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Middle to Late Miocene marine ecostratigraphy: clay minerals, planktonic foraminifera and stable isotopes from Sicily

Clay minerals
Planktonic foraminifera
Stable isotopes
Miocene paleoenvironment
Sicily

Minéraux argileux
Foraminifères planctoniques
Isotopes stables
Paléoenvironnement Miocène
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ABSTRACT

Distinct changes during the Middle to Upper Miocene in the clay mineral composition of the Caltanissetta Basin, Sicily, permit the distinction of seven intervals, which jointly cover the time-span from about 14.6 to 5.3 MY. The boundaries between these intervals coincide with major, presumedly Atlantic-born changes in the abundance patterns of planktonic foraminifera. First-order changes in the clay mineral record are expressed also in the stable isotopes patterns.

Major changes in the physico-chemical and biotic records occurred in the Serravallian ($\simeq$13.8 and 12.8 MY), at the transition from the Serravallian to the Tortonian ($\simeq$10.6 MY), in the Tortonian ($\simeq$8.7 and 7.2 MY) and at the Tortonian-Messinian boundary (5.6 MY). The synchronism of these changes in the biotic and abiotic records is attributed to the complex interplay between climatic fluctuations, sea-level changes and tectonically-controlled paleogeographic reorganizations in the central Mediterranean during the Middle and Late Miocene.

A tentative scheme is proposed in which the biotic and abiotic paleoenvironmental changes in the Sicilian record are correlated with the succession of sporomorph associations in the eastern Mediterranean and with continental chronostratigraphic units and regional stages of the Paratethys.

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RÉSUMÉ

Écostratigraphie du Miocène marin moyen à supérieur : données des minéraux argileux, foraminifères planctoniques et isotopes stables du bassin de Caltanissetta, Sicile

Des modifications nettes des assemblages argileux terrigènes sont constatées dans le bassin de Caltanissetta, en Sicile, au cours du Miocène moyen à supérieur. Elles permettent l'identification de trois zones principales, subdivisées en 7 sous-zones, qui couvrent la période 14, 6-5, 3 M.A. B.P. Les limites entre ces intervalles coïncident avec des changements majeurs dans les assemblages de foraminifères planctoniques. Les principales zones minéralogiques reconnues correspondent en outre à des caractères particuliers des isotopes stables de l'oxygène et du carbone des tests calcaires.

Les modifications principales des marqueurs physico-chimiques et biogènes se situent au Serravallien (environ 13,8 et 12,8 M.A.), à la transition Serravallien/Tortonien (environ 10,6 M.A.), au cours du Tortonien (environ 8,7 et 7,2 M.A.) et à la limite Tortonien/Messinien (5,6 M.A.). Le synchronisme entre ces changements des composants biotiques et abiotiques des sédiments est attribué à une interaction complexe

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entre les fluctuations du ciment continental et marin, du niveau de la mer, des relations Atlantique-Méditerranée, et de l'activité tectonique en Méditerranée centrale et occidentale.

Les changements observés dans les successions sédimentaires marines de Sicile pourraient avoir une signification plus globale, ainsi que le suggèrent les correspondances constatées avec les associations de sporomorphes de Méditerranée orientale, ainsi qu'avec les unités chronostratigraphiques de la Paratethys.

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INTRODUCTION

Recently Chamley (1983) summarized the data that have become available on the qualitative and quantitative distribution of clay minerals of Mediterranean late Neogene marine sequences. These data show that the analyses of clay mineral associations provide a useful tool in unraveling tectonic and climatic signals in the Mediterranean marine record. Clay mineralogy is especially powerful when applied to long and continuous time-series in combination with microfossil and stable isotope data. Integrated clay-mineralogical and micropaleontological studies have already been performed on several Quaternary and Pliocene sequences (Blanc-Vernet *et al.*, 1969; Chamley, 1975; Cita *et al.*, 1977) but are lacking for the Mediterranean Miocene. A unique opportunity of exploring the potential of an integrated approach in the Mediterranean Miocene was offered by the presence of samples from the Giammoia-Falconara series in Sicily (Fig. 1), from which foraminiferal frequencies and stable isotope data were already available.

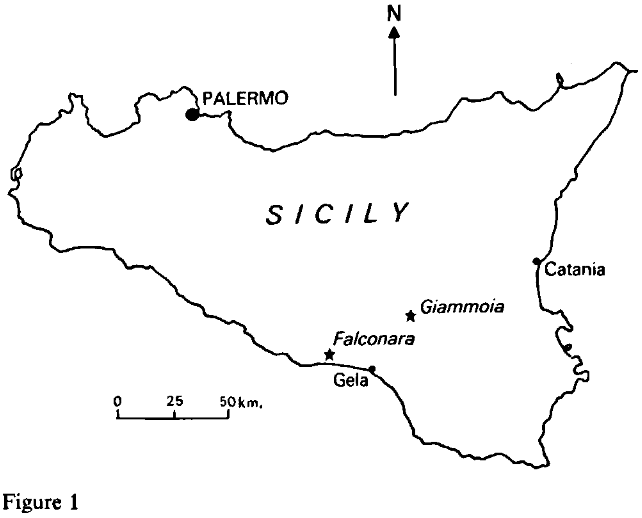

Figure 1

Location of sections Giammoia and Falconara, Caltanissetta Basin, Sicily.

Localisation des coupes de Giammoia et Falconara, bassin de Caltanissetta, Sicile.

GEOLOGICAL SETTING, SECTIONS AND SAMPLES

The Giammoia and Falconara composite sequence comprises 180 metres of hemipelagic clays which pass upwards into diatomites and limestones of the Messinian (Fig. 2). Organic-rich interbeds are frequently

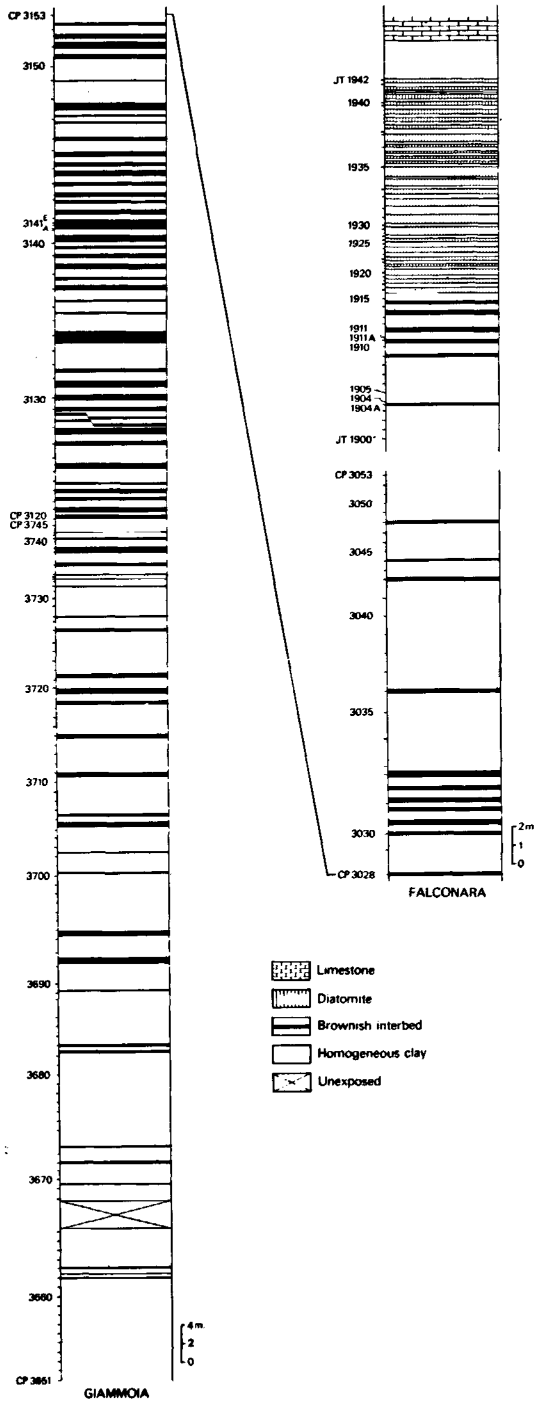

Figure 2

Lithostratigraphic columns of sections Giammoia and Falconara.

Lithostratigraphie des coupes de Giammoia et Falconara.

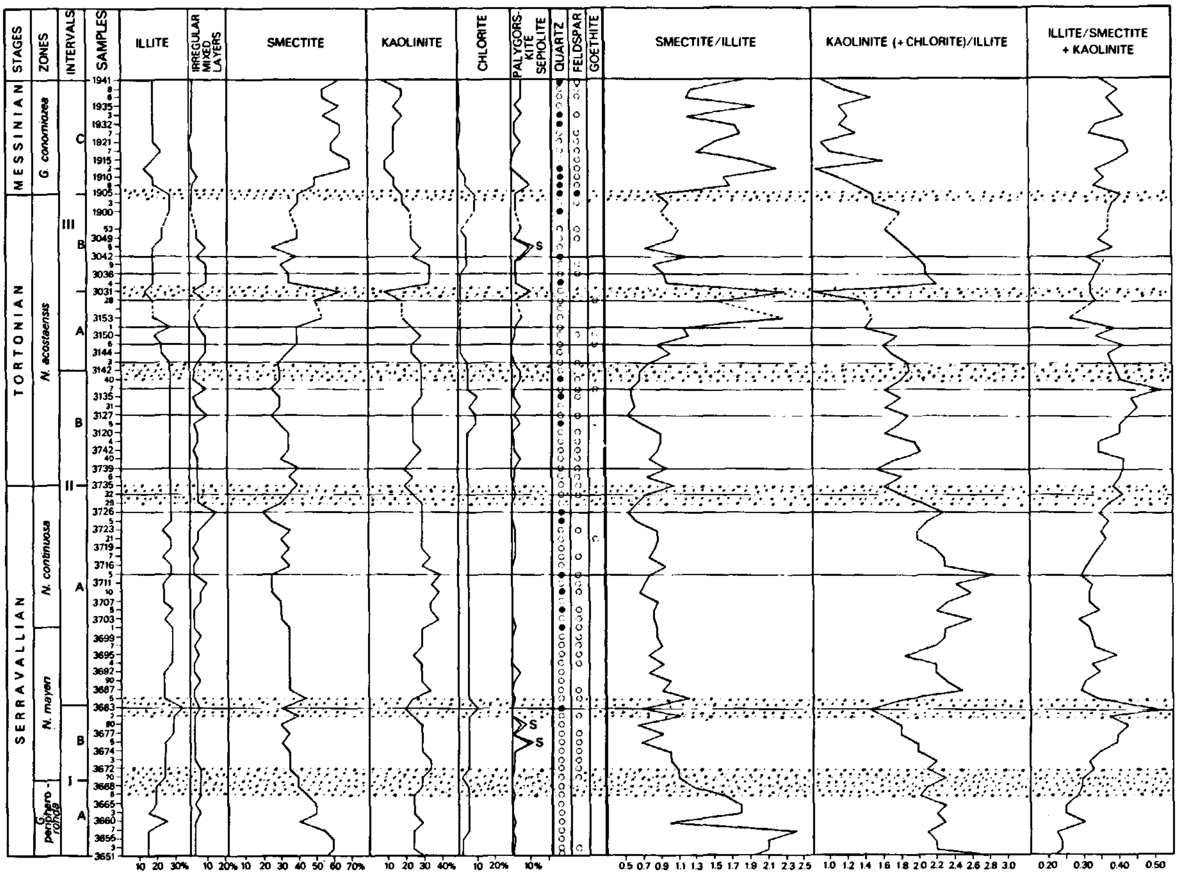

Figure 3

Percentage estimates of clay minerals, distribution of non-clay minerals and ratios of clay minerals along the composite column of sections Giammoia-Falconara. Horizontal lines refer to samples taken from sapropelitic interbeds; shading marks the position of the transitions between the successive clay mineral intervals.

Proportions des minéraux argileux et associés et rapports d'abondance relative. Les traits horizontaux correspondent à des niveaux sapropéliques, les bandes en pointillé aux transitions entre intervalles (I, II, III) et sous-intervalles (A, B, C) minéralogiques.

intercalated in the hemipelagic clays. Biostratigraphically the sequence embraces the planktonic foraminiferal *G. peripheroronda-G. conomiozea* zones (Zachariasse, Spaak, 1983) and the calcareous nannofossil zones NN6-NN10 (Theodoridis, 1984). The geochronostratigraphic scale is based on the extrapolation of the accumulation rates calculated for the interval between the FAD (first appearance datum) of *Globorotalia conomiozea* and the LAD (last appearance datum) of *G. menardii* 4, the ages of which are 5.6 and 6.6 Ma, respectively (Langereis *et al.*, 1984).

The studied sequence overlies the "argille scagliose" which represents the highest unit of a thick autochthonous succession and underlies the (par)autochthonous post-Lower Miocene sediment cover in the Caltanisetta Basin. The multicoloured clays of the "argille scagliose" originated from the decollement of parts of the older sediment cover is the north and their transport by gravity-sliding to the south, into the rapidly subsiding "pre-Caltanissetta Basin" (Meulenkamp *et al.*, 1981). The northern margin of this basin is bounded by the Mt. Kumeta-Alcantara shear zone of Ghisetti and Vezzani (1982). The Caltanissetta Basin proper originated in the course of the Late Miocene and its present contours were shaped in Plio-Pleistocene time.

Poorly exposed Uppermost Burdigalian and Lower Langhian hemipelagic sediments are sandwiched between the base of the (almost) continuously exposed Giammoia and Falconara sequence and the "argille scagliosa". These older sediments may be partly incorporated in the "argille" and are not studied.

CLAY MINERALS

X-ray diffraction analyses were performed on 87 samples and applied to oriented pastes of decalcified sediments (particles smaller than 2 µm). The data set of the diatomite unit was obtained from clay interbeds, the amount of clay minerals from the diatomite proper being too low for reliable analyses. The results of the X-ray analyses are graphically represented in Figure 3, by semi-quantitative data and specific rations measured on glycolated-samples diagrams (smectite/illite = 18/10 Å; kaolinite (+chlorite)/illite = 7/10 Å; illite/smectite + kaolinite = 10/18 + 7 Å).

The relative abundance calculations on glycolated samples in combination with the percentage estimates of clay and non-clay minerals permit the distinction of three major units (I, II, III), which can be further subdivided into altogether seven intervals. The average values of the ratios concerning smectite (s), kaolinite (k) and illite (i) in the successive intervals are given in Figure 4.

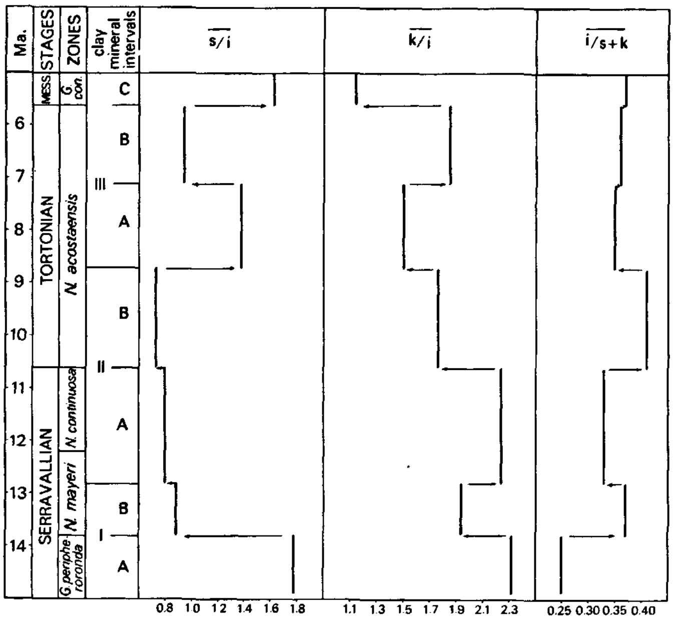

Figure 4

Average values of the smectite/illite (s/i) kaolinite/illite (k/i) and illite/smectite + kaolinite (i/s + k) ratios in the successive clay mineral intervals of the Giammoia-Falconara series.

Valeurs moyennes des rapports smectite/illite (s/i), kaolinite/illite (k/i) et illite/smectite + kaolinite (i/s + k), dans les intervalles et sous-intervalles minéralogiques.

The clay mineral associations lack any indication of secondary alteration in the marine environment, which is in accordance with observations on other Mediterranean Upper Cenozoic sediments (Emelyanov, 1972; Mélières *et al.*, 1978; Monaco, 1981; Chamley *et al.*, 1982; Chamley, 1983). Thus changes in the composition of clay mineral associations could reflect changes in the nature and intensity of pedogenesis and erosion in the hinterland.

Smectite is formed mainly in poorly-drained soils in downstream parts of drainage systems under warm, semi-arid conditions, whereas kaolinite formation is favoured by humid conditions in upstream, well-drained soils. Palygorskite and sepiolite are formed in restricted, alkaline environments (Millot, 1964; Weaver, Beck, 1977; Chamley *et al.*, 1980; Clauzon, Robert, 1984). The amount of illite-micas is a measure for the amount of unaltered "source-rock" from which smectite and kaolinite are formed. Thus the kaolinite/illite ratio may be interpreted in terms of the relative amount of kaolinite formed in upstream, humid and rather warm areas, whereas the smectite/illite ratios reflect the relative amount of smectite formed in downstream, poorly-drained, warm areas.

The high relative amounts of smectite and kaolinite and the low amounts of illite and non-clay minerals in the lowermost part of the sequence point to the existence of a mature drainage system providing large amounts of kaolinite from upstream, humid, and of smectite from downstream, semi-arid and warm areas. Probably the Caltanissetta Basin was situated in the (sub)tropical belt and bordered by a vast, relatively flat landmass. The positive correlation between the s/i and k/i ratios in unit I, caused by the increase of illite-micas, suggests a general decrease of soil formation, both in downstream and upstream areas, in the course of the Serravallian. This assumption is supported by the increase of rock-derived, non-clay minerals, such as feldspars. The increase of illite-micas and non-clay minerals may have been related to a sustained, strong rejuvenation of the subaerial relief, caused either by a eustatic sea-level lowering or by tectonic uplift. Such a rejuvenation would have impeded the formation of surficial soils (Diester-Haass, Chamley, 1983). From the differences between the s/i and k/i patterns one might infer that smectite formation in the downstream areas started to decrease earlier than kaolinite formation upstream, because the impact of an increasing relief on pedogenesis could have been larger in the immediate borderlands ("érosion régressive").

The effects of the lowering of the base level of erosion obliterates any clear climatic signal that might be inferred from the changes in the composition of the clay mineral associations in unit I. One might speculate, however, that the relatively high amounts of palygorskite and the occurrence of sepiolite in interval IB reflect an increased aridity, although reworking could be an alternative explanation. In the Late Serravallian interval IIA, environmental conditions were completely different from those before. The pronounced drop of the i/s + k ratio across the boundary between units I and II and the high relative amount of kaolinite in interval IIA suggest increased pedogenesis and the predominance of kaolinite-rich soil formation. Probably the paleogeographic setting was characterized by the existence of fairly pronounced reliefs in a relatively stable hinterland where such kaolinite-rich soils could develop under humid conditions. More humid climatic conditions of the Late Serravallian can also be inferred from palynological data (Bessedik, 1985).

At about the transition from the Serravallian to the Tortonian (transition IIA-IIB) the supply of kaolinite decreased, whereas the amount of smectite in the Upper Serravallian interval IIA and the Tortonian interval IIB is roughly the same. This may reflect a decrease in annual rainfall. Increased aridity under unchanged paleogeographic conditions, however, would imply an increase of smectite formation in downstream areas. Therefore, the changes across the Serravallian-Tortonian boundary may better be explained as having been caused by a renewed rejuvenation of the relief. This assumption is in line with an increased supply of rock-derived minerals (indicated by the increase of the i/s + k ratio) from the latest Serravallian onward.

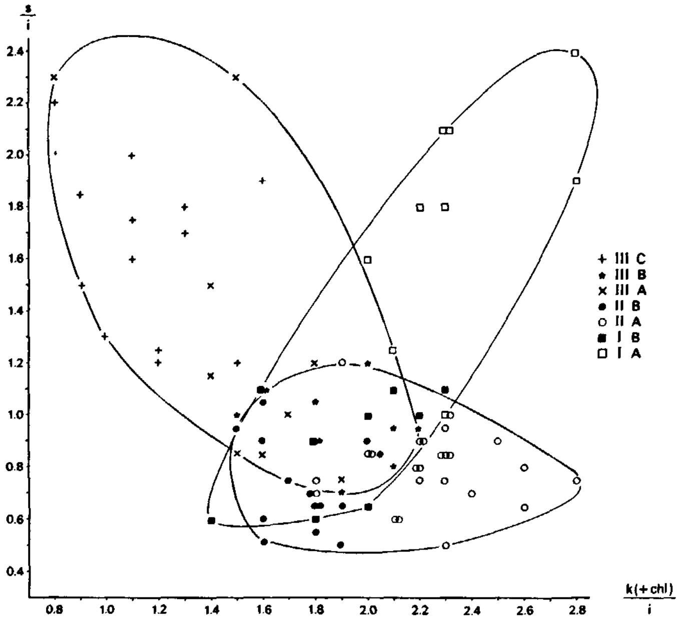

Figure 5

Relation between the smectite/illite (s/i) and kaolinite (+chlorite)/illite (k(+chl)/i) ratios in the clay mineral associations of the Giammoia-Falconara series.

Relations entre les rapports smectite/illite (s/k) et kaolinite (+chlorite)/illite (k(+chl)/i) dans les divers intervalles et sous-intervalles minéralogiques.

During the Late Tortonian and Early Messinian unit III the environmental conditions in the borderlands of the Caltanissetta Basin had changed fundamentally. The inverse relationship between the s/i and k/i ratios (Fig. 4, 5) suggests alternating periods with development of smectite-rich soils in poorly-drained and of kaolinite-rich soils in well-drained areas. This alternation was most probably controlled by climatic fluctuations.

The conspicuous increase of smectite and the associated decrease of kaolinite and of illite-micas in the Late Tortonian interval IIIA suggest an important flattening of the relief and the development of smectite-rich soils in vast borderlands under semi-arid conditions. This flattening of the relief was caused either by peneplanation or by sea-level rise.

In the latest Tortonian interval IIIB there may have been a return towards more humid climatic conditions, as indicated by the sudden and strong increase of kaolinite and concomittant decrease of smectite at the transition IIIA-IIIB. The ensuing decrease of kaolinite in interval IIIB seems to have been roughly balanced by a staggering increase of the supply of rock-derived illite-micas. This suggests a lowering of the base level of erosion, due to a glacio-eustatic lowering of the sea-level or to tectonic uplift.

At about the transition from Tortonian to Messinian (transition IIIB-IIIC) conditions became favourable again for the widespread development of smectite-rich soils. This was probably due to a major aridification and a flattening of the relief of the borderlands, which flattening must be attributed to a relative sea-level rise. Apparently fairly similar environmental conditions must be postulated for the late Tortonian interval IIIA and the Early Messinian interval IIIC. These conditions were defined by seasonal contrasts in humidity, which favoured the formation of smectite in surficial, poorly-drained soils and prevented the formation of kaolinite in relatively better drained areas (Millot, 1964; Chamley, 1983). During the Messinian the development of smectite-rich soils was accentuated by the effects of the Messinian salinity crisis (Chamley, Robert, 1982).

PLANKTONIC FORAMINIFERA

The percent distribution of planktonic foraminiferal species in the composite section of Giammoia-Falconara (Fig. 6) is based on counts of the size-fraction greater than 125 µm of 198 samples. The percent distribution plot has previously been presented and reported on by Zachariasse and Spaak (1983). Comparison between the frequency distribution patterns and the clay mineral record shows that boundaries between clay mineral intervals are associated with prominent faunistic changes. The boundary between clay mineral intervals IA and IB is time-correlative with the disappearance of *Globorotalia peripheroronda*. This species is the first evolutionary form of the tropical *G. fohsi* group and is wide-spread in the Early-Middle Miocene of the North Atlantic. In the Middle Miocene *C. peripheroronda* vanishes from the mid to high latitudes of the northeast Atlantic and from the Mediterranean, whereas its evolutionary successors have been reported from low latitudes only (as far as latitude 33°N, Berggren, 1984).

Apparently the extermination of *Globorotalia peripheroronda* in the Mediterranean is closely bound up with a dramatic contraction of the distribution area of the *G. fohsi* group in the North Atlantic. The migration of the *G. fohsi* group, to some degrees of latitude south of the Mediterranean gateway(s), prevented phylogenetically advanced forms from entering the Mediterranean. The strong reduction in latitudinal extent of the tropical *G. fohsi* group is a first indication for southward migrating cool waters. Serravallian climatic cooling conditions are reflected also by the upward decrease in the abundance distributions of the thermophylic groups of *Globigerinoides trilobus* and globoquadrinids, which attain highest numbers in clay mineral interval IA.

Slightly above the extermination of *Globorotalia peripheroronda* (in the basal part of clay mineral interval IB) *G. partimlabiata* arrives abruptly in the Sicilian record. In the northeast Atlantic DSDP Holes 397 and 398 the FAD of *G. partimlabiata* is reported from time-equivalent levels: off Portugal (Hole 398) postdating the LAD of *G. peripheroronda* (Iaccarino, Salvatorini, 1979). Also in the superbly preserved record of the northeast Atlantic DSDP Hole 369A (off northwest Africa) the beginning of *G. partimlabiata* is abrupt and time-correlative with its appearance in the Mediterranean (Zachariasse, in prep.). Contrary to the Mediterranean and DSDP Hole 398, and in conformity with DSDP Hole 397,

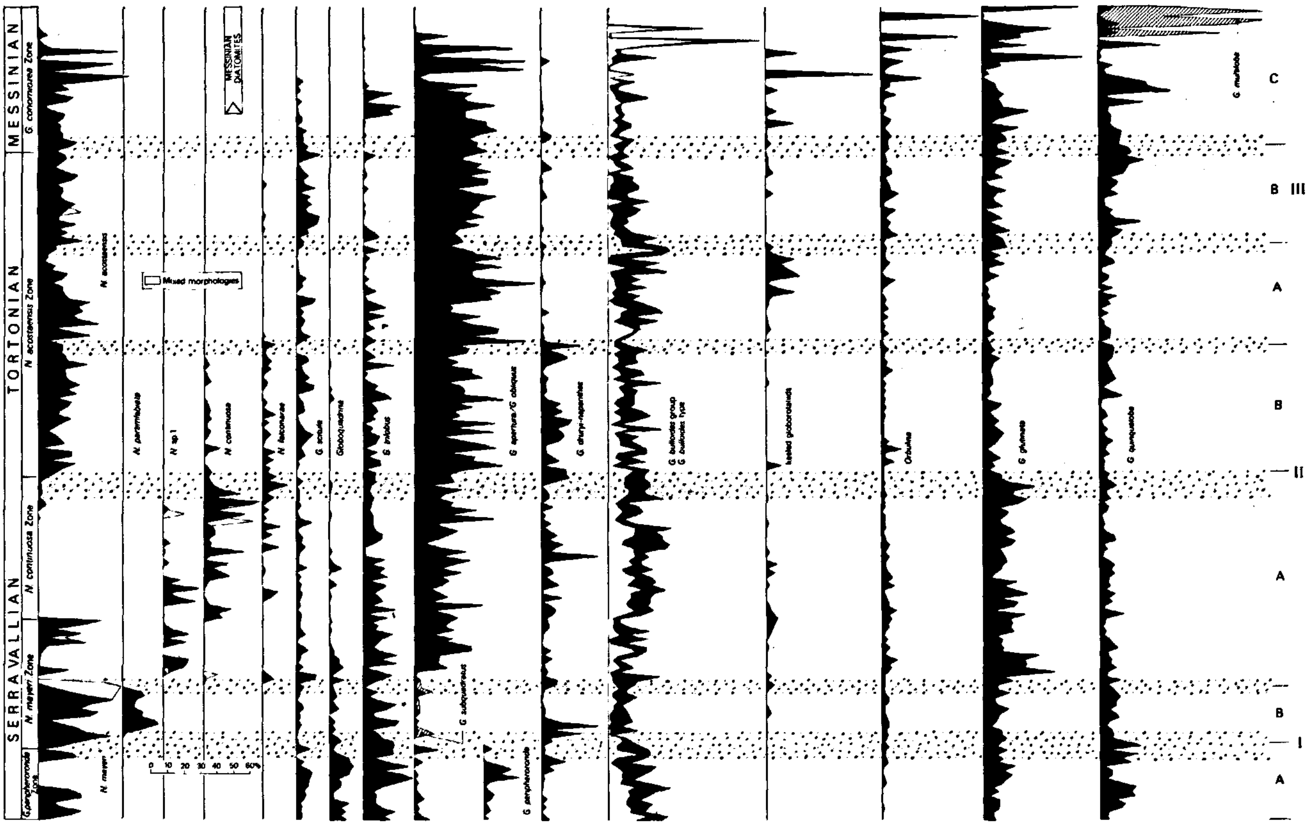

Figure 6

Frequency distribution patterns of planktonic foraminifera in the Giammoia-Falconara series (after Zachariasse and Spaak, 1983). *Shading marks the position of the transitions between the successive clay mineral intervals.*

Distribution en fréquences des foraminifères planctoniques dans la série de Giammoia et Falconara (d'après Zachariasse et Spaak, 1983). Les bandes en pointillé correspondent aux transitions entre les divers intervalles (I, II, III) et sous-intervalles (A, B, C) minéralogiques.

G. partimlabiata in DSDP Hole 369A co-occurs with (keeled representatives of) the *G. fohsi* group. Unfortunately, sedimentary gaps truncate the vertical range of *G. partimlabiata* in the northeast Atlantic DSDP Holes 369A, 397 and 398. In the Mediterranean *G. partimlabiata* (including specimens previously singled out as *Neogloboquadrina* sp. 1: Zachariasse and Spaak, 1983; *see* also Fig. 6) extends its range up into the uppermost part of clay mineral interval IIA.

All evidence together clearly indicates that the sudden spreading of *Globorotalia partimlabiata* in the Mediterranean and in the area off northwest Africa results from migration. The close affinity of *G. partimlabiata* with the cool-water species *G. zealandica* suggests that the biogeographic origin of *G. partimlabiata* lies in the temperate North Atlantic. Preliminary results obtained from DSDP Hole 400A (Gulf of Biscay) and Hole 406 (Rockall Plateau) strongly support the northern biogeographic origin of *G. partimlabiata.* The sudden arrival of this species, therefore, indicates that the inflow of cool water into the Mediterranean, signalled first at the top of clay mineral interval IA, sustained well into interval IB.

The transition from clay mineral interval IB to IIA is associated with the massive increase in the combined frequency of *Globigerina apertura* and *Globigerinoides obliquus.* The abrupt and massive arrival of *Globigerina apertura-Globigerinoides obliquus* in Sicily seems to be a Mediterranean-wide phenomenon and has been said to mark the replacement of a dominant tropical fauna by a subtropical one (Zachariasse, Spaak, 1983). If this is true, the Mediterranean faunal turn-over must be mirrored in the northeast Atlantic faunal record. Amongst material provided by the Deep Sea Drilling Project from Holes 369A, 397 and 400A, that of Hole 369A contains a high-quality, Serravallian, faunal record showing a subdued counterpart of the high-amplitude shift in the Mediterranean frequency pattern of *Globigerina apertura-Globigeronoides obliquus.* Unfortunately, Holes 397 and 400A contain a poor-quality faunal record due to extensive reworking and strong dissolution respectively. Without additional data from more northerly located DSDP Sites the preliminary results from DSDP Hole 369A are not conclusive enough fully to support the earlier view in which the abrupt and massive spreading of *Globigerina apertura-Globigerinoides obliquus* in the Mediterranean is interpreted as an Atlantic-borne signal. For the present we surmise that the extinct group of *G. apertura-G. obliquus* could have thriven in stratified and low productive waters such as exemplified by central watermasses. The massive spreading of *G. apertura-G. obliquus* in the Mediterranean at the base of clay mineral interval IIA, therefore, could indicate that from that time onwards the Mediterranean became the easternmost extension of the North Atlantic subtropical gyre, lodging a subtropical association admixed with northern elements. In this view, the flourishing of *G. apertura-G. obliquus* basically mirrors an oceanic signal, which could have been amplified by a tectonically governed increased hydrographic isolation of the Mediterranean, leading to steepened density gradients and allied low surface water productivity. Augmented numbers of *Globigerinita glutinata*, high abundances of large-sized *Globigerina bulloides*, the vanishing of the warm water species *Neogloboquadrina mayeri*, and the dominance of the cool water species *N. continuosa* in clay mineral interval IIA (Fig. 6) indicate that Serravallian cooling conditions temporarily culminated in the Late Serravallian *Neogloboquadrina continuosa* zone.

The transition from clay mineral interval IIA to IIB correlates with the boundary between the *Neogloboquadrina continuosa* and the *N. acostaensis* Zone. At this boundary sinistral *N. acostaensis* start to dominate over dextral *N. continuosa.* This conspicuous change in morphology and coiling of the Mediterranean neogloboquadrinids most probably reflects a shift in the areal distribution of two different forms: the dextral, tightly-coiled *N. continuosa* being associated with cool-water conditions and the sinistral, loosely-coiled *N. acostaensis* being indicative of warmer water conditions. If true, the cool-water species drops off at the expense of the warm-water forms at the transition from clay mineral interval IIA to IIB, which could monitor a climatic amelioration and concomitant weakening of the eastern boundary current.

Climatic warming conditions close to the transition from clay mineral interval IIA to IIB are reflected also by the frequency drop of large-sized *Globigerina bulloides*, and *Globigerinita glutinata*, the slight increase in the abundance of the warm water group of *G. nepenthes-druryi*, as well as by the disappearance of *Globorotalia partimlabiata* from the Mediterranean record. Unfortunately, Upper Serravallian-Lower Tortonian faunal records are missing in DSDP Holes drilled in the northeast Atlantic due to the wide-spread occurrence of erosional gaps (Salvatorini, Cita, 1979; Cita, Vismara Schilling, 1980).

The next-younger and distinct faunal change is positioned halfway within the *Neogloboquadrina acostaensis* Zone, at the transition from clay mineral interval IIB to IIIA. This change is marked by the drop in frequency of the *G. nepenthes-druryi* group, the vanishing of *N. continuosa* and of globoquadrinids and the highest common occurrence of *N. falconarae.* The true significance of these faunistic changes is difficult to understand fully. The common to frequent presence of *G. nepenthes* and globoquadrinids in the upper Miocene of DSDP Hole 366A (Sierra Leone Rise; Krasheninnikov, Pflaumann, 1978) and the relatively high numbers of *G. nepenthes* and the continuous presence of globoquadrinids in the Upper Miocene of DSDP Holes 369A (Krasheninnikov, Pflaumann, 1978) and 397 (Salvatorini, Cita, 1979) indicate that *G. nepenthes* and globoquadrinids are correctly interpreted as warm-water taxa. The vanishing of globoquadrinids shortly before the frequency drop of the group of *G. nepenthes-druryi* may therefore signal the return to climatic cooling conditions at the transition from clay mineral interval IIB to IIIA.

Dextral neogloboquadrinids persistently dominate the *N. acostaensis* Zone of DSDP Hole 400A (Gulf of Biscay; Zachariasse, in prep.), whereas at the same time sinistral neogloboquadrinids thrive in the Mediterranean. The absence of dextral neogloboquadrinids in the upper half of the *N. acostaensis* Zone of the Mediterranean attests to the low-amplitude character of the postulated climatic cooling. Dextral neogloboquadrinids did not invade the Mediterranean until the latest Miocene (Zachariasse, 1975).

The boundaries between clay mineral intervals IIIA-IIIB and IIIB-IIIC are correlative with the top of an acme interval of keeled globorotaliids and the FAD of *Globorotalia conomiozea*, respectively. *G. conomiozea* and the younger, dextral, *Neogloboquadrina acostaensis* represent successive invasions of "northern intruders" indicating that Late Miocene cooling conditions culminated in the Messinian. The response of the Mediterranean fauna to an almost interrupted connection between the Mediterranean and the Atlantic Ocean in latest Miocene time is exemplified by the highly fluctuating and alternating frequencies of the eurytopic, epipelagic species *G. bulloides, G. quinqueloba, G. multiloba, G. glutinata* and *Orbulina universa.*

In conclusion, the planktonic foraminiferal record of the composite sections of Giammoia-Falconara contain a great number of Atlantic-borne faunistic changes which essentially reflect successive stages in the Middle to Late Miocene paleobiogeographic and paleoceanographic evolution of the northeast Atlantic-Mediterranean and global climate. Surprisingly, these faunistic changes have well-correlatable counterparts in the clay mineral record.

STABLE ISOTOPES

Stable isotope analyses were performed on the planktonic foraminiferal species *Globigerinoides trilobus* and *G. obliquus* from 84 samples. Analyses on 30 of these samples (from the Falconara section) formed part of an earlier study (Van der Zwaan, 1982); for the present study 54 additional samples from the Giammoia section were analyzed.

The oxygen and carbon isotope patterns (*see* Fig. 7) are very complex and it is difficult to give a straightforward interpretation. Therefore, only overall trends are discussed here. The data and a detailed interpretation are presented by Van der Zwaan and Gudjonsson (1986).

From the Giammoia section mainly specimens of *Globigerinoides trilobus* were analyzed, where in the Falconara section only *G. obliquus* was abundant enough. In order to calibrate these data, the two species were analyzed in nine samples where they were both frequent. This resulted in an estimate of the average difference, the $\delta^{18}O$ values of *G. obliquus* being $0.35^0/_{00}$ heavier and the $\delta^{13}C$ values being $0.7^0/_{00}$ lighter than those of *G. trilobus*. In Figure 7 the values of *G. trilobus* are adjusted correspondingly.

In order to simplify the isotope patterns, we constructed a three-point moving average curve of the stable isotope values (Fig. 8); in the calculation of these three-point moving averages we disregarded the laminated samples. The $\delta^{18}O$ and $\delta^{13}C$ curves indicate that some major events are recorded in the Giammoia-Falconara sequence. A conspicuous one is marked by a considerable shift in the average $\delta^{18}O$ towards lighter values across the transition from interval IB to IIA. If this shift is interpreted in terms of temperature, it would imply a considerable warming of the surface waters. In theory a warming is not impossible and there is no real evidence from the stable isotopes that such an increase in temperature did not take place. However, in interval IIA a significant negative correlation exists between the $\delta^{18}O$ and the $\delta^{13}C$ values (Van der Zwaan, Gudjonsson, 1986). The latter shift to heavier values. Since the $\delta^{13}C$ composition is independent of temperature (Emrich *et al.*, 1970) one has to conclude that at least another factor next to temperature is involved in

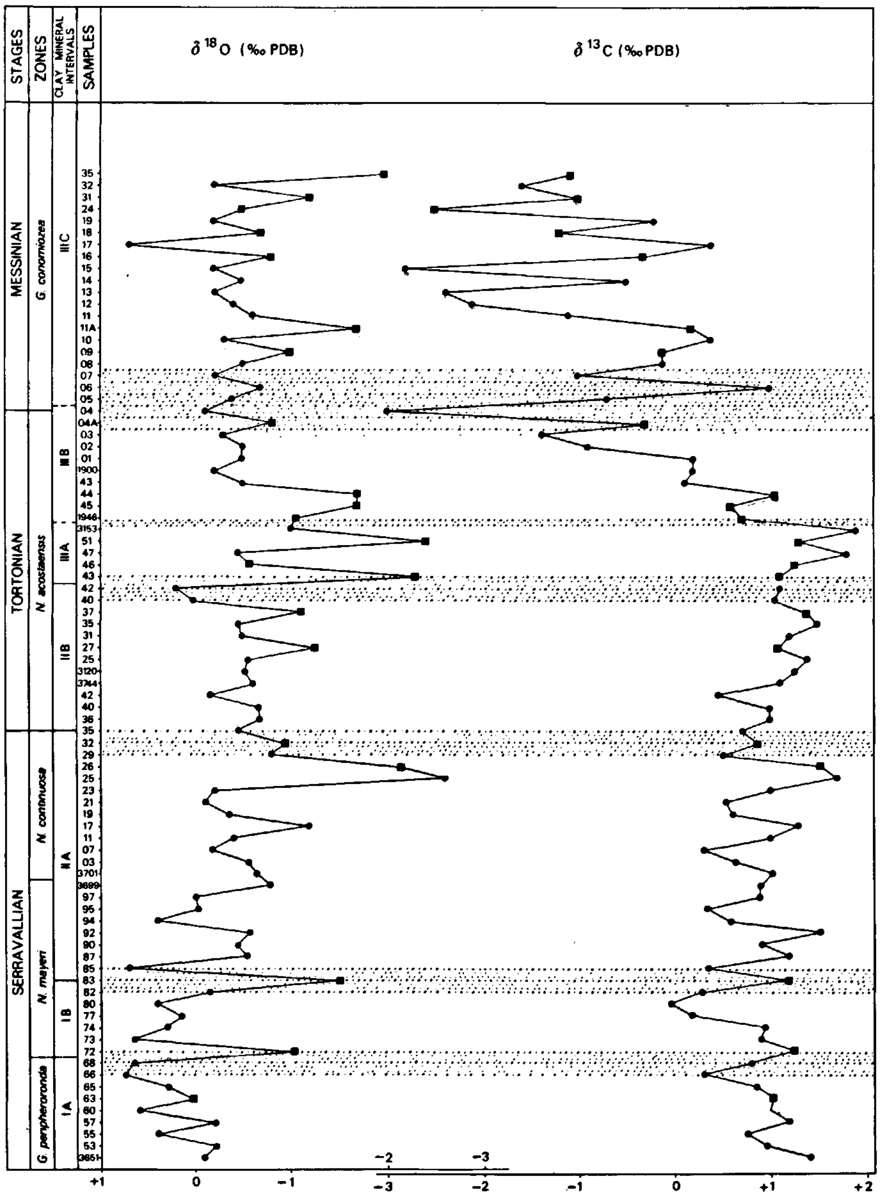

Figure 7

Oxygen and carbon isotope values of planktonic foraminifera in the Giammoia-Falconara sections. ■: samples from sapropelitic interbeds; shading marks the position of the transitions between the successive clay mineral intervals.

Données des isotopes de l'oxygène et du carbone des tests de foraminifères planctoniques, dans les divers intervalles et sous-intervalles identifiés par la minéralogie des argiles dans les coupes de Giammoia et Falconara. ■ : données relatives à des niveaux sapropéliques.

the determination of the oxygen isotope pattern. This is supported by planktonic foraminiferal evidence from this part of the section and data from the open ocean (Shackleton, Kennett, 1975; Haq, 1980; Woodruff *et al.*, 1981; Thunell, Belyea, 1982) which indicate the onset of a considerable cooling rather than a warming during this time span (*see* section on planktonic foraminifera).

An alternative explanation for the trends in stable isotope values can be found in a considerable lowering of the surface water salinity. One could hypothesize that, due to a restriction of the Mediterranean inflow/outflow patterns, a strongly stratified watermass came into existence. A hindrance of the outflow would result in increasing salinities of the deeper water and would cause the increasing separation between these deeper waters and the less saline inflowing surface water. When the mixing of the surface water with the deeper Mediterranean waters decreased, the surface water increasingly preserved its characteristics, *i.e.* a relatively low salinity, which caused a shift to relatively light $\delta^{18}O$ values. At the same time, the development of the pronounced stratification would result in a strongly reduced reflux of isotopically light carbon from deeper waters, thus causing a shift to heavier $\delta^{13}C$ values of the surface-water CO_2 (McKenzie, 1982). In this model the isotope trends starting at the base of interval IB could signify an important paleogeographic event.

There is no reason to assume that. Apart from the salinity trend, the other fluctuations in the oxygen isotope patterns are temperature independent. This would imply that interval IA is characterized by a progressive cooling, followed by a slight warming in interval IB. In interval IIA the smaller fluctuations are rather obscured by the salinity trend, but it seems safe to assume relatively cool temperatures in the larger part of interval IIA. At the top of interval IIA a considerable warming can be postulated, whereas from that time onwards the Miocene record is characterized by a rather irregular shift to slightly cooler values. The cooling trend starting at the transition IIA-IIB was only interrupted by a low amplitude warming in interval IIIA.

The average $\delta^{13}C$ values indicate some important changes throughout the record, independent of the $\delta^{18}O$ pattern. The generalized, three-point moving average curve indicates four levels of particular interest, which coincide more or less with the clay mineral intervals. In interval IB the carbon isotope record shows a significant excursion towards lighter values. In fact, this excursion already starts in interval IA. A second important change can be observed in interval IIB where the values shift to heavier ones; this trend culminates in the middle of interval IIIA. Intervals IIIB and IIIC are each characterized by strong drops to negative values. These drops are separated at the transition from interval IIIB to IIIC by a shift to less negative values.

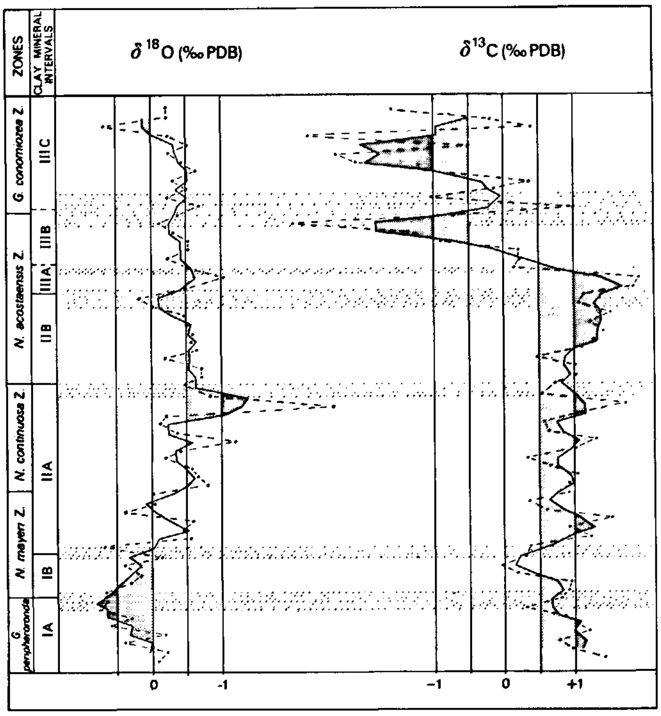

Figure 8

Three-point moving averages of the $\delta^{18}O$ and $\delta^{13}C$ values in the Giammoia-Falconara series (full line). Dotted lines record isotopic averages without samples from laminae interbeds.

Moyennes, par série de trois niveaux voisins, des valeurs de $\delta^{18}O$ et $\delta^{13}C$ dans la série de Giammoia-Falconara (lignes pleines). Les lignes pointillées correspondent au même regroupement, à l'exclusion des niveaux à laminations.

The carbon isotope chemistry is considerably less well understood than the chemistry of oxygen isotopes and there are a number of models to explain changes in the carbon isotope patterns (*see* discussions in *e.g.*; Berger *et al.*, 1981; Andersen, Arthur, 1983). In the Giammoia-Falconara record, however, we are dealing with changes of considerable magnitude (1-3 $^0/_{00}$), especially when compared with the oceanic record. In view of the magnitude of the shifts, we have to conclude a substantial input of isotopically light carbon in the case of the negative excursions. It seems that the only likely mechanism to transfer such amounts of carbon is by a considerable sea-level change (Van der Zwaan, Gudjonsson, 1986). Broecker (1982) advanced the hypothesis that a lowering of the sea-level could cause an increase in the supply of isotopically light carbon which had previously been stored in carbonates and organic matter on the shelves. If true, the carbon isotope pattern would imply considerable lowering of the base level of erosion in intervals IB, IIIB and the higher part of IIIC. Especially the shifts to lighter values of intervals IIIB and IIIC would have been of great magnitude. The shift to more positive values, starting in interval IIB and culminating in interval IIIA, would in this model indicate a considerable sea-level rise. In fact, the pattern of sea-level changes which are inferred from the Giammoia-Falconara carbon isotope record, is very similar to the pattern of global sea-level changes as given by Vail *et al.* (1977; *see* also Keller, 1981).

Of particular interest is the carbon shift which starts in interval IIIA. The beginning of the shift can be dated at about 7.0 Ma and it culminated at about 5.6 Ma. It could thus very well be correlative to the oceanic carbon event, which is widely recognized (Bender, Keigwin, 1979; Vincent *et al.*, 1980; Bender, Graham, 1981; Savin *et al.*, 1981), although the magnitude of the Mediterranean shift is much greater. However, as yet it is difficult to establish whether the Mediterranean and oceanic shift were the common response to some global event.

DISCUSSION - CONCLUSION

1) Relative abundances of clay minerals and planktonic foraminifera, and the stable isotope ratios, show a number of time equivalent changes, the interpretation of which is summarized in Figure 9. The planktonic foraminiferal patterns are thought to be primarily shaped by climatic fluctuations. The net results of these climatic changes point to an overall climatic deterioration and a stronger inflow of cool Atlantic water into the Mediterranean in the course of the Middle-Late Miocene.

A similar conclusion can be drawn from the clay mineral record. Bearing in mind that the main source area of the clay minerals was located north of the present Caltanissetta Basin, the long-term change in clay mineral composition might indicate that the climatic regime of the hinterland shifted from (sub)tropical to (semi-arid) temperate in the course of the Miocene.

2) In addition to the climatic signals, the stable isotope and clay mineral record indicate significant sea-level fluctuations controlled either by climate (glacio-eustatic) or by tectonics (tectono-eustatic). A first pronounced sea-level drop is manifested in clay mineral interval IB (Fig. 9). The change in clay mineral association indicates that this sea-level fall originates from tectonic processes corresponding with the final break-up of the hitherto existing vast and relatively flat hinterland of the Caltanissetta Basin. This sea-level fall is clearly reflected in the carbon isotope record as well. Concomittantly the planktonic foraminiferal record shows the replacement of a tropical association by a subtropical one, suggesting the onset of climatic cooling conditions during the Late Serravallian. This cooling is partly masked by salinity changes in the oxygen isotope record. However, the stable isotope record suggests that during that time the Mediterranean watermass became increasingly stratified.

The onset of climatic cooling conditions and the associated sea-level drop in the Upper Serravallian interval IB correlate well with a global fall in sea-level reported by Vail *et al.* (1977) and is furthermore roughly synchronous with several extra-Mediterranean regional events of global importance. Amongst these are the isolation of the Red Sea (El-Heiny, Martini, 1981; El-Heiny, 1982), the isolation of the Paratethys (Rögl, Steiniger, 1983), and the definitive submergence of the shallower parts of the Iceland-Faroe Ridge (Nilsen, Kerr, 1978; Schnitker, 1980). All these events may have contributed to the well-known Middle Miocene global cooling. The effects of the Red Sea area and the definitive submergence of the Iceland-Faroe Ridge on global climatic conditions and oceanic circulation are nicely summarized by Van Hinte (1982) and Schnitker (1980), respectively. Inevitable in their scenarios is the expansion of the Antarctic icecap, global climatic cooling and reinforced oceanic circulation. The processes pictured by Schnitker (1980) may have been strongly assisted by the injection of Mediterranean Intermediate Water into the flow of NADW ever since the Late Serravallian. The stable isotope record from the Giammoia-Falconara sequence suggests that during the Late Serravallian the Mediterranean changed into

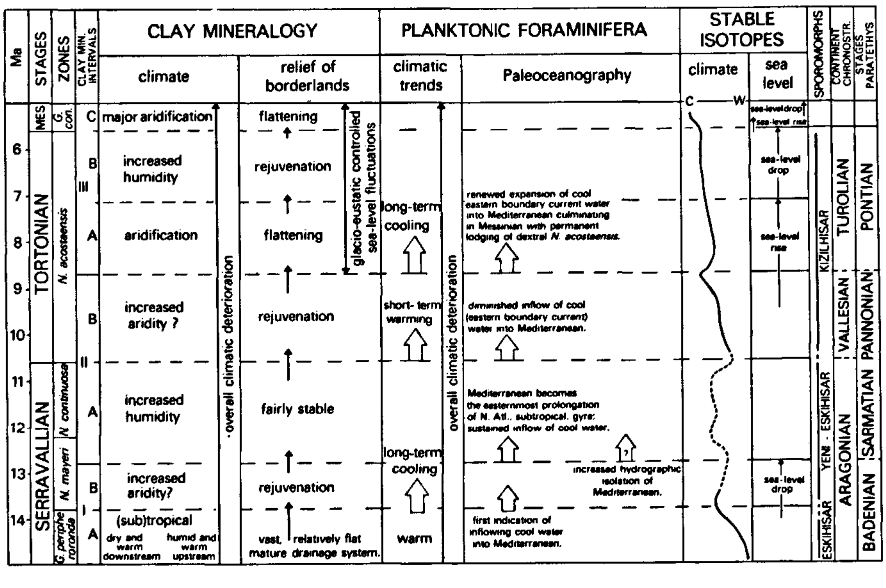

Figure 9

Compilation table summarizing the main conclusions inferred from the integrated study of clay minerals, planktonic foraminifera and stable isotopes of the Giammoia-Falconara series. Tentative correlations with the ranges of sporomorph associations and some continental and paratethyan stages are incorporated.

Tentative d'interprétation synthétique des données minéralogiques, microfaunistiques et isotopiques du Miocène moyen à supérieur du bassin de Caltanissetta (Sicile). Essai de corrélation avec les données polliniques, et avec les coupures stratigraphiques continentales et paratethysiennes.

a semi-enclosed basin with a lagoonal circulation which may have followed from the isolation of the Paratethys and, hence, the interruption of Mediterranean-Indopacific water exchange. It is worth mentioning here that the Late Serravallian palaeogeographic and climatic changes are clearly reflected in the overall Mediterranean flora composition as well. During the Late Serravallian the Eskihisar sporomorph association was replaced by the Yeni-Eskihisar one (Benda, Meulenkamp, 1985).

3) At the Serravallian-Tortonian boundary interval (transition IIA-IIB), clay mineral changes suggest a rejuvenation of the reliefs, while the planktonics and the stable isotopes suggest a climatic amelioration after a period of cooling in the later part of the Serravallian. Fundamental changes in paleogeography and basin configurations and climate-controlled changes in the general composition of floras at the Serravallian/Tortonian transition have been reported from other parts of the Mediterranean as well (*e.g.*, Meulenkamp, 1979; 1985; Benda *et al.*, 1982; Benda, Meulenkamp, 1985). In terms of mammal stages the Serravallian-Tortonian boundary interval corresponds to the transition from the Aragonian to the Vallesian, marked by the immigration of *Hipparion* in Europe.

4) Fundamental changes in clay mineralogy, composition of planktonic foraminifera and stable isotope patterns emphasize the impact of a major intra-Tortonian event, at about 8.7 MY ago, expressed by the change in the relation between the smectite/illite and kaolinite/illite ratios and the frequency drop of the *Globigerina nepenthes-druryi* group at the transition IIB-IIIA. The clay mineralogy suggests the beginning of a period (Late Tortonian-Early Messinian, intervals IIIA, B, C) in which environmental conditions became largely defined by climatic fluctuations, which seem to have been connected with glacio-eustatic controlled sea-level changes. The stable isotope record is in line with this assumption. Planktonic foraminifera suggest the onset of a renewed cooling after the Early Tortonian warming phase, at the transition IIB-IIIA.

It should be emphasized that these major changes in the Mediterranean occurred well before the beginning of the Messinian, which conclusion is supported by pronounced shifts in the $\delta^{13}C$ already starting in the IIB-IIIA transitional interval. These shifts indicate an intra-Tortonian sea-level rise, followed by two cycles of considerable sea-level lowering, one of which is intra-Messinian.

It is tempting to speculate on correlative counterparts of the intra-Tortonian event in the continental record and in the Paratethyan realm. Probably the major changes inferred from the Sicilian record (transition IIB-IIIA) correspond to the transition from the Vallesian to the Turolian (mammal) stages and to the large-scale changes in paleogeography and basin configurations that occurred in the Paratethys at the transition from the Pannonian to the Pontian. The position of the latter transition relative to Mediterranean marine chronostratigraphy is in line with that proposed by Rögl and Steininger (1983). Consequently we have to envisage a model in which the Messinian salinity crisis forms but an overprint on general paleogeographic/paleoenvironmental conditions originating already in Late Tortonian time, *i.e.*, about 8.7 MY ago, both in the Mediterranean proper and the Paratethys.

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