & Hsü (1987) correlation between the Fortuna Basin and the nearby Sorbas Basin based on event stratigraphy is correct; and two, that the coiling change of N. acostaensis in the Abad Member of the Sorbas Basin is not local but synchronous with coiling changes of this species in other sections within and without the Mediterranean Sea (Gersonde & Schrader 1984, Hodell et al. 1989). In addition we accept the biostratigraphic interpretation of Santisteban (1981) with a Tortonian-Messinian boundary on top of the Fenazar Member.

Several datings permit to calibrate the chronology of the deposition in the Fortuna Basin. The Tortonian-Messinian boundary is located at 6.3 Ma (Channell et al. 1989, Hodell et al. 1989). The calkalcaline volcanic rocks (lamproites) of Cabecito Negro (Fig. 1) intruding into marls of the Sanel Member were dated 6 ± 0.4 Ma (Bellon & Brousse, 1977). Accumulation of the diatomites of the Tripoli Formation, which is considered synchronous with a part of Sanel marls, extended between 5.9–6.0 and 5.5–5.6 Ma, according to comparative data in the Mediterranean Sea and in the open ocean (e.g. Gersonde & Schrader 1984). The correlation of the coiling change of *N. acostaensis* in Sicily and in a paleomagnetically dated section from Western Morocco suggests that the onset on the Lower Evaporite deposition began at 5.5 Ma (Hodell et al. 1989), contemporary with the Sanel marl – Tale Gypsum transition. The Upper Evaporites of the Tyrrhenian Sea, considered as synchronous with the onset of Rambla Salada deposits (Müller & Hsü 1987), were most likely deposited in the lower reversed interval of the Gilbert paleomagnetic stage and are therefore younger than 5.3 Ma (Channell et al. 1989). Finally the Miocene-Pocene boundary at 4.9 Ma is based on bio- and magnetostratigraphic, and strontium-isotope data from Southern Italy and Sicily (e.g. Hilgen & Langereis, 1988; McKenzie et al. 1988). These absolute ages are employed in the discussion below and indicated on Fig. 8.

Tectonic activity

Late Neogene basins (Tortonian to Pliocene) of the Eastern Betic Chains are located within a wide NE-SW trending shear-zone. The Fortuna Basin, located within the boundary of the External and Internal Zones of the Betic Cordillera (Fig. 1), is a strike-slip furrow basin created by wrenching during late Middle and Late Miocene time (Montenat et al. 1987). The Subbetic Zone within the External Zone at the northern border of the Fortuna Basin is characterized by folded Triassic and Jurassic sediments and seems to be a central zone of weakness, wrenched between the 'Prebetic' and the 'Internal' Zones (De Smet 1984). The late Neogene shearing affected a mosaic of 'pre-cut blocks', inherited from earlier (at least early Miocene) structural stages (Montenat et al. 1987). From the northwest to the southeast there are three prominent lines along the wrenched zone, the contact between the Prebetic and the Subbetic Zones, the Crevillente Fault, and the contact between the External and Internal Zones (De Smet 1984). In the centre of the Fortuna Basin no sediments can be found younger than Tortonian north of the Crevillente Fault, suggesting that the fault acted as a barrier for evaporitic Messinian sediments. The depositional centre of the late Miocene sediments migrated gradually from NW to SE (Lukowski 1988). The most important deformation phase in the Prebetic units (External Zone) took place during the Langhian – Tortonian time span, causing local erosion of Triassic sediments during the Tortonian (Santisteban 1981, De Smet 1984). The compressional tectonics during the Betico-Rifian orogenic phase were relatively slow and caused a gradual narrowing and shallowing of the connecting seaways in southeastern Spain. Vertical movements along the Crevillente Fault occurred in the Pliocene, elevating the External relative to the Internal Zone, as well as deforming the Messinian sediments expressed in folds and evaporite diapirism (Santisteban 1981).

Sea level changes

The drop in sea level noted in the top of the Mamoya marls is probably the prelude to the Messinian salinity crisis. In addition, tectonic events in the Betic Straits narrowed and shoaled the seaway and contributed to the formation of the clastic Fenazar Member, as well as of its equivalent in the Sorbas Basin which is called the Azagador Member (e.g. Völk & Rondeel 1964, Müller & Hsü 1987). The Tripoli Formation was deposited during the fullmarine lower part of the Sanel Member. The occurrence of freshwater ostracods in the Sanel Member, synchronous in the Sorbas Basin with a faunal break (Abad Member), is considered indicative of a second sea level drop in the connecting seaways. This event at around 5.8 Ma coincides with intense glaciation of the Southern Hemisphere and a worldwide sea level drop (Hodell et al. 1986, Müller et al. in press). Marine water was supplied into the Mediterranean Sea to form the Main Salt during the cyclic marine incursions noted in the upper part of the Sanel Member and probably also during the Tale Gypsum deposition. This is in line with interpretations inferred from the record of Western Morocco (Hodell et al. 1989).

Methods

Clay mineral analyses were performed by x-ray diffraction of 101 late Tortonian to Messinian sediments sampled in the Fortuna Basin (Müller 1986), and were complemented by transmission electron microscope observations on 17 selected samples. For x-ray diffraction, the samples were dissociated in water, then calcium carbonate was removed in 1/5 N hydrochloric acid. Deflocculation was done by successive centrifuging and microhomogenization. The fraction smaller than 2 μm was decanted according to Stokes' law, and oriented pastes were made on abraded glass slides. A Philips 1730 diffractometer (copper radiation) was used to make the x-ray diffraction scans at $2°\theta$/min on air-dried, glycolated and heated samples (Holtzapffel 1985). The quantitative evaluation is based on peak heights and areas. The height of illite and chlorite 001 peaks (diagram for glycolated sample) were taken as reference. By comparison with these values, heights for smectite, palygorskite, and mixed-layer clays were corrected by addition of peak height (× 1.5 to 2.0 according to decreasing crystallinity of a given species), whereas values for well-crystallized kaolinite were corrected by subtraction (× 0.7 to 0.5 according to increasing crystallinity of the mineral). The relative proportions of chlorite and kaolinite were determined from the

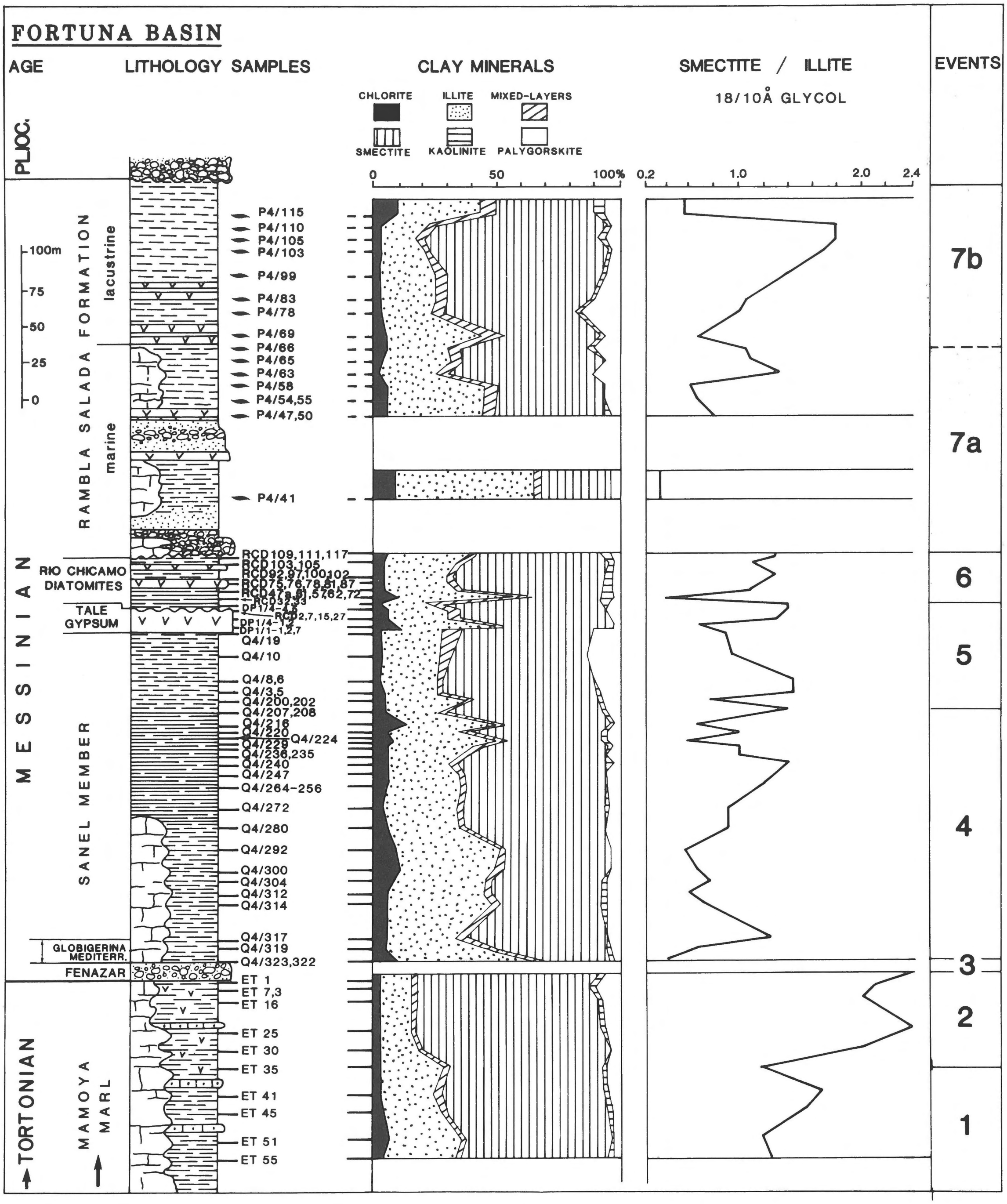

Fig. 2. General lithologic and clay mineral data from Rambla Salada and Rio Chicamo sections, Fortuna Basin. The sample location is precise for Mamoya Marl and Sanel Member, and approximate for Tale Gypsum, Rio Chicamo Diatomite and Rambla Salada Formations (see Figs. 5, 6, 7). Lithologic symbols as usual for claystones, sandstones, conglomerates and carbonate rocks. v = gypsum.

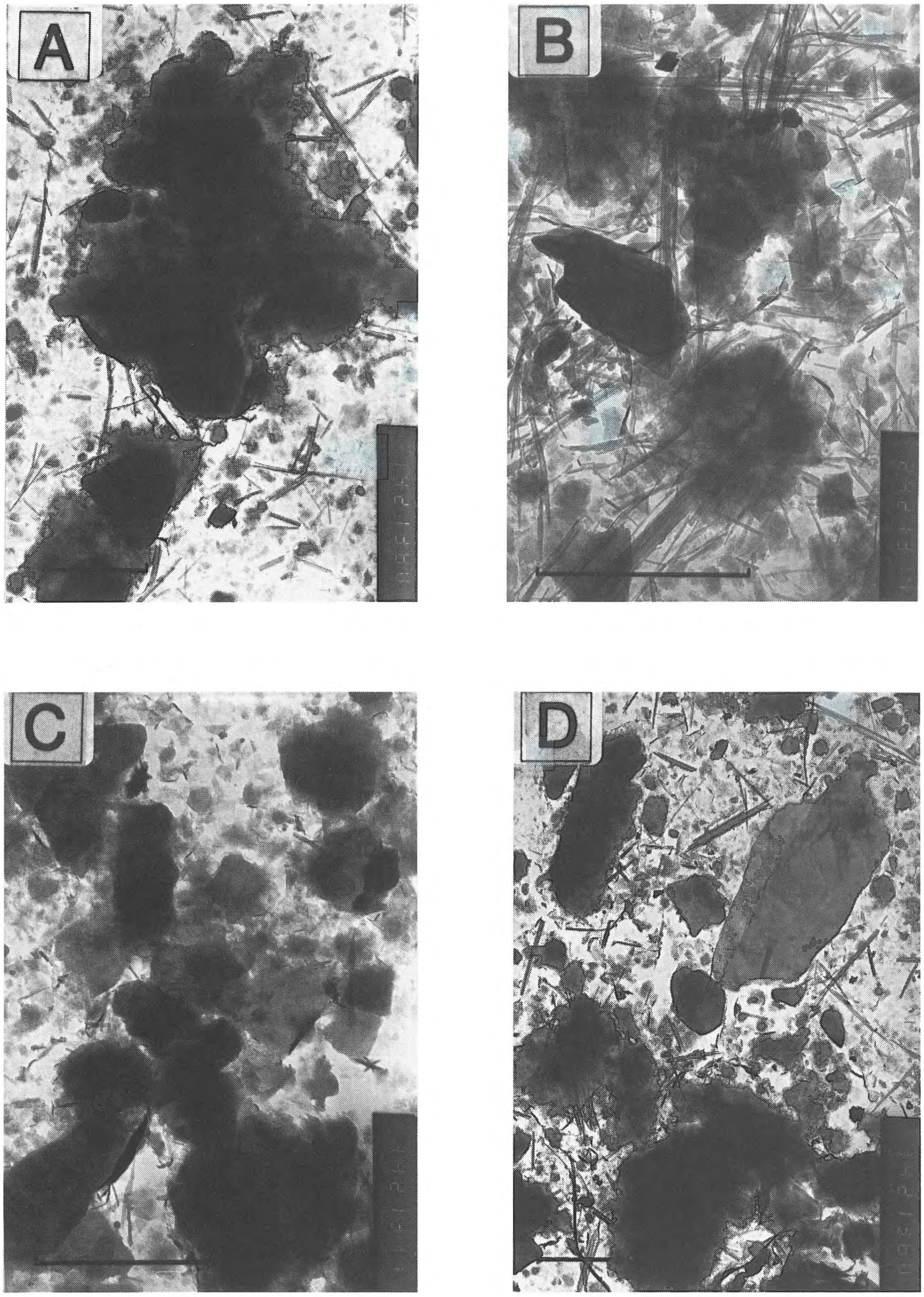

Fig. 3. Electronmicrographs (bar = 1 μm) of clay minerals from Rambla Salada and Rio Chicamo Formations. (A, B, C) Rambla Salada Formation, late Messinian. (A) Sample P4/105, light gray lacustrine marl. Abundant fleecy smectite, little well-edged illite sheets, rare and short palygorskite fibres. (B) Sample P4/78, gray lacustrine marl. Fairly abundant bundles and isolated fibres of palygorskite, associated with smectite and illite. (C) Sample P4/41, yellowish marine mudstone. Abundant well-edged and fresh sheets of illite and chlorite, little abundant smectite flakes. (D) Rio Chicamo Diatomite, late Messinian. Sample RCD 32, yellowish-brown marl. Fresh and abundant illite sheets, rare debris of palygorskite fibres.

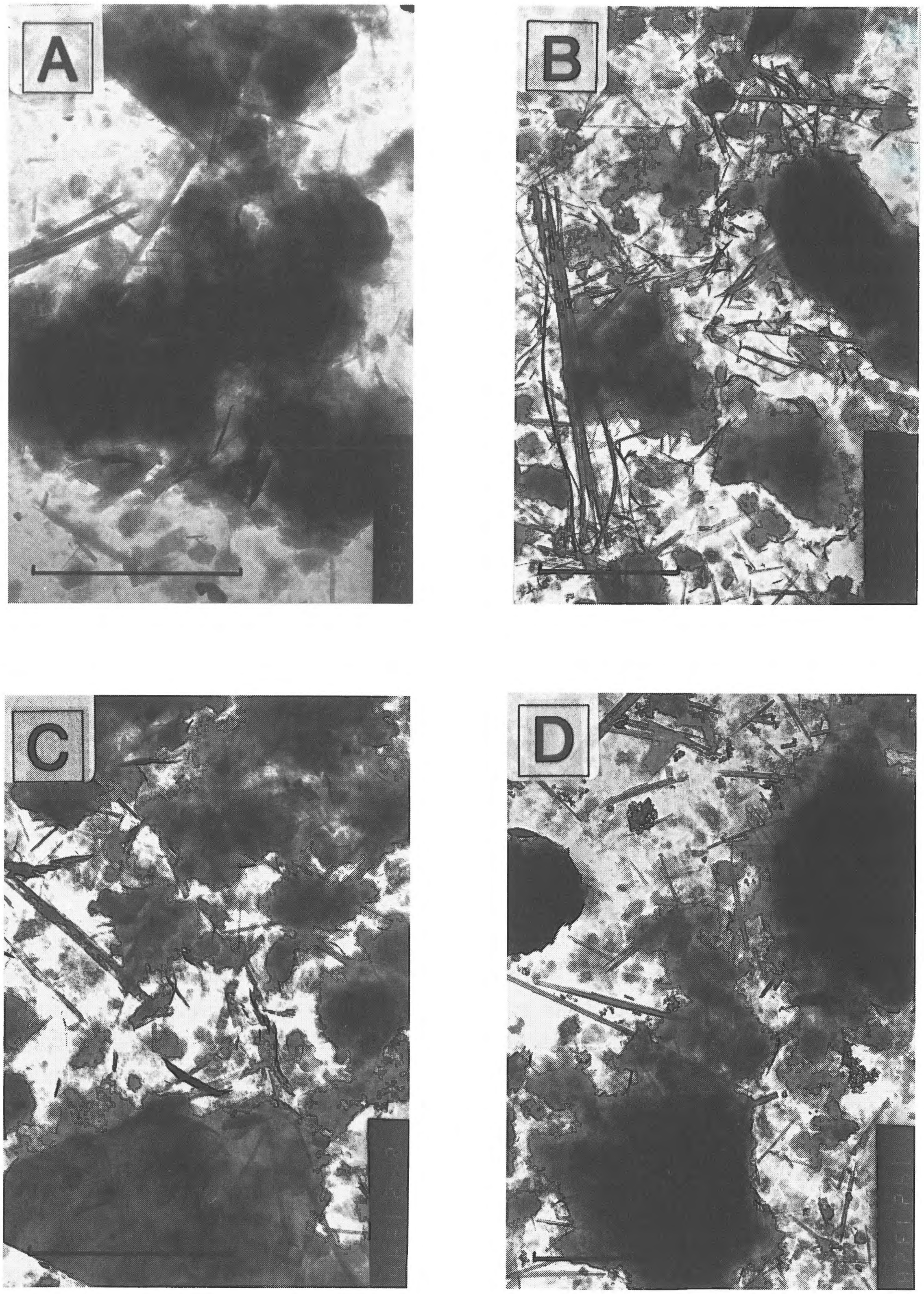

Fig. 4. Electronmicrographs (bar = 1 μm) of clay minerals from Rio Chicamo Diatomite, Sanel and Mamoya Marls. (A) Rio Chicamo Diatomite, late Messinian. Sample RCD 15, light gray marl. Abundant fleecy smectite, little palygorskite fibres. (B) Upper Sanel Marl, early Messinian. Sample Q4/10, light gray marl. Abundant smectite and fairly abundant palygorskite. (C) Middle Sanel Marl, early Messinian. Sample Q4/247, light gray marl. Fairly abundant and fresh sheets of well-outlined illite, beside smectite flakes and rare palygorskite fibres. (D) Mamoya Marl, latest Tortonian, Sample ET3, light gray marl. Abundant smectite flakes, few broken and reworked fibres of palygorskite, fairly rare well-outlined sheets of illite.

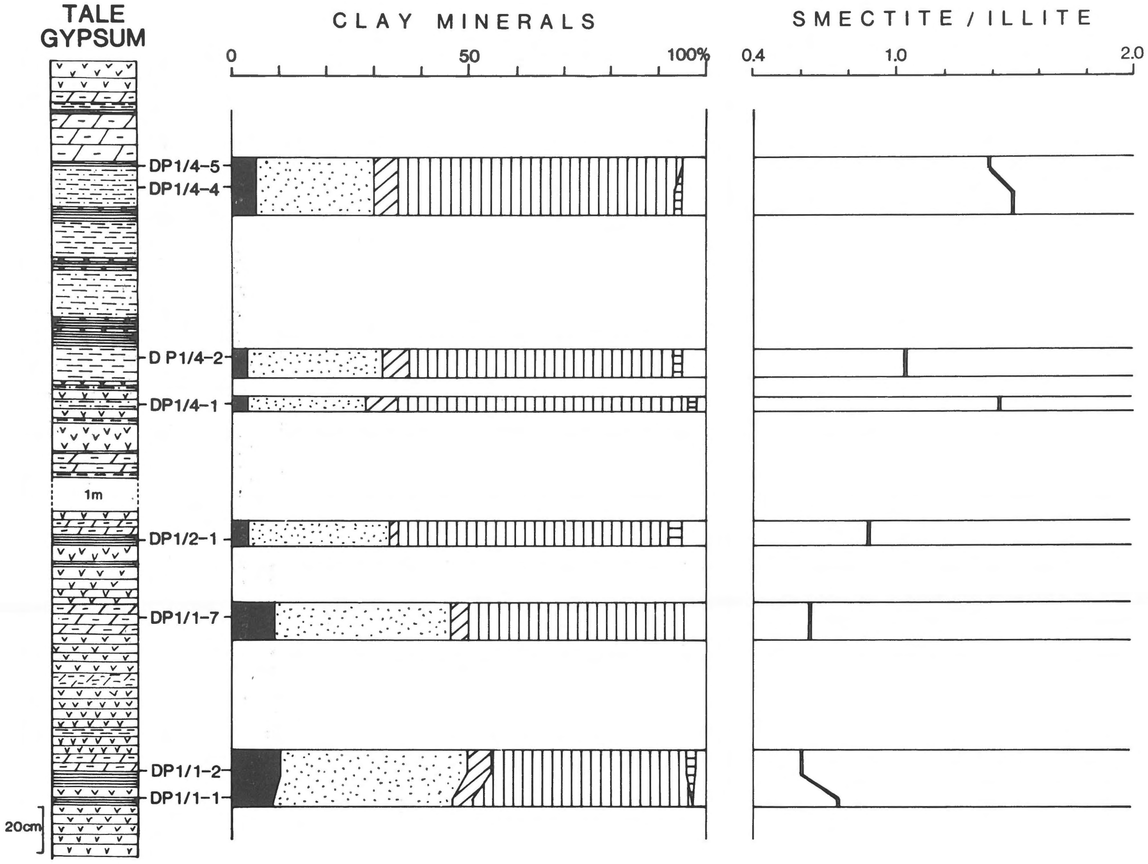

Fig. 5. Tale Gypsum, lithologic and clay mineral data.

ratio of the heights of the 3.54 and 3.57 Å peaks; when this ratio was 1, the amount of chlorite was assumed to be twice that of kaolinite. Data are given as percentages, the relative error being estimated at ± 5% (Holtzapffel 1985). Transmission electronmicroscope observations were made with a Jeol 120-CX equipment on less than 8 μm particles deposited on copper grids covered with a collodion film after carbonate removal and physical deflocculation.

Clay mineralogy

Constituents

Most clay minerals are ubiquitous in the late Tortonian-Messinian sediments of the Fortuna Basin, except kaolinite which is absent in about 15% of the samples analysed (Fig. 2). The most abundant mineral is fairly well to well crystallized smectite (from 30 to 80% of the less than two micrometer fraction), which displays on electron micrographs common fleecy particles (Figs 3, 4). Illite represents the second abundant species with percentages ranging from 15 to 60%. The amounts of illite, as well as those of chlorite (usually trace amounts to 10%), quartz (rare to common), and feldspars (absent to rare), vary generally symmetrically to those of smectite. Illite and chlorite are recognizable on electron micrographs by their well-edged, sometimes transparent, non polygonal aspect. Palygorskite occurs in all sediments, its abundance varies from trace amounts to more than 10% of the clay minerals; the palygorskite fibres are usually short, more or less broken and arranged as individual

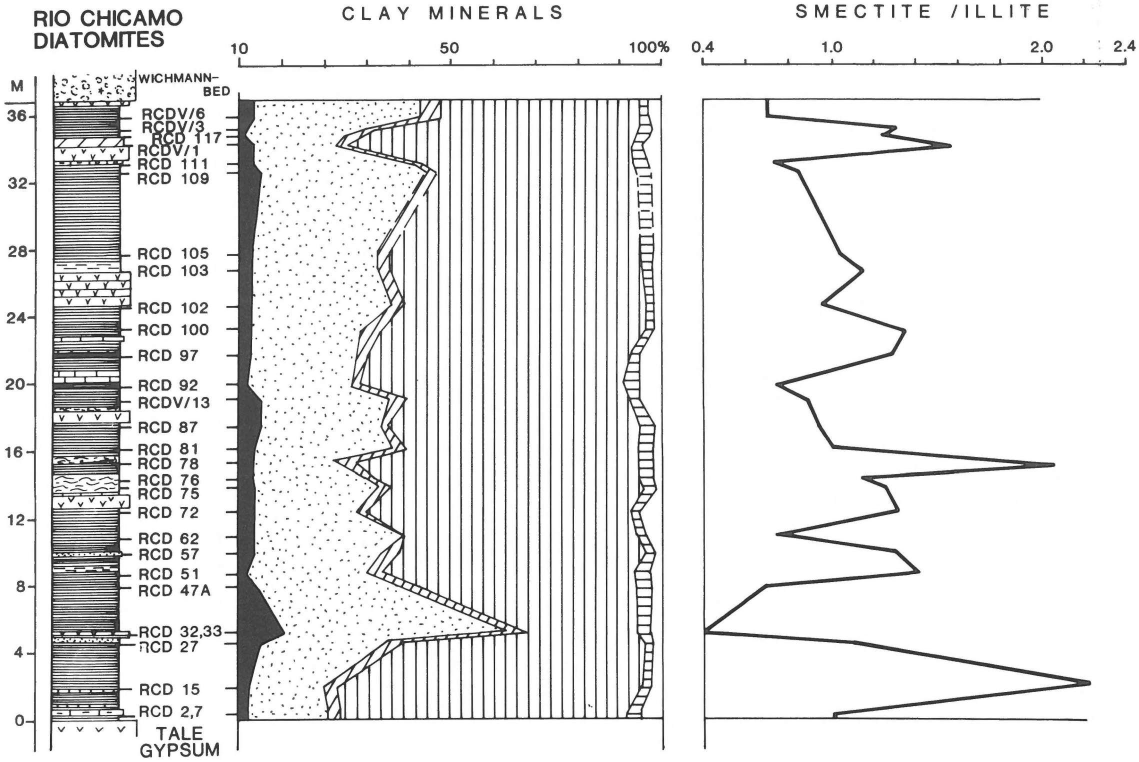

Fig. 6. Rio Chicamo Diatomite, lithologic and clay mineral data.

particles or small bundles. Mixed-layer clay minerals are poorly represented (trace amounts to less than 10%), of a random nature, and mainly of the illite-smectite and chlorite-smectite types. Kaolinite is absent of forms everywhere less than 5% of the clay minerals. Beside quartz and feldspars, associate non-clay minerals include occasional and little abundant opal and goethite; opal in the $<2\,\mu$m fraction mainly consists of skeletal debris of diatoms.

Clay stratigraphy

Clay mineral associations display many quantitative variations from the base to the top of the late Miocene sections studied (Figs 2, 5, 6, 7). These variations do not show any continuous vertical trend. In addition the changes are only to a small extent related to the main lithological facies; for instance, some samples of the Mamoya Marl contain the same clay mineral assemblage as some of the Tale Gypsum; illite is either abundantly or poorly present in marine marls of the Sanel Member and of the Rambla Salada Formation (Fig. 2); many samples are marls in which strong mineral variations are recorded. The results are extensively plotted in Fig. 2 for Mamoya Marl and Sanel Member samples, and given in more details on Figs 5, 6 and 7 for samples from Tale Gypsum, Rio Chicamo Diatomites and Rambla Salada Formation, respectively. The description follows the successive events recorded by Müller & Hsü (1987) in the Fortuna Basin (Figs 2, 8).

Event 1

Mamoya Marl, normal marine deposition (>6.5 Ma BP). Smectite is abundant in the clay fraction of late Tortonian sediments, tending to increase from bottom to top from 65 to 70%. Illite plus chlorite constitute about one third of the clay minerals, and are associated with low amounts of palygorskite, kaolinite and randomly mixed-layers.

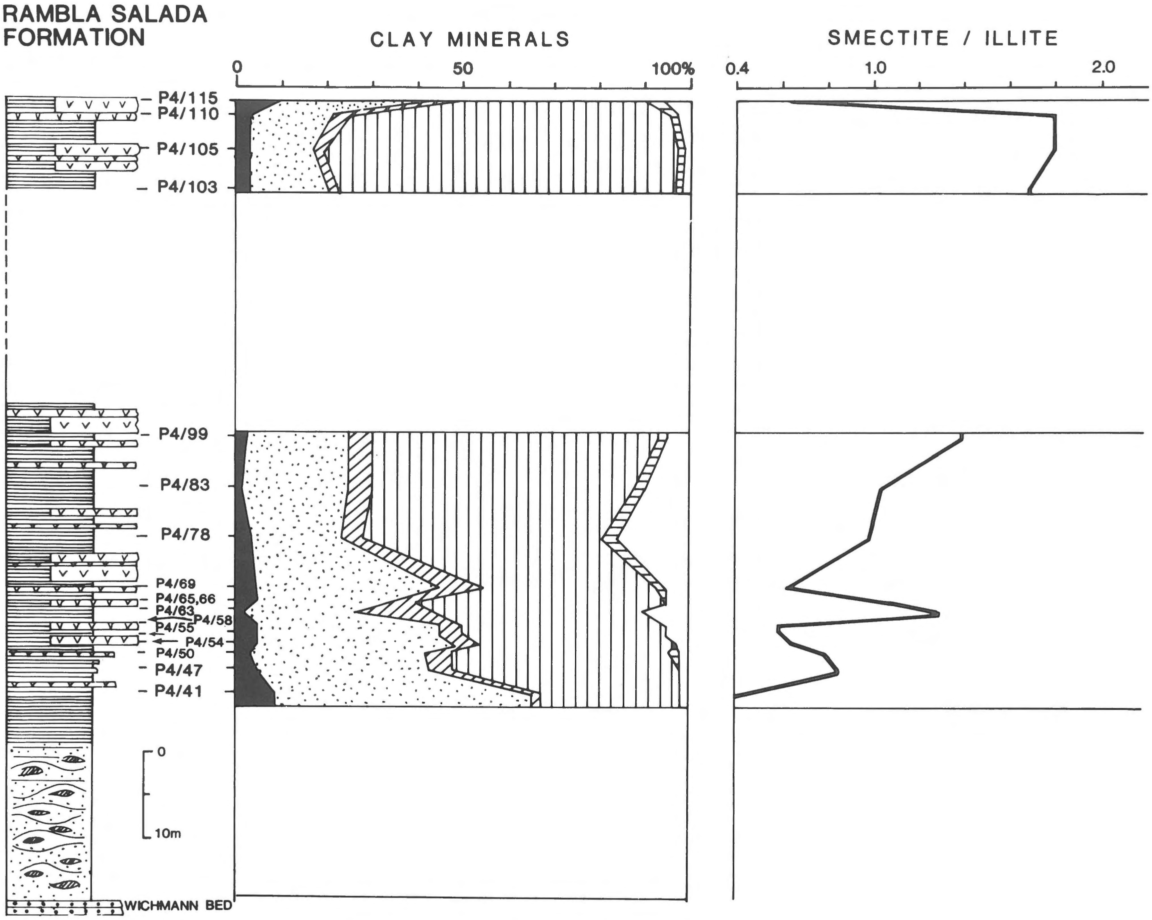

Fig. 7. Rambla Salada Formation, lithologic and clay mineral data.

Event 2
Mamoya Marl, regressive deposits, latest Tortonian (about 6.5 to 6.3 Ma). The amounts of smectite continue to increase. Maximum percentages of the mineral (70 to 80%) are recorded during this event, significantly before the onset of the Messinian salinity crisis. The abundance of illite decreases (15%) whereas that of palygorskite slightly increases (5 to 10%). On electronmicrographs smectite presents typically fleecy outlines without any overgrowth structures; palygorskite displays short, broken and isolated fibres (Fig. 4D).

Events 3, 4
Lower Sanel Marl (< 6.3 Ma), lower Messinian. Above the coarse detrital sediments of the Fenazar Member (= Event 3; not analyzed), the Sanel marls contain abundant illite (40 to 50% of clay minerals), relatively abundant chlorite (up to 10%), as well as common quartz in the clay fraction. Illite generally forms large, well edged and fresh particles (Fig. 4C) suggesting a rapid erosion of source rocks. Smectite shows its lowest amounts near the top of Fenazar conglomerates (30%) and tends to increase irregularly upwards (50 to 65%). Palygorskite occurs throughout the series as scattered and short fibers.

Event 5
Upper Sanel Marl, Tale Gypsum (about 5.6 to 5.2 Ma). The upper part of Sanel marls is characterized by increasing amounts of both smectite (from 45 to 65%) and palygorskite (from trace amounts to more than 10%). The maximum values of paly-

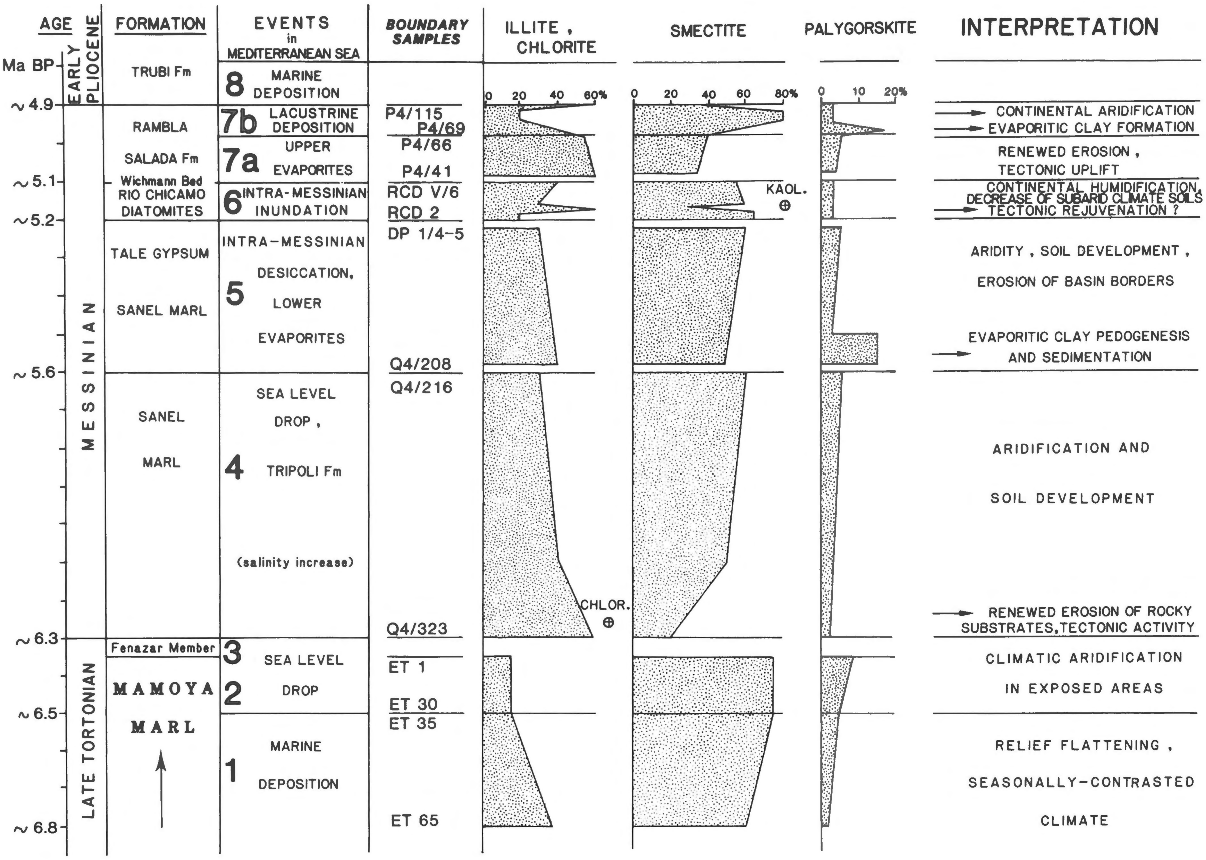

Fig. 8. Summary of clay mineral data and interpretations, late Miocene of the Fortuna Basin.

gorskite, which are attained just beneath the evaporitic layers of the Tale Gypsum, are marked by the frequent presence of long and flexuous fibres, sometimes arranged as thin bundles (Fig. 4B). The amounts of palygorskite rapidly decrease in gypsiferous layers from the Tale gypsum interval (5% to trace amounts), where opposite trends of both smectite and illite groups occur : smectite increases upwards from 45 to 60%, while illite and chlorite decrease from 50 to 30% (Fig. 5). Notice that this clay sedimentation pattern is very similar to that recorded in under- and overlying non-evaporitic sediments.

Event 6

Rio Chicamo Diatomites, late Messinian (about 5.2 to 5.1 Ma). The base of the diatomite deposits, which corresponds to a recurrence of marine conditions, displays abundant fleecy smectite (60 to 80%, Figs 4A, 6) and minimum amounts of illite. The abundance of smectite strongly diminishes close to some gypsum layers, whereas that of illite and chlorite increases (from 20 to 55%, and from trace amounts to 15%, respectively. Fig. 6). The samples RCD 32 and RCD 33 are especially marked by abundant, fresh, large and well-outlined particles of micaceous and chloritic minerals (e.g. Fig. 3D). Quartz and feldspars are well represented in these illite-rich horizons. The upper part of the diatomite formation resembles the lowermost part, with nevertheless slightly less abundant smectite (55 to 70%) balanced by noticeable amounts of illite (30 to 40%) and chlorite (5%). Palygorskite is particularly rare (trace amounts) whereas kaolinite displays the highest amounts of the whole section (5% of clay minerals. Fig. 6).

Event 7

Rambla Salada Formation, latest Messinian (about 5.1 to 4.9 Ma). The marine marls and gypsum layers of the lower Rambla Salada Formation (event 7a), which overlie a conglomeratic unit (Wichmann bed) and reworked sands and limestones, contain abundant illite (40 to 60%) and chlorite (5 to 10%. Figs. 3C, 7). Palygorskite is very rare, as well as kaolinite. The upper part of this subunit contains slightly increasing amounts of smectite, and decreasing amounts of illite and chlorite.

The lacustrine marl/gypsum cycles superimposed to marine sediments constitute the last Messinian deposits and display three successive clay associations (event 7b): (1) Assemblage enriched in palygorskite (10 to 15%), forming the second maximum stage of the fibrous mineral: palygorskite fibres are often long, flexuous and arranged in bundles (Fig. 3B). (2) Smectite-rich association (65 to 85%); smectite reveals typically flaky plates; illite is present in small abundances and palygorskite is very rare (Fig. 3A). (3) Illite- and chlorite-rich association (45%), located just beneath the first continental Pliocene deposits.

Discussion

Clay deposition and sedimentary environment

The clay mineral composition of the late Miocene deposits investigated does not depend strictly on the marine or continental character of the sedimentation. For instance, the clay assemblages of the lower and upper parts of the Sanel Marl are roughly the same (Fig. 2), or do not vary in relation with the saline of freshwater environment. The clay minerals in the marine sediments of the Rambla Salada Formation are very similar to those deposited in the uppermost lacustrine sediments of the same formation. The assemblages recorded in Tale Gypsum interbeds are little different from those of upper Sanel marls, despite important differences in the paleosalinity. *The saline chemical environment seems therefore to have no control on the nature of clay minerals,* which agrees with many data on recent and past sediments (e.g. Chamley 1989).

Other chemical constraints appear to have very little or no control on the nature of clay mineral assemblages, as shown by the independence registered between these assemblages and the presence of diatomites, gypsum or carbonates. This is the case for all mineral species, and especially for smectite. Note that the occurrence of calkalcaline volcanism (lamproite) in the Fortuna Basin at 6 ± 0.4 Ma BP (Bellon & Brousse 1977), i.e. within the Sanel Marl (Fig. 2), is not associated locally with an especially high abundance or a special shape of smectite. This absence of volcanic control is also indicated by the occurrence of common flakes of smectite on electron micrographs (Figs. 3, 4). The apparent lack of sedimentary or diagenetic influence on the presence of smectite, a fact still under debate (e.g. Galan et al. 1985, Sanchez et al. 1987), agrees with the study of many other sediments from the Mediterranean Basin (e.g. Chamley & Robert 1980, Azzaro et al. 1988), and suggests that *most smectites are reworked from upstream sedimentary or pedologic sources.* Such an interpretation is documented by the fact that most Messinian smectites belong to the Al-Fe beidellite group, which typically forms in exposed soils (Chamley 1989).

Palygorskite is a fibrous clay mineral that can be reworked as a detrital species much more easily than usually believed (in Chamley, 1989). In the Fortuna Basin palygorskite occurs in small amounts throughout the late Miocene series. Its abundance ranges from trace amounts to 15% of the clay minerals. Palygorskite almost everywhere displays very short fibres, evoking breakage *during transportation.* Only two episodes, one in the upper Sanel marls and the other in the lower part of lacustrine deposits of the Rambla Salada Formation, show the presence of larger particles arranged in bundles beside broken fibres (Figs. 3B, 4B). This suggests that palygorskite formed in marine sediments or exposed soils close to the deposition area (e.g. Millot 1964), and that the distance of transportation was short. The abundance of palygorskite is not correlated with the presence of saline evaporites (e.g. Tale Gypsum) or with other chemical or biochemical facies (e.g. Rio Chicamo Diatomite); consequently the conditions favouring the genesis of palygorskite differ from those determining other evaporative chemical environments, a fact already quoted by Trauth (1977). It is likely that palygorskite preferentially formed in calcareous crusts (calcretes) developing on the borders of the Fortuna Basin, and that it was subsequently reworked from these pedologic formations into the sedimentary environment. To summarize, palygorskite is considered as a *mainly reworked mineral in the study area.* This of course is also the case of typically terrigenous minerals such as illite, chlorite, kaolinite and random mixed-layers.

Climatic control

Smectite

Smectite represents the most abundant clay mineral in late Miocene sediments of the Fortuna Basin. This resembles what is recorded in most contemporaneous series of the Mediterranean range (Chamley et al. 1977), the Fortuna Basin displaying nevertheless values somewhat lower than elsewhere (see below, tectonic control). Smectite in most Messinian sediments is an Al-Fe beidellite, the characters of which suggest an essentially pedologic formation. Soils rich in authigenic smectite form preferentially in temperate-warm regions marked by a rather short humid season and poor drainage (in Chamley 1989). Such conditions are typical of a subarid climate. As soil products are preferentially eroded and reworked towards lacustrine and marine basins, the increase of smectite in a given basin is chiefly attributed to the development of soils on exposed areas subject to a more arid climate. The richness of smectite in Messinian sediments is therefore considered to result mainly from a priviledged pedogenic formation and to subsequent reworking (see discussion in Chamley & Robert 1980). The desiccation of the Mediterranean basins is supposed to have induced major changes in weathering processes on exposed land masses. *Smectite is interpreted as having abundantly formed in continental soils through chemical leaching under temperate-warm conditions and strong seasonal contrasts in precipitation* (*i.e. subarid climate*), typical of Messinian time. The Mediterranean salinity crisis is therefore supposed to have been associated with a peri-Mediterranean climate crisis. Of course this particular condition did not exist outside the Mediterranean where no desiccation occurred, and ended in early Pliocene time when the Mediterranean was filled again with open ocean water. The stratigraphic zones in late Tortonian and Messinian deposits of the Fortuna Basin in which this aridification is particularly obvious are the following (Figs 2, 8):

– Mamoya Marl, prior to 6.5 Ma BP, event 1: increasing amounts of smectite in open marine deposits of the upper Tortonian correlate with synchronous smectite-rich sediments in the Caltanissetta Basin, South Sicily (Chamley et al. 1986). This supports the idea that a semiarid climate responsible for the pedogenic formation of smectite became established in Mediterranean areas a fairly long time before the onset of Messinian evaporitic sediments. Indications about a late Tortonian aridification in southeastern Spain are all the more convincing since the collision of the Alboran and European plates at that time caused strike-slip movements along the Crevillente Fault (Lukowski 1988): such tectonic activity, which tended to impede the normal development of surficial soils by rejuvenation of relief, was in fact not strong enough to determine a decrease in smectite supply.

– Mamoya Marl, uppermost Tortonian, 6.5 to 6.3 Ma, event 2: a severe drop in sea level is recorded in both the Fortuna and Sorbas Basins, and is proved by the progradation of deltas and declining growth levels of coral reefs successively (Müller & Hsü 1987). The values of $\delta^{18}O$ of planktonic and benthic foraminifera are decreasing, and an increase of silt-to-sand sized detritus was noted. Maximum smectite contents fit these changes and suggest a stabilization of subarid conditions. The smectite increase just before Messinian time probably heralded the development of a negative waterbalance in the Mediterranean Sea (Benson et al. in press), the final result being the cessation of outflowing warm and saline Mediterranean deep water into the Atlantic Ocean.

– Other episodes of climatic aridification associated with a drop in sea level are indicated by smectite increases twice during the Messinian deposition of Sanel Marl and Tale Gypsum: (1) event 4, comtemporaneous with the sedimentation of the Tripoli Formation (before 5.6 Ma); and (2) event 5, synchronous with the Intra-Messinian desiccation close to 5.2 Ma. A recurrence of smectite-rich deposits occurs in the basal part of the Rio Chicamo Diatomite, which corresponds in time to the beginning of the intra-Messinian inundation (event 6).

– The last indication by smectite of semi-arid conditions occurs in late Messinian time, before the Pliocene marine ingression (event 7b), during the deposition of lacustrine marl/gypsum cycles of the Rambla Salada Formation. The latter are contemporaneous with the Lago Mare sediments in the Eastern Mediterranean Basins.

Palygorskite

The ubiquitous but not highly abundant occurrence of short and broken fibres of palygorskite in the Fortuna Basin indicates a reworking from exposed areas which may consist of Tertiary evaporative sediments or of pedogenic calcareous crusts (e.g. Singer & Galan 1984, Pozzuoli 1985). Palygorskite therefore does not usually bear any specific climatic message in Messinian sediments. Two short episodes, however, are characterized by higher amounts of this mineral, which then forms some bundles of flexuous, not broken fibres (Figs 3, 4); these episodes probably reflect *strongly evaporitic, arid conditions, favouring the growth in nearby locations of evaporative clays* (e.g. Millot 1964, Trauth 1977): (1) One episode occurs at the base of event 5 (upper Sanel marls, 5.6 Ma) and correlates with the onset of the deposition of lower evaporites. This increase in palygorskite abundance coincides with an increasing dolomite content (Müller 1986), pointing to either an aridification and Mg-carbonate formation on the basin borders or to an increasing erosion of Triassic dolomites from the northern part of the basin. (2) The other episode occurs at the base of lacustrine deposits of the Rambla Salada Formation (event 7b, about 5.0 Ma), just before a semiarid period suggested by high smectite amounts. In addition, notice that the palygorskite content tends to increase at each period marked by a lowering of sea level or by the development of lacustrine conditions (Fig. 8), which confirms its dependence on especially an arid climate.

Kaolinite

Kaolinite forms essentially in soils under warm and humid conditions, at the expense of various types of sedimentary, metamorphic or magmatic rocks (e.g. Millot 1964). The rareness or absence of kaolinite within late Tortonian-Messinian sediments in the Fortuna Basin where arid conditions have prevailed is therefore not unexpected. The very low amounts of the mineral suggest that kaolinite was hardly derived from the reworking of kaolinite-bearing rocks, and that it rather formed in and was reworked from late Miocene soils which developed particularly in the upstream zones of river basins. Only one episode is marked by a significantly increasing amount of kaolinite. This episode suggesting a *wetter climate* characterizes the Rio Chicamo Diatomite (event 6, about 5.2 to 5.1 Ma), which corresponded to the intra-Messinian inundation. Fairly humid climate during event 6 is also indicated by the lowest amounts of palygorskite (Fig. 2). During this period winds forced estuarine circulation and upwelling, providing the nutrients for the diatoms (Müller & Schrader 1989).

Tectonic and eustatic control

Despite its abundance, the average amount of smectite in the Fortuna Basin is lower than in most other contemporaneous Mediterranean or peri-Mediterranean sections (Chamley & Robert 1980). Smectite rarely reaches values as high as 75 to 80% of the clay minerals in the Fortuna Basin whereas it frequently constitutes 90 to 95% in other sections. Smectite in the Fortuna Basin is always associated with *noticeable amounts of illite, chlorite, quartz, feldspars,* all mineral species directly inherited from rocky substrates and not from soil blankets. This feature can best be explained by a *subpermanent tectonic instability in the Betic Chains* during the late Miocene (e.g. Montenat 1973, Lukowski 1988), inducing in sedimentary areas such as the Fortuna Basina a constant reworking of rock-derived instead of soil-derived minerals. The steepness of slopes combined with the proximity of continental sources determined a subcontinuous erosion of substrates and prevented the extensive formation of smectite-rich soils.

The major changes recorded in the relative abundance of the illite group can basically be attributed to variations in tectonic activity on the exposed areas surrounding the Fortuna Basin, periods of *uplift* favouring an increased supply alternating with relaxation stages which generated pedogenic smectites. However, this scenario *may have been complicated by sea level changes,* which occurred several times during the late Miocene and which could have positively or negatively affected the clay supply. A drop in sea level associated with a tectonic uplift would a priori intensify the reworking of the illite group (relief rejuvenation) while a rise in sea level could have invalidated such an effect. It is therefore necessary to consider the clay mineral changes in a geological context, as well defined as possible.

Three major increases of the illite group amounts are recorded in the sections studied (Figs. 2, 8): (1) just above the Fenazar conglomerate in lower Sanel marls (events 3, 4); (2) just above the Wichmann conglomerate in marine Rambla Salada marl/gypsum alternations (Fig. 7, event 7a); and (3) as a short episode near the base of Rio Chicamo Diatomite above Tale Gypsum (samples RCD 32 and 33, Fig. 6, event 6). These three episodes are considered *to reflect particularly high tectonic activity* (Montenat et al. 1987, Lukowski 1988): (1) An unconformity at the Tortonian-Messinian boundary, noted in several Betic Neogene Basins, was created by very intense deformation in the Fortuna Basin (uplift and strike-slip movement); in the nearby Sorbas Basin fairly high amounts of chlorite were also measured in contemporaneous sediments of the Azagador Member and the base of the Abad Member (Chamley & Robert 1980. (2) The clastic Wichmann bed expresses a significant deformation in the Fortuna Basin. This tectonic event could well be the prelude to the pre-Pliocene uplift in southeastern Spain, leading to the deposition of lacustrine sediments during the latest Messinian. Notice that in both cases the tectonic rejuvenation is apparent in the clay assemblages of common marly sediments, that are located above coarse clastic deposits contemporaneous with the deformation: this points to the sensitivity of clay mineral variations to tectonic events. (3) The short illite increase at the base of the diatomites also correlates with a probable deformation phase after the deposition of the Tale Gypsum (Lukowski 1988). But a rapid fall in sea level could also have contributed to this mineral change, since the samples are located very close to selenitic gypsum layers suggesting shallow-water sedimentation (Müller 1986, Lukowski 1988, Müller & Schrader 1989). In this case it is especially difficult to discriminate between the effects of tectonic movement and sea level change.

In contrast to tectonic activity, the sea level changes usually do not appear to have significantly controlled the variations of the clay mineral assemblages in the Fortuna Basin. Sea level drops such as those registered during the deposition of upper Mamoya marls, upper Sanel marls and Tale Gypsum, and upper Rambla Salada sediments, are characterized by unchanged or decreasing amounts of the illite group, a trend opposite to that normally expected (Fig. 8). In a general way the Messinian deposits, which correlated with desiccation phases and low sea levels, were marked by an increase in smectite rather than in illite abundance. This does not mean that sea level variations are always of little importance in the control of the detrital minerals supplied to a basin. We must nevertheless admit that the climatic constraints more effectively controlled the clay mineral assemblages than did eustatic changes in the Fortuna Basin during late Miocene times. Recall also that at the Miocene-Pliocene boundary in the Mediterranean domain, the sudden increase of the illite group and the clay mineral diversification were determined by a general climatic change, at a time marked by a major rise in sea level (Chamley & Robert 1980).

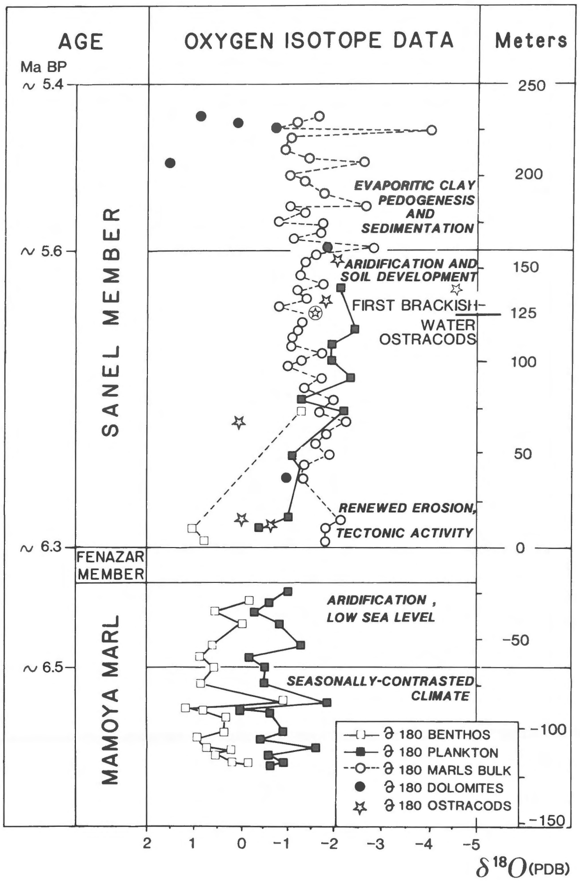

Fig. 9. Marmoya Marl and Sanel Marl. Oxygen isotope data (Müller & Hsü 1987) compared to clay mineral interpretations (italics).

Possible correlation to oxygen isotope data (foraminifera, ostracods)

Data by Müller & Hsü (1987) for Mamoya and Sanel Marls allow to consider possible relationships between clay mineral and oxygen isotope data (Fig. 9). Prior to 6.5 Ma, the seasonally contrasted climate corresponds with a marine environment which had a well developed surface to deep temperature gradient. The climate was subarid. A seasonally induced precipitation allowed rivers to deposit eroded sediments on the shelfs. The sedimentary record shows the presence of turbiditic horizons. One of these could be represented by the negative $\delta^{18}O$ shift at -84 m.

From 6.5 to 6.3 Ma, the oxygen isotope values of benthonic foraminifera tend to become slightly more negative. The temperature gradient between the surface and bottom water decreases. This could be interpreted as a warming of the bottom water due to a shallower basin, caused by a drop in sea level. Such a change concurs with a continental aridification, a rainfall depletion causing frequently a temperature increase. An increasing influence of freshwater is not very likely, because the surface water isotope ratios are around the average.

From 6.3 to 5.6 Ma, illites suggest a rapid erosion of source rocks at the beginning of this interval. The planktonic foraminifera $\delta^{18}O$ values become systematically more negative. This indicates a change in temperature from 20 to 28° C, if we assume a constant δw (= 0.5‰. Müller 1986). The clay minerals indicate aridification which agrees with a temperature increase. But the first occurrence of brackish water ostracods at 125 m indicates also an increasing influence of freshwater. Therefore the two effects, a temperature increase during climatic aridification and an increasing freshwater influence due to in drop sea level, are probably combined and it is difficult to discriminate the respective influence of each. The oxygen isotopes of the carbonate fraction of the marls show small variation throughout this interval. The brackish water ostracods at 125 m are correlated with the faunal break in the Sorbas Basin (around 5.8 Ma), when sea level started to drop 50 to 100 m as reported in Müller & Hšu (1987). In the Fortuna Basin this event is followed by the presence of freshwater ostracods with a very negative oxygen isotope ratio. That and the previously decreasing $\delta^{18}O$ values of the foraminifera would suggest a freshwater environment. But the fact that the ostracods above this event have $\delta^{18}O$ values similar to those of the planktonic foraminifera could also suggest that these freshwater ostracods were washed into a lagoonal or brackish water environment.

From 5.6 to 5.4 Ma, the onset of large variations in the $\delta^{18}O$ of the carbonate fraction of the marls and positive values in the dolomites are in close relation with the noteworthy occurrence of palygorskite. Palygorskite suggests more evaporitic, arid conditions, favouring the growth of magnesium-bearing clays in nearby locations. This interpretation is supported by the fact that the dolomites have positive $\delta^{18}O$ values relative to the values recorded between 6.3 and 5.6 Ma. These sabkha-like dolomites were compared to similar settings belonging to the Tripoli-Formation of Abu Dhabi (Müller & Hsü 1987). The dolomites were transported from evaporite ponds to the nearby Fortuna Basin. In the same way palygorskite was incorporated in the upper Sanel marls. The negative spikes in the marls may express strong freshwater periods and/or turbiditic influences. The gypsum arenite layers in between these marls also suggests the presence of evaporite ponds around the Fortuna Basin.

Conclusion

1. The clay mineral study of late Miocene sediments from the Fortuna Basin, Southeastern Spain, provides information about the sedimentary, tectonic and paleogeographic evolution in the westernmost Mediterranean domain during late Tortonian and Messinian. Such information supports the interpretations previously given for the circum-Mediterranean area (Chamley et al. 1986), with some distinctive features due to the position of the Fortuna Basin within the Betic seaway. The synsedimentary control on clay assemblages appears to be of minor importance since most mineral species were reworked from the basin borders or adjacent continental areas. This is obvious for typically terrigenous minerals such as illite, chlorite, kaolinite, random mixed-layers, and associated quartz or feldspars. A similar conclusion arises from x-ray diffraction and electron microscope investigations for smectite and palygorskite. Clay minerals in the Fortuna Basin appear to have been reworked from either rocky substrates, or from late Miocene sediments and surficial soils cropping out upstream. A pedologic origin followed by a reworking fits particularly well to justify the abundance of smectite flakes, and of usually short and broken palygorskite fibres. The almost complete independence between the clay mineralogy and the marine or nonmarine character of the environment, or the presence of volcanic, saline, biosiliceous or carbonate particles, agrees with such widespread reworking.
2. The relative proportions of the different clay mineral species strongly vary along the late Miocene sedimentary column. The comparison of mineralogical data and published geological information reveals that variations in climate and tectonic activity were responsible for the major changes registered in the clay stratigraphy. By contrast changes in sea level appear to have been of minor importance. This kind of paleoenvironmental control seems to especially characterize southeastern Spain during that period, since the continental climate experienced a severe aridification during the Mediterranean desiccation and the tectonic instability in the Betic Chains was particularly strong. In a general way, increasing amounts of smectite and sometimes of palygorskite express aridification, whereas high values of illite and associated chlorite and quartz designate major episodes of tectonic activity. The climatic effects are probably obliterated during episodes of intense tectonic activity. Kaolinite is usually very rare or even absent in the sections studied, which confirms the dominantly arid character of soil-formation.
3. The late Miocene clay mineral stratigraphy in the Fortuna Basin area mirrors the effects of the following paleogeographic changes (Fig. 8), which correlate with the main events registered in the Mediterranean range (e.g. Müller & Hsü 1987):
   - Late Tortonian, before 6.5 Ma BP, marine Mamoya Marl: relief flattening, seasonally-contrasted climate.
   - Latest Tortonian, about 6.5 to 6.3 Ma, sea level drop ending in a freshwater facies on top of the Mamoya Marl: strong aridification on land, pointing to the occurrence of specific climatic changes and pedogenesis before the onset of the Messinian salinity crisis.
   - Earliest Messinian, after 6.3 Ma, lower Sanel marls overlying Fenazar conglomerates: tectonic activity (uplift) expressed in the fine-grained clayey deposits.
   - Early Messinian, before 5.6 Ma, Sanel Marl

passing from open marine to regressive facies: progressive aridification on land favouring the growth of smectite-rich soils.

- Late Messinian, about 5.6 to 5.2 Ma, upper Sanel Marl and Tale Gypsum contemporaneous with the deposition of Lower Evaporites and a major intra-Messinian desiccation: successive development of evaporative clay facies (palygorskite-bearing calcareous soils and perhaps sediments) and of renewed aridification in continental areas.
- Late Messinian, 5.2 to 5.1 Ma, Rio Chicamo Diatomite, synchronous with a major intra-Messinian inundation: relative increase of continental humidity, suggested by kaolinite and preceded by a short tectonic rejuvenation possibly accompanied by a drop in sea level.
- Latest Messinian, 5.1 to 4.9 Ma, Rambla Salada Formation: the successive episodes indicated by clay variations include a tectonic uplift related to the Wichmann bed deposition (illite group), the development of evaporative clay correlative to first lacustrine marl/gypsum alternations (palygorskite bundles), a last aridification (smectite), and finally a mineral diversification probably announcing the Pliocene climatic and environmental changes in the Mediterranean domain.

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