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Integrated stratigraphy and paleoenvironmental reconstruction of the Miocene series of the Châteauredon Dome, S.E. France

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Key words: Palynology, paleoenvironment, carbon and oxygen stable isotopes, Miocene, France

ABSTRACT

This study presents the results of a palynological analysis (dinocysts, spores and pollen) that are discussed with those obtained from stable isotopes geochemistry ($\delta^{13}C$ and $\delta^{18}O$) on Miocene coastal and continental deposits in the southern area of the Digne Valensole Basin. Palynology study has been conducted on dark levels while isotopic analysis was performed on paleosol carbonate nodules.

Stratigraphic attributions based on palynology are restricted to dinoflagellate cysts associations as spore and pollen assemblages are scarcely identified. They confirm the stratigraphy based on the micromammal fossil sites and propose an Aquitanian to early Serravallian age. From a selection of ODP-DSDP sites, the marine $\delta^{13}C$ chemostratigraphy shows several characteristic isotopic intervals. These were also identified on the continental signal from the paleosols.

Stratigraphic interpretation from the isotopic continental signal is in good agreement with both palynological data and micromammal sites attributions. It can offer a high resolution correlation, a few 100 kyr when paleosols are frequent and $\delta^{13}C$ fluctuations significant. The method puts also in evidence hiatuses (during middle Aquitanian and late Burdigalian) and precise the age of formations interbedded between micromammal sites.

Regarding paleoenvironmental reconstruction, the palynological study is more efficient than isotopic data and shows a flora evolution from mesothermic riparian and coastal vegetation during Aquitanian/Burdigalian to herbaceous and more open vegetation during the Langhian period in association to a drier and warmer climate.

This study brings also new insights on paleogeographic reconstructions. The studied area was located close to the sea coast during the lower Miocene. Marine incursions occurred during the middle Aquitanian and from late Burdigalian to early Serravallian. These are characterized by tidal facies as well as dinoflagellate cysts and benthic foraminifera occurrences. These marine incursions, better recorded in the eastern part of the Châteauredon Dome, argued for a northern or a southern connection with the Miocene sea in relation to the foreland basin geodynamic evolution.

RESUME

Cette étude présente les résultats de la palynologie (kystes de dinoflagellés, spores et pollen) discutés avec ceux de la géochimie des isotopes stables ($\delta^{13}C$ et $\delta^{18}O$) réalisée sur les séries côtières et continentales d'âge miocène dans la partie sud du bassin de Digne. L'étude palynologique a été réalisée sur des niveaux noirs et les analyses isotopiques sur les nodules carbonatés des paléosols.

Les attributions stratigraphiques sont basées sur la palynologie établie à partir des associations de dinokystes et non sur les assemblages de spores et pollen, peu diversifiés. Elles confirment la stratigraphie établie d'après les sites fossilifères de micromammifères et proposent un âge Aquitanien à Serravallien inférieur. A partir d'une sélection de plusieurs sites ODP-DSDP, la chimiostratigraphie $\delta^{13}C$ marine montre plusieurs intervalles isotopiques spécifiques. Ces intervalles sont aussi identifiés sur le signal continental des paléosols.

L'interprétation stratigraphique obtenue par le signal isotopique continental concorde bien avec les données palynologiques et celles des gisements de rongeurs. Elle permet une corrélation à haute résolution à quelques 100 ka, quand les paléosols sont fréquents et les fluctuations du $\delta^{13}C$ significatives. La méthode met également en évidence des hiatus (au cours de l'Aquitanien moyen et du Burdigalien terminal) et précise l'âge des formations intercalées entre les sites de micromammifères.

Sur le plan paléoenvironnemental, l'étude palynologique, plus significative que les données isotopiques, montre une évolution de la végétation depuis une flore arbustive mésotherme de type ripisylve à littorale au cours de l'Aquitanien/Burdigalien vers une flore herbacée plus ouverte au cours du Langhien en association avec un climat plus chaud et plus sec.

Cette étude apporte de nouveaux éléments pour les reconstitutions paléogéographiques. La zone d'étude était localisée à proximité du trait de côte marin au cours du Miocène inférieur. Des incursions marines ont été enregistrées durant l'Aquitanien moyen et depuis la fin du Burdigalien jusqu'au Serravallien inférieur. Celles-ci sont caractérisées par des faciès tidaux ainsi que par la présence de kystes de dinoflagellés et de foraminifères benthiques. Ces incursions marines, mieux enregistrées dans la partie orientale du Dôme de Châteauredon, plaident en faveur d'une connexion de la mer miocène par le nord ou par le sud en relation avec l'évolution géodynamique du bassin d'avant-pays.

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Introduction

The continental or coastal formations of the foreland basins from southern France are not well tied to the international stratigraphic scale for two main reasons. The first one is that the number of fossil sites is quite limited in these series. Marine fossils such as planktonic foraminifera or nannofossils are rare (Besson et al., 2002; Callec, 2001; Montenat et al., 2001; Crumeyrolles et al., 1991; Debrand-Passard et al., 1984a, b). The benthic foraminifera that are more frequent do not provide any precise stratigraphic indication because they extend over very long periods (Lalaï, 1986; de Graciansky et al., 1982). The micromammal fossil sites provide the best stratigraphic attributions (Aguilar et al., 2003, 1999; Couëffé & Maridet, 2003; Hugueney et al., 1992; Lalaï, 1986; Mein, 1984; de Graciansky et al., 1982). However, their limited number does not permit investigating for potential sedimentary gaps such as hiatuses or unconformities.

A first attempt at calibrating these formations by using the chemostratigraphy has shown the potentiality of this method (Bialkowski, 2004; Lopez et al., 2000). However, such an approach relies on the calibration of the oceanographic data to the geomagnetic polarity time scale and on the fact that the $\delta^{13}C$ isotopic signal is considered as global.

In this study, we focussed on the palynological analysis of the Châteauredon series in order to obtain a direct correlation with the marine stratigraphy. Then, we go back to the results from the micromammal sites and the chemostratigraphy data by presenting a comparative discussion of the available data. Finally, a paleoenvironmental reconstruction is proposed by combining the palynological data with the results from the isotopic analysis.

Setting and stratigraphy

The Châteauredon area is part of the eastern Alpine foreland Basin (southeast France). It belongs to the central area of the Digne-Valensole Basin. This basin is bordered by the Durance fault system to the west, and separated from the Tertiary Barrême Basin by the Digne thrust front to the east (Fig. 1a, 1b).

The Châteauredon Formation

The Tertiary series unconformably lays over the Early Cretaceous substratum (marls and limestones alternations, marly sediments). They are composed of lagoonal to marine facies with some intercalations of continental deposits (Fig. 2a). The coastal sediments correspond to silty to sandy tidal deposits (*Ostrea crassissima*, benthic foraminifera) and to carbonate or

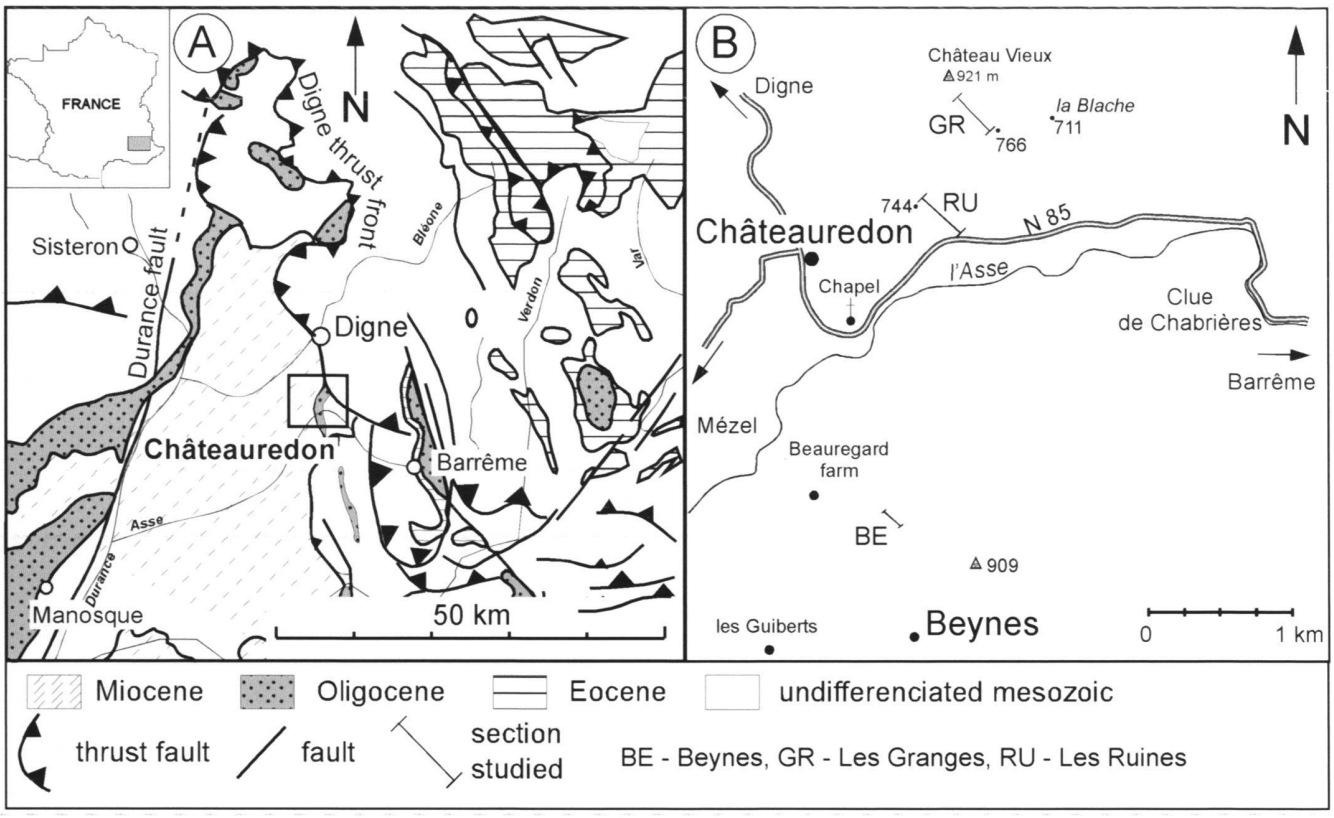

Fig. 1. A) Schematic geological map of South-Eastern France. B) Location map of the studied sections.

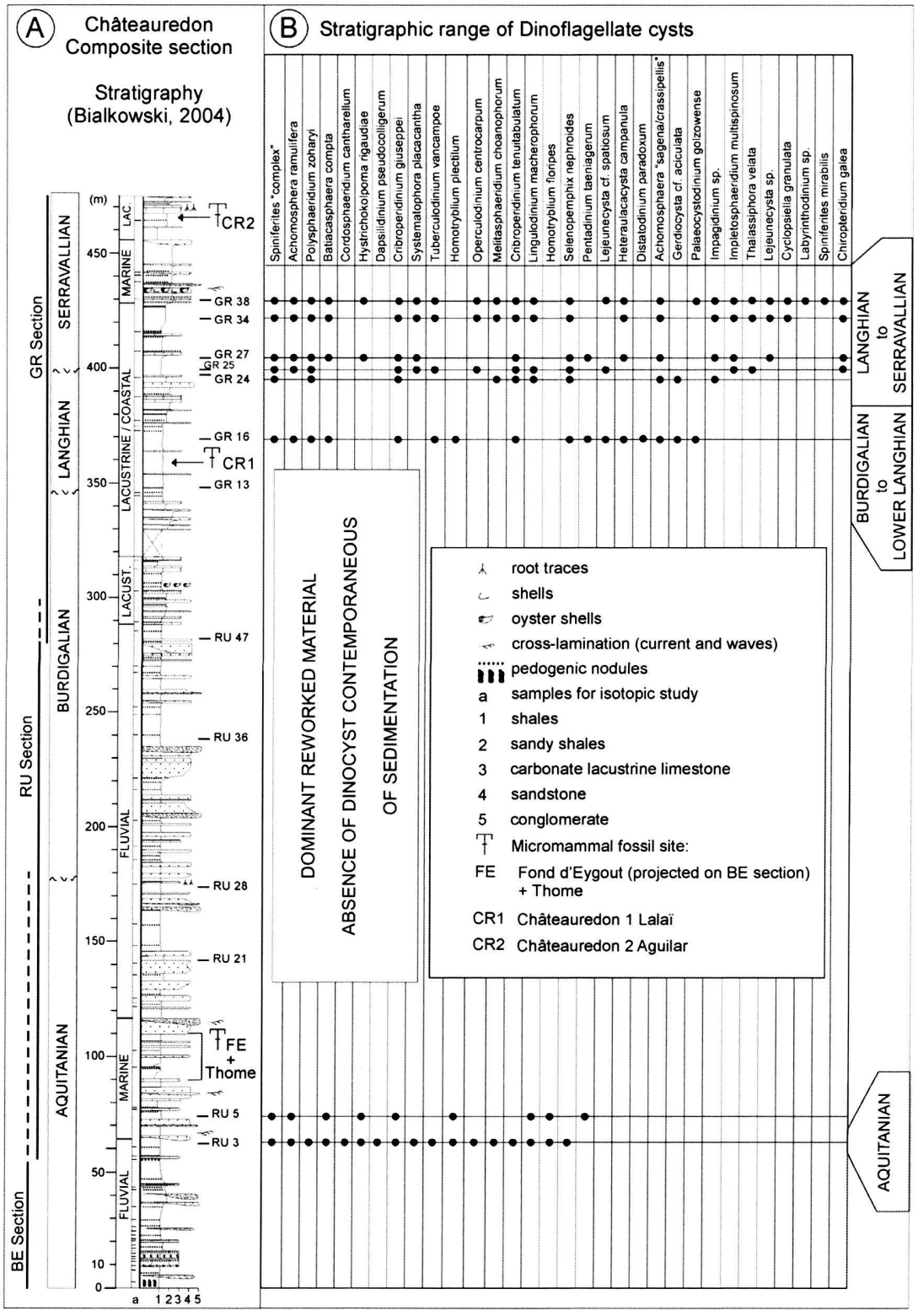

Fig. 2. Composite section of Châteauredon and palynological results
A) Lithologic column and previous stratigraphic attribution. Measured sections have been placed on the left side of the lithologic column. Palynological samples and microfossil sites are located on the right side of the composite section. B) Stratigraphic range of Dinoflagellate cysts. Occurrence of species is indicated as samples were not rich enough to permit counting.

shaly organic-rich lagoonal facies interbedded within the clastic facies. The continental deposits correspond to distal alluvial plain sediments, in the lower part of the series and to a distal fluvial system in the middle part of the section. The first continental deposits are characterized by isolated conglomeratic channels in a shaly formation that comprise numerous paleosols. Then, the fluvial facies are mainly composed of overbank alluvium modified by pedogenesis with more or less amalgamated channels of metric size, crevasse splays and palustrine carbonates of limited extension.

The Early to Middle Miocene series from the Châteauredon Dome have been investigated based on three sections that were physically correlated on the field thanks to excellent outcrops exposition (Fig. 1b). Results are presented on a composite section that has been built from the above mentioned sections (Fig. 2a): the base of the Tertiary formation is described by the Beynes section (BE) that has been measured in the southern part of the Châteauredon Dome; then, the Ruines section (RU) starts a few tens of meters above the base of the series and covers a longer stratigraphic interval; finally, the Granges section (GR) overlaps the Ruines section for the lower terms and extends to the top of the Tertiary series.

Stratigraphy

The biostratigraphy of the Châteauredon series was mainly based on three mammal fossil sites (Fig. 2a): the Font d'Eygout site (Beynes section), the Châteauredon 1 and Châteauredon 2 sites (Granges section).

The Font d'Eygout micromammal fossil site (FE) is situated in marly deposits (m1 on the geological map, de Graciansky et al., 1982). Based on field correlations it can be placed at 105 m on the composite section. This site is attributed to the MN 2 a/b zone (de Graciansky et al., 1982), which corresponds to the middle to Late Aquitanian (Mein, 1990; Lalaï, 1986; Aguilar, 1982, 1981). Another micromammal fossil site has been found close to the RU section. It is situated around 95 m on the composite section, in the stratigraphic interval of the FE site (Thome et al., 1989). It contains one of the characteristic species (*Ritteneria manca*) of the FE assemblage.

The Châteauredon 1 micromammal site (CR1) has been discovered in a lignitic interval interbedded within grey marls and lacustrine carbonates (Lalaï, 1986). This site is placed on the composite section at 360 m by field correlation. Laterally and a few hundred of meters away from this site, some marine deposits contain benthic foraminifera that give an Aquitanian/Early Langhian age (Anglada *in* Lalaï, 1986). This micromammal fossil site is attributed to MN4 (Aguilar et al., 1999, 1996), a micromammal zone that covers the late Burdigalian/Early Langhian interval. The occurrence of *Avicennia* pollen in this dark layer (Châteauneuf et al., 2006), gives an age range similar to that deduced from the micomammal fauna (Bessedik et Cabrera, 1985).

The Châteauredon 2 micromammal site (CR2) is located in a lignitic level that is situated just below the uppermost lacustrine carbonate described in the section (465 m on the composite section) (Lalaï, 1986). It has been attributed to the lower part of MN 7/8 zone (Aguilar et al., 1999) that extends from Early to Middle Serravallian interval.

The chemostratigraphy is based on the $\delta^{13}C$ signal of the carbonate nodules from the paleosols (Cojan et al., 2000; Koch et al., 1992). This continental record has been correlated to a reference marine curve based on the identification of some specific fluctuations (positive or negative excursion, bell shape evolution; Lopez et al., 2000). Six intervals were thus identified; the first terms of the series correspond to the Aquitanian and the uppermost ones to the middle Serravallian (Bialkowski, 2004). This chemostratigraphy is in agreement with the ages given by the micromammal fossil sites.

Results

The palynological results obtained during this study and the published data that have been considered are presented according to the Tertiary time scale published by Berggren et al. (1995).

Palynology

The dark levels that seemed potentially favourable for palynological analysis were sampled. Out of the 13 samples palynologically prepared, 8 samples were suitable for a detailed analysis.

Only samples from the base and the top of the section yielded organic matter suitable to identification. This organic matter contains various palynological remains contemporaneous of the sedimentation as well as reworked material. Around thirty dinocysts taxa have been identified. Their light colour and transparent appearance is distinct from those of the reworked species. However, the associations are not rich enough to carry out a significant counting. We have only considered the occurrence of the genera or species that were identified (Fig. 2b). Moreover, in the fossiliferous levels, spores and pollen are abundant enough to enable quantitative evaluations (Fig. 2c). They provide an estimation of the plant communities that were present either close to the area of sedimentation or in the uplands of the catchment area.

The stratigraphic interpretations are mainly based on the dinoflagellate cysts assemblages. Three associations have been identified (Fig. 2b):

- a) the first one, at the base of the section (RU3 and RU 5), contains among other forms *Cordosphaeridium cantharellum, Dapsilidinium pseudocolligerum, Homotryblium floripes* and *Tuberculodinium vancampoe*. The Aquitanian age proposed for this association is based on the simultaneous occurrence of the first and the last species.
- b) the second one in the middle part of the section (GR 16). The following species were identified: *Homotryblium plectilum, Heteraulacacysta campanula, Distatodinium*

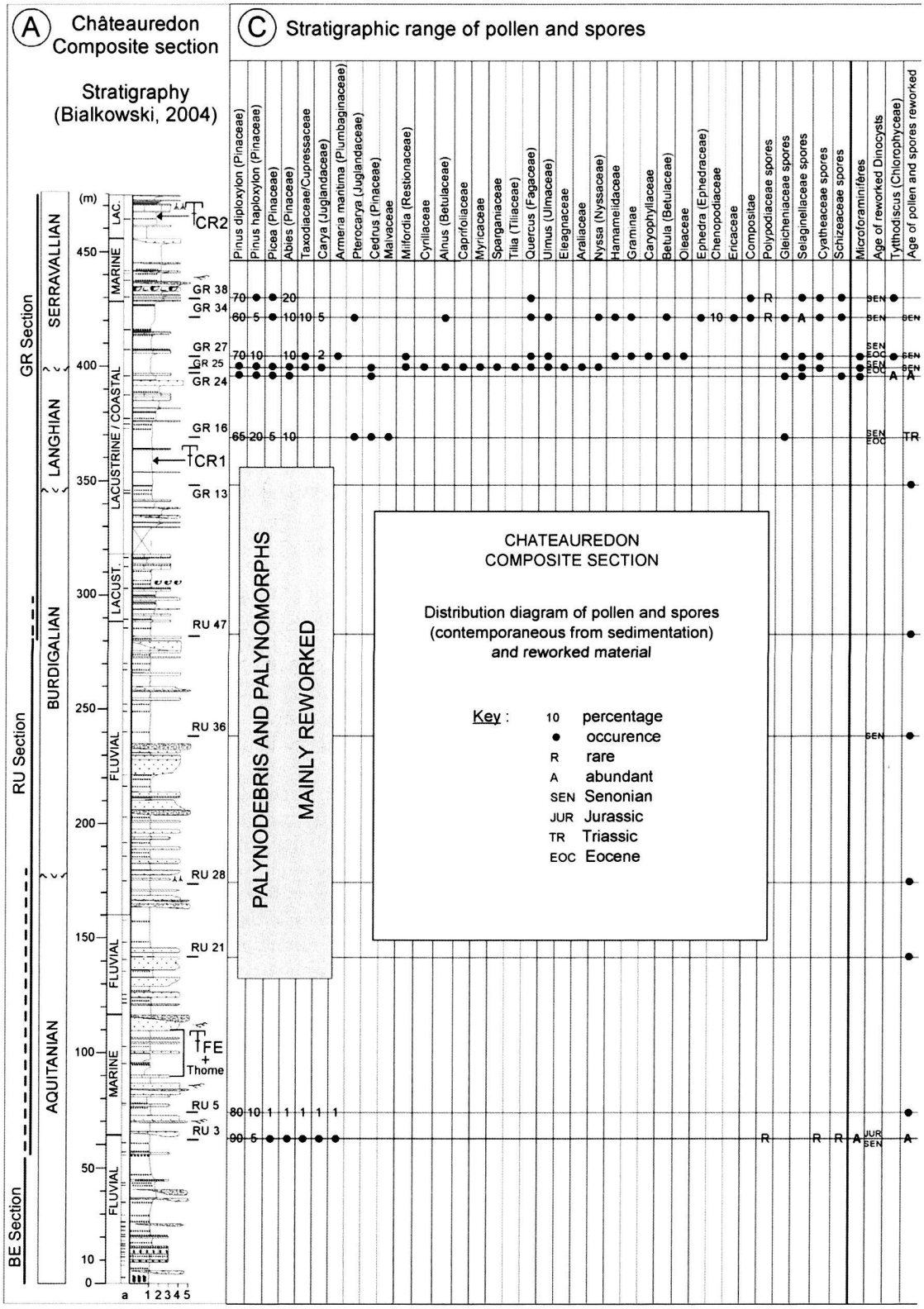

Fig. 2. Composite section of Châteauredon and palynological results
C) Stratigraphic range of pollen and spores. A semi-quantitative evaluation of the species distribution is indicated. Data are placed along the same stratigraphic column as for Fig. 2a. Legend, see Fig. 2.

Tab. 1. Selected sites for the marine isotopic reference curve. 1, Miller & Fairbanks, 1985; 2, Wright et al,. 1992; 3, Flower & Kennett, 1993; 4, Kennett, 1986; 5, Woodruff et al., 1990; 6, Barrera et al., 1993; 7, Corfield & Cartlidge, 1993; 8, Flower et al., 1997; 9, Zachos et al., 2001b. n.d. not determined.

SITE	Reference	Benthic F.	Interval (Ma)	Ocean	Paleodepth (m)
563	1,2	*Cib. spp*	12,1-28,3	N Atl.	3400
588A	3	*Cib. mundulus*	12,4-16,9	SW Pac.	1350
588C	4	*Cib coryelli*	15,1-25,1	SW Pac.	1350
608	2	*Cib. spp*	12,1-24,7	N Atl.	3115
709A,B	5	*Cib. spp*	12,1-23,7	Indian	2800
803D	6	*Cib. spp*	18,5-29	SW Pac.	n.d.
806B	7	*Cib. spp*	12,1-19,2	SW Pac.	n.d.
926A,B	8,9	*Cib.mundulus*	14-24,9	Central Atl.	3598
929A	8,9	*Cib. mundulus*	15,8-25,2	Central Atl.	4358

paradoxum, Achomosphaera sagena and *crassipellis*. A late Burdigalian to early Langhian age is attributed to this assemblage because the last known occurrences of *D. paradoxum* and *H. plectilum* in the western European Basins occur in the N7 upper part and in the lower N8 zones (Blow, 1969).

- c) the third one characterizes the upper part of the section (GR 24 to GR 38). This association includes species whose stratigraphic range extends from the Langhian to Serravallian. Nevertheless at GR38 level, it shows a renewal of the species with the presence of *Spiniferites mirabilis* and the genus *Labyrinthodinium* which could correspond to the outset of the Serravallian.

A stratigraphic attribution based on pollen is made difficult in the Neogene because of the disappearance of the main tropical guide species during the Paleogene. The rare thermophile species remaining disappeared and reappeared as a result of the climatic or hygrometric fluctuations existing until the Quaternary. Being quite careful, we assume that the species *Armeria* (close to *Armeria maritima*) and the Malvaceae appearing during the uppermost Chattian in the Tertiary Basins of Provence (Chateauneuf & Nury, 1995) were quite abundant during the Late Burdigalian/Early Langhian part of the studied section (GR 16 of the Granges section). In the same area, complementary sections well correlated with the Granges one have been recently investigated by the same authors and have yielded in levels equivalent to GR16 and CR1 beds, a megathermic microflora with an acme of *Avicennia marina* and *A. alba* (Châteauneuf et al. 2006).

Discussion on the marine isotopic data

The quality of the selected marine isotopic data is crucial for the interpretation of the continental chemostratigraphy. Among the numerous DSDP/ODP sites covering the studied interval (Chattian to Serravallian), we selected nine sites that fulfilled the following criteria (Table 1, Fig. 3):

1) The isotopic data were obtained from a single genus of benthic foraminifera. These show a better stability of the isotopic signal than those acquired from the planktonic species. The data from the genus *Cibicidoides* have been selected based on the low isotopic fractionation of this species. Despite the theoretical stability attributed to the benthic foraminifera, fluctuations from one site to the other are easily seen on Fig. 3. They show that the isotopic signal often bears local influences that have to be considered.
2) The numerical age of the site is reliable, based on a sufficient number of calibration points at well-defined depth. Stratigraphic calibration of the sites is either based on biostratigraphy or magnetostratigraphy (Table 1). The numerical ages have been converted according to the Berggren time scale (Berggren et al. 1995). It should also be noted that the age models are not always fully reliable as shown by the shifting of some main trends either between different sites (Fig. 3, sites 563, 608, 709A) or within the same site (Fig. 3, site 588C; Zachos et al., 2001a; Spencer-Cervato, 1999; Kennett, 1986; Kennett et al., 1986; Lohman, 1986; Martini, 1986). These shifts reflect the uncertainties on the calibration points, mainly the exact location of the biostratigraphic limits (up to 50 m on site 588C).

Among the selected sites, the whole stratigraphic interval is only covered by site 563 that presents some intervals with a quite low resolution sampling. For the Miocene period this site shows trends that are well in agreement with these observed on the other sites. For the correlations with the continental data we also considered sites that are documented by isotopic data at a high resolution scale. For the lower and the middle part of the studied interval, we chose the site 926A, B that presents a high resolution isotopic data and a good age model. Then, for the upper part, we chose the site 588A that offers a very high resolution scale with a good calibration for the most recent part of the studied interval. Although not located in the same Ocean, this choice is validated by the good consistency between these curves and the other ones.

Along the Chattian/Serravallian interval, the amplitude of the $\delta^{13}C$ fluctuations is 1.8‰. Five isotopic marine intervals have been identified: 1) a first one characterized by low isotopic values corresponding to the Late Oligocene (ends at ≈ 24 Ma – present in all sites); 2) the second one is represented by high values and covers most of the Aquitanian period (extends from ≈ 24 Ma to ≈ 22 Ma); 3) the third one corresponds to low isotopic values and extends over the late Aquitanian/Burdigalian and shows a minimum around 19-20 Ma (interval from ≈ 22 Ma to ≈ 17.5 Ma); 4) the fourth one shows a

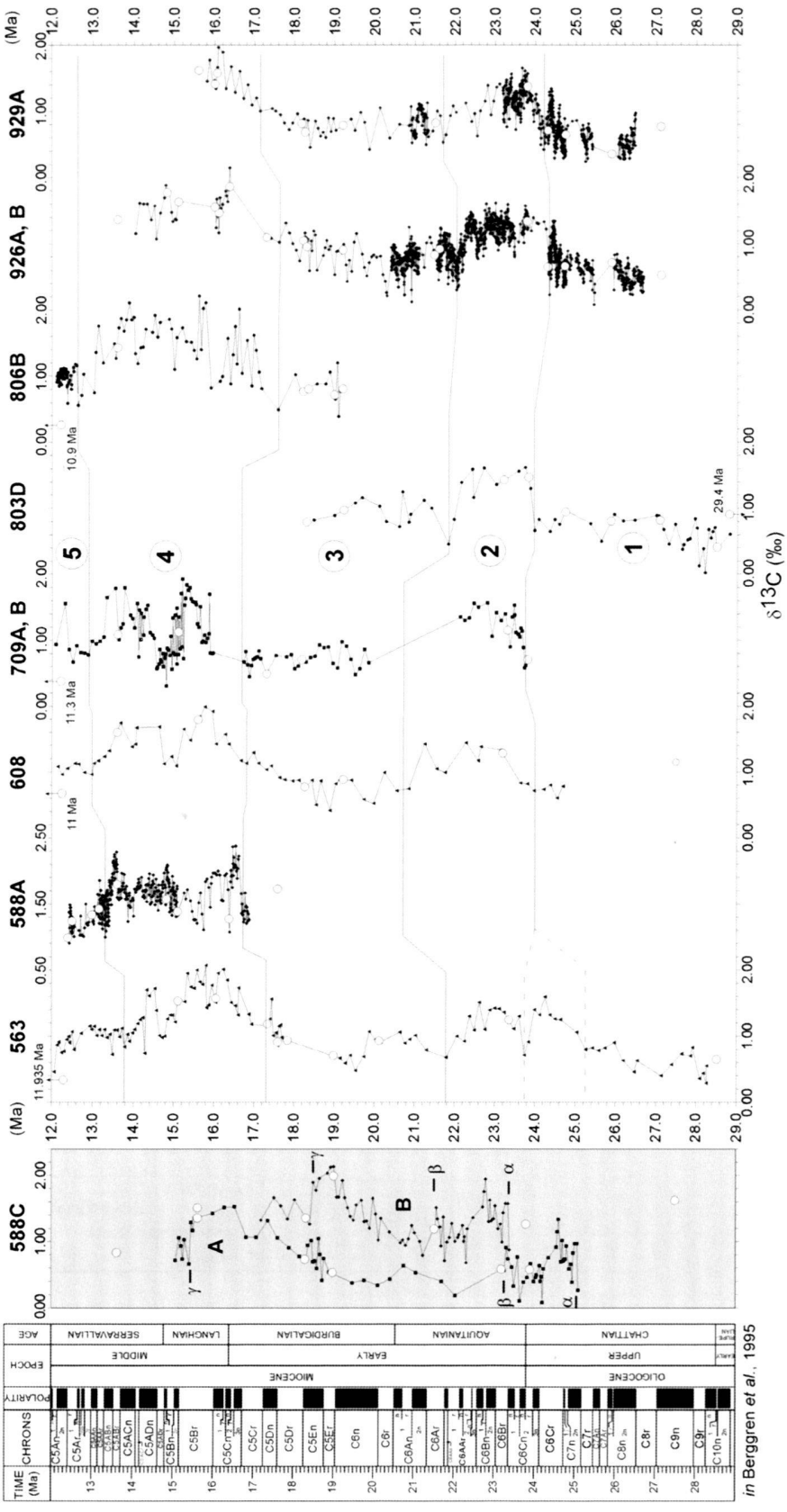

Fig. 3. Variability of the marine carbon isotopic signal, from different DSDP and ODP sites. (open dots – age models). Two different age models are presented for site 588C that is not well calibrated. α, β, γ are selected points which illustrate the differences between the two stratigraphic calibrations (Lohman, 1986, Martini, 1986, for model A and Kennett 1986, Kennett et al., 1986, for model B).

The five isotopic intervals are labelled 1 to 5. Correlations should be time-lines, considering the fluctuations as global. The variability shows the imprecision of the age models.

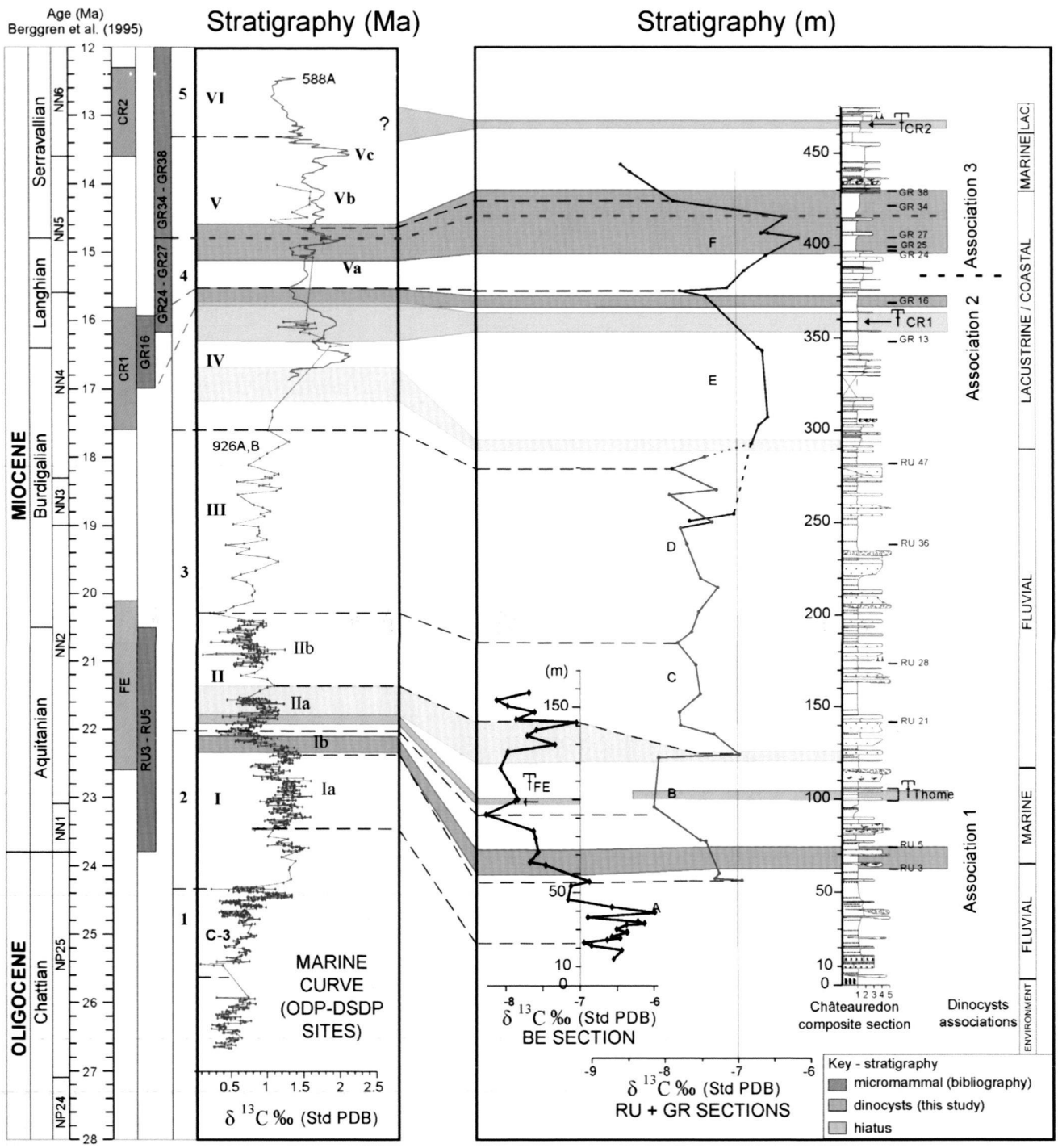

Fig. 4. Integrated stratigraphy of the composite section of Châteauredon (stratigraphy in meters) and correlations to marine data from ODP-DSDP sites recalibrated according to Berggren et al., 1995 (stratigraphy in Ma). Lithologic column, see Fig. 2a,b for key.

rapid increase of the isotopic values associated with ample fluctuations that characterize the Langhian and Early Serravallian times and known as the "Monterey Event" (Vincent & Berger, 1985) (from ≈ 17.5 Ma to ≈ 13 Ma); 5) the fifth one is marked by a clear drop of the isotopic values that began in the Serravallian (starts at ≈ 13 Ma).

These intervals are easily identified on the continental record and they correspond to the intervals that were originally

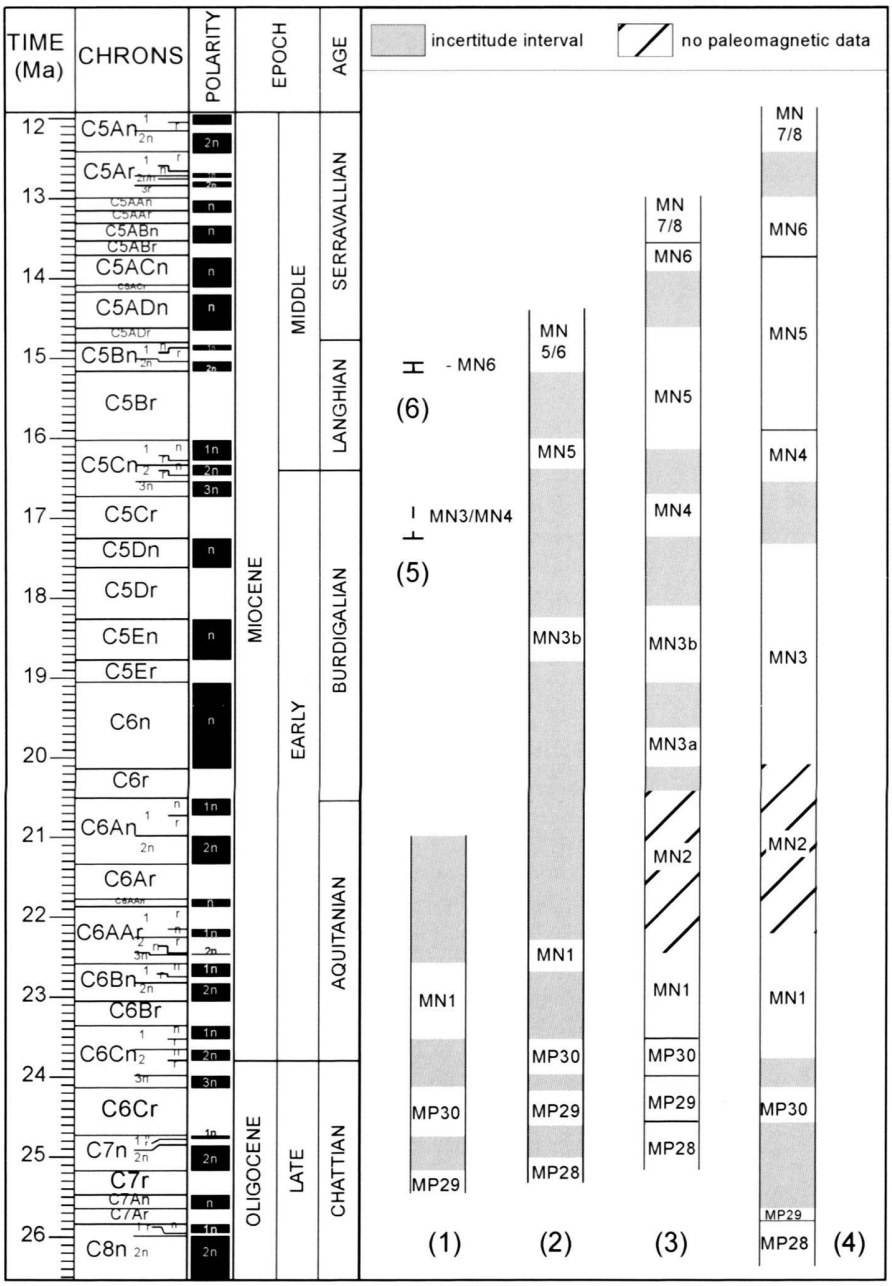

Fig. 5. Correlations of the micromammal biozones to the geomagnetic polarity time scale (1. Burbank et al., 1992; 2. Schlunegger et al., 1996; 3. Kempf et al., 1997; 4. Agusti et al., 2001; 5. Sen, 1997; 6. Aguilar et al., 2003).

characterized (intervals A to F, Lopez et al., 2000; intervals I to VI, Bialkowski, 2004; Fig. 4). Marine interval 2 is recorded on the BE and RU sections (from 0 to 100 m on composite section, original interval I). The lower terms are probably missing in the RU section (interval Ia). The marine interval 3 is present along most of the RU section (from 100 m to 280 m on composite section, original intervals II and III). The interval 4 is represented on the GR section (original intervals IV and V). Transition from intervals 3 to 4 is located at 290 m on composite section. The last points probably do not correspond to the end of interval 4 but to the relatively low values around 14.5 Ma.

The MN scale and the geomagnetic polarity time scale

The European Neogene mammalian units are based on the evolution of key-taxa recorded in some type localities as well as the presence or absence of others (Agusti et al., 2001; Aguilar et al., 1999; Sen, 1997; Steininger et al., 1996, 1990; Aguilar, 1982, 1981). However, correlation of this biochronology scale with the absolute timescale is not yet fully fixed. Over the ten last years, a large contribution to solve the problem has been provided by paleomagnetic studies in these continental formations (Fig. 5) (Agusti et al., 2001; Kempf et

al., 1997; Sen, 1997; Schlunegger et al., 1996; Burbank et al., 1992). Nevertheless, it should be noted that these continental formations are not really favourable for paleomagnetic studies and that most of the published magnetostratigraphic data present quite a loose sampling when compared to marine magnetostratigraphy. Moreover, some mammal units have not yet been successfully calibrated by magnetostratigraphy (for example MN2 biozone). These difficulties probably explain the different interpretations that are proposed for the correlation of the biochronology with the standard geomagnetic polarity time scale.

Regarding the mammal sites that are present on the Châteauredon composite section, we can propose the following interpretation (Fig. 5). The Font d'Eygout site (MN2a/b) corresponds to a mammal zone that is not calibrated by magnetostratigraphy. Its stratigraphic attribution is deduced from the upper limit of MN1 and lower limit of MN3. Based on the published data, the upper limit of MN1 is at most at the top of C6Aar2r (22.3 Ma; Agusti et al., 2001) and at least at the base of C6AAr (22.6 Ma; Schlunegger et al., 1996). Base of MN3 is placed at least at the base of C6n (20.1 Ma; Agusti et al., 2001; Kempf et al., 1997). Therefore, the MN2a/b unit is comprised between these two boundaries, i.e. an interval covering at most 22.6 Ma to 20.1 Ma. The Châteauredon 1 site (MN4) corresponds to a mammal zone whose stratigraphic attribution is largely variable. According to the authors its extension varies between 16.5 to 17.5 Ma (Kempf et al., 1997) and 15.8 to 16.6 Ma (Agusti et al., 2001). The beginning of the zone is placed at 17.6 Ma by Aguilar and collaborators (2003). The Châteauredon 2 site (lower MN7/8) corresponds to a mammal zone that is not well calibrated. If we consider the boundary between MN6 and MN 7/8 its stratigraphic attribution varies from 13.6 Ma (Kempf et al., 1997) to 12.3 Ma (Agusti et al., 2001). Aguilar proposes a 13.5 Ma dating for the age of this site (Aguilar, personal communication).

Discussion

Stratigraphic conclusions

Based on the results of the palynological study and the review on the uncertainties regarding the stratigraphic calibration of the marine isotopic data and mammalian units, we propose the following stratigraphic interpretations for the Tertiary series of the Châteauredon area (Figure 4, meters according to composite section).

– Aquitanian – from 0 to ≈ 180 m. This stratigraphic attribution is based on the palynological data (65 m), the Font d'Eygout fossil site (90 – 110 m) and the identification of marine isotopic intervals I and II. Close to the end of interval II, the limit between the Aquitanian and the Burdigalian is placed around 180 m, based on the low isotopic values at this stratigraphic height.

Moreover, the isotopic record allows defining a higher resolution within this interval. Sub-intervals Ia and Ib are characterized on the BE section. Data from RU section would start within interval Ib. Record of sub-interval IIa is well identified on the BE section whereas on the RU section the upper part of this interval is only expressed by a significant shift (around 120 m). This shift put in evidence a hiatus that is situated in the continental sediments just above the marine deposits. No evidence of a hiatus was observed on the field. Duration of the hiatus is estimated to some 400 kyr. It is interpreted as a difference of sedimentation rates between the BE and the RU sections corresponding to a local deformation in the western part of the Châteauredon Dome.

This stratigraphic attribution of the lower part of the series to the Aquitanian characterized by marine facies (tidal deposits) and dinocysts occurrences in the dark marly levels show that the Miocene marine transgressions occurred as early as the Aquitanian in the Digne Valensole Basin, whereas the classic paleogeographic reconstructions place these during the Burdigalian (Demarcq, 1984). The marine influence is more significant to the east of the basin suggesting a marine connection either via the north or the south in the continuity of the Oligocene evolution of the foreland basin (Callec, 2001). The correlation of the hiatuses identified in the Châteauredon area with those associated to the incised valley in the Rhodanian domain (Besson et al., 2005, Besson, in press) is not straightforward. The first hiatus is situated within the Aquitanian and would be placed between sequence S-1 and S0 in the Rhodanian domain.

The precise location of the Font d'Eygout micromammal site and the detailed isotopic continental curve on the BE section help to estimate an absolute age around 21.8 and 22 Ma for this fossil site. This result is in agreement with both rodents attribution (MN biozones) and palynological determinations.

– Burdigalian – from 180 m to ≈ 320 m. To characterize the Burdigalian we must rely on the isotopic data. Intervals III and IV are well recorded, but the few isotopic data associated to high frequency fluctuations/ low amplitude fluctuations of the isotopic signal do not allow to establish high resolution correlations. The shift from interval III to interval IV is tentatively placed close to the base of the GR section (around 290 m).

– The Burdigalian-Langhian limit – between 320 and 370 m. Despite the fact that, over this interval, we possess palynological data, a micromammal site and isotopic values, none of them clearly discriminates the location of limit. Nevertheless, based on these different elements, we propose that the low isotopic values between the two bell shapes identified in the Châteauredon section (375 m) correspond to the low marine isotopic values around ≈ 15.6 Ma. As the environments in this zone corresponded to lagoons, isotopic sampling has been quite discontinuous. The Burdigalian/ Langhian limit is probably quite close to the Châteauredon 1 fossil site (360 m). This site is situated in a zone where isotopic data are rare and so a precise age can not be defined. An age around 16 Ma could be proposed, a result that is in

agreement with the upper part of the MN4 biozone, and the occurrence of the *Avicennia* pollen (Châteauneuf et al., in press).

Moreover another hiatus is suspected around 290 m considering the facies changes from fluvial deposits to coastal lagoonal sediments. Correlations with isotopic values over this interval allow a broad estimation of the hiatus in the range of 0.5 Myr.

The major incision characterized at the base of the Burdigalian in the Rhodanian domain is not observed in the fluvial deposits. The second hiatus in the Châteauredon area could correspond to the second major incision observed in the Rhodanian domain (the hiatus is overlain by Late Burdigalian/ Early Langhian sediments; Besson et al., 2002, Besson, 2005).

– Langhian – from around ≈ 320 m to ≈ 420 m. The low isotopic values around 420 m are interpreted as corresponding to those at 14.8 Ma in the marine record (limit between intervals Va and Vb), an age close to the Langhian/Serravallian boundary. Palynological data seem to indicate a Langhian age from 370 to 420 m when considering that the change in species is corresponding to the limit between the Langhian and the Serravallian. Thus, palynological determinations bring stratigraphic data that help to correlate the 370/420 m peak in the continental isotopic signal with the Va interval, among several hypotheses (intervals Va, Vb or Vc).

– Serravallian – from ≈ 420 m to 475m (top of the section). Data are quite limited over this interval. The Châteauredon 2 micromammal site (470 m) is attributed to the middle Serravallian. It corresponds to the uppermost stratigraphic data that we possess.

When comparing this new interpretation to the previous stratigraphic attributions (Bialkowski, 2004; Lopez et al., 2000), the originally identified fluctuations are kept, but some of the age limits have been displaced, notably in the upper part of the section, following a better calibration of the $\delta^{13}C$ isotopic marine curve. The integrated stratigraphy allows to correlate more precisely the fossil sites as well as the isotopic fluctuations with the geomagnetic polarity time scale. Our study comforts the large potentiality of the integrated approach to study environments that are not favourable to fossil preservation.

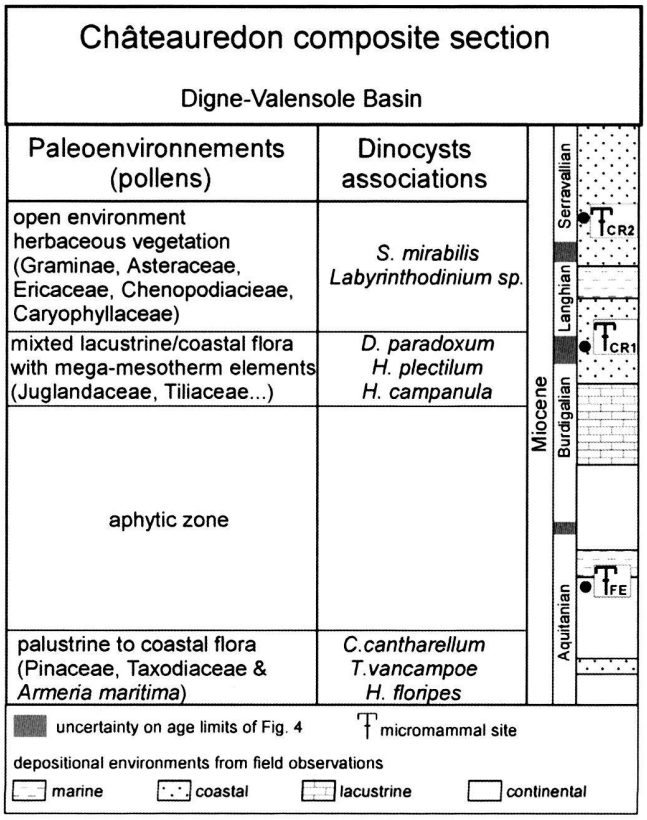

Fig. 6. Paleoenvironmental reconstruction based on pollen and dinocycts associations.

Paleoenvironmental interpretation

The paleoenvironments are reconstructed based upon facies, palynological data and isotopic results.

Without quantitative evaluation, the dinocyst data are difficult to use in the schemes relating species distribution to paleoenvironments (Brinkhuis, 1992). Nevertheless, we can propose some hypothesis based on the relative presence of some groups of species. In most of the analysed levels, the joint presence of species from the genera *Spiniferites*, *Homotryblium*, *Operculodinium*, *Selenopemphix*, *Polyspheridium* and *Lingulodinium* is characteristic of supralittoral zones. In the upper part of the section (GR 16 to GR 34), some species are distinctive of more open marine environments and may have been brought in by marine incursions: *Impagidinium*, *Distatodinium* or *Spiniferites mirabilis*. This renewal of species, in association with the *Avicennia* mangrove, could correspond to the Langhian transgression that is known in the Mediterranean zone (Bessedik & Cabrera, 1985).

As far as pollen is concerned, the environments of the lower part of the section (samples from the coastal plain) are characterized by wind-transported pollen of Pinacae (70 to 90% of the determined pollen), marshy species (Taxodiacae) or coastal ones (Armeria; Fig. 6). Above the barren zone (RU 21 to GR 13), the fluvio-lacustrine then coastal environments permitted the development of a more diverse flora. The riparian and swampy vegetation is composed of Avicenniaceae, Malvaceae, Restionaceae, Cyrillaceae, Betulaceae, Caprifoliaceae, Myricaceae, Sparganiaceae, Eleagnaceae, Nyssaceae et Hamamelidaceae, as well as of mesothermic flora represented by Juglandaceae, Tiliaceae, Fagaceae, Ulmaceae and Oleaceae. Finally, the last samples (GR 34 to GR 38) show environments that were more open and drier, corresponding to an herbaceous vegetation rich in Graminae, Caryophyllacae, Chenopodiaceae, Asteraceae and Ericaceae. This change in the assemblages may announce the beginning

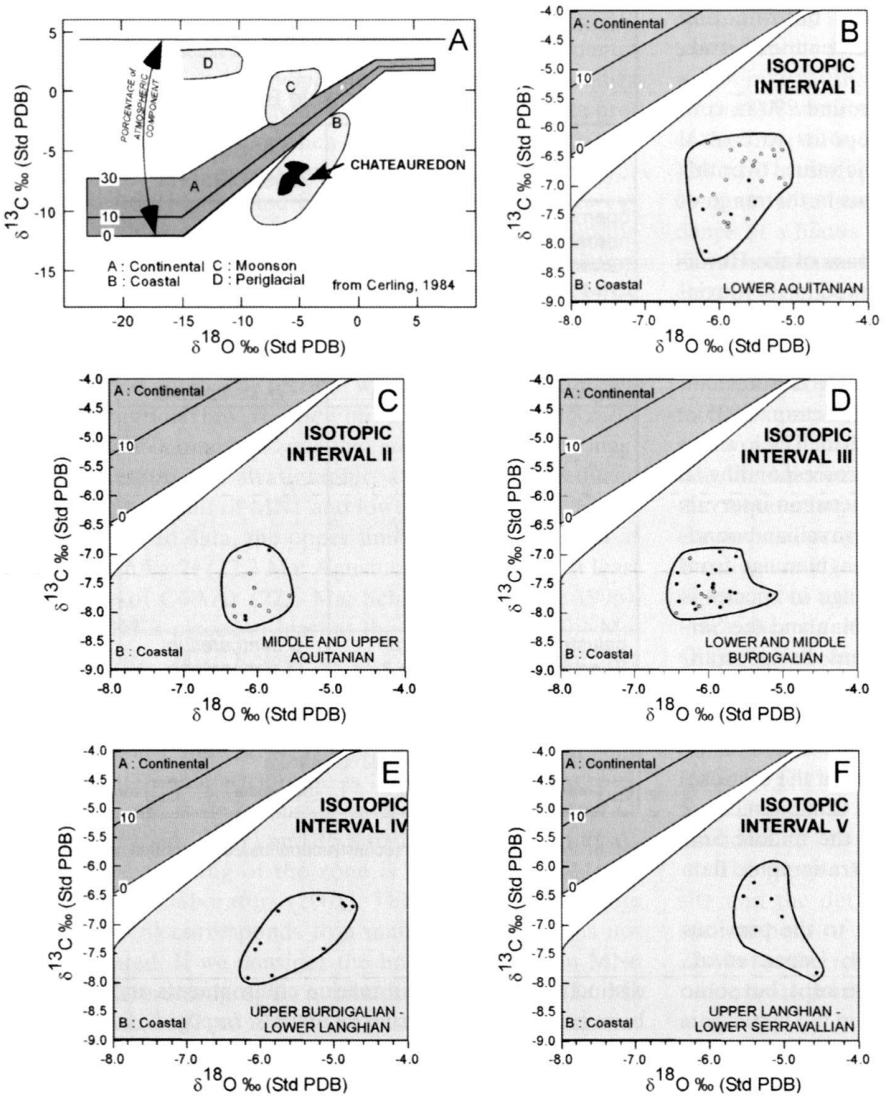

Fig. 7. Cross-diagrams $\delta^{18}O/\delta^{13}C$ for paleoenvironmental reconstruction (modified from Cerling, 1984; open dots: BE section; back dots: RU and GR sections).

of the climatic deterioration which followed in Europe the Miocene climatic optimum (MCO) in the early Serravallian (Jimenez-Moreno et al., 2003).

The $\delta^{18}O$ and $\delta^{13}C$ results obtained from the pedogenic carbonates can also be used for reconstructing the paleoenvironmental conditions. Studies on modern environments have shown that cross-diagrams ($\delta^{18}O/\delta^{13}C$) provide interesting informations regarding the paleoclimatic zones (Cerling, 1984). The $\delta^{18}O$ values are quite complex to interpret because they combine several parameters such as continentality, temperature of rain and temperature of calcite crystallization. Nevertheless, in the case of a relatively low relief landscape, an evolution towards more positive values of the $\delta^{18}O$ can be interpreted as a continentality effect if no climatic evolution is observed. On the other hand, the $\delta^{13}C$ values reflect the vegetation type (C3 or C4 plants), the rate of respiration in the soil, the hygrometry of the environment. In a C3 context, negative $\delta^{13}C$ values can easily be interpreted as a record of wetter environments where respiration rates are high (Cerling, 1999, 1984; Cerling et al., 1997; Cerling & Quade, 1993).

On such a diagram (Fig. 7), our data falls within the coastal domain. An attribution that is well in agreement with the sedimentological and palynological results. Nevertheless, the isotopic data can provide information on the paleoenvironments that could not be obtained from the sedimentological or palynological studies. The oxidized alluvium deposits of the floodplain constitute an excellent case study. These facies indeed are not favourable to the preservation of spore or pollen. Their isotopic values show proximity of the fluvial plain to the coastal domain that could not be deducted from the fluvial facies.

Consequently, pollen associations bring crucial information about paleoenvironments because they allow the reconstruction of the paleovegetation, whereas the isotopic data bring information on the paleogeography.

Conclusions

Results from this study show that the correlation of continental formations with the marine standard scale is possible by using combined methods. Integrated stratigraphy brings high resolution correlations both for age estimations or paleoenvironmental reconstructions, according to quality and/or frequency of sampling.

Stratigraphic results are based on dinocysts associations, a reliable marine $\delta^{13}C$ chemostratigraphy built from selected ODP sites and a micromammal scale calibrated on the GPTS. Palynological data are in agreement with stratigraphic attributions of the micromammal sites. The isotopic fluctuations of the continental signal are very similar to that of the marine isotopic signal. The consistency between the different methods allows to propose a detailed stratigraphy of the Châteauredon area. Depending on sampling density and amplitude of the specific isotopic fluctuations, integrated stratigraphy offers in average a 1 Myr resolution and a few 100 kyr resolution in favourable conditions. For example, the age of the Font d'Eygout micromammal site is estimated between 21.8 and 22 Ma. Thanks to chemostratigraphy, hiatuses have also been identified: sediments condensation during middle Aquitanian and during late Burdigalian.

Paleoenvironmental reconstructions benefit from the association of various methods: facies analysis, palynology and C and O stable isotopes. Dinocysts data, pollen and spores assemblages lead to more precise paleovegetation reconstructions than the isotopic data. The latter show that even when fluvial facies are dominant, the area was situated in a coastal environment. The palynological study indicates an evolution from an internal neritic to a marine environment from Late Burdigalian to Early Serravallian. A noticeable change in the pollen assemblages (from a riparian and coastal vegetation to an herbaceous drier vegetation) is observed during the same interval in southern France (Bessedik, 1985).

This study brings also new insights on paleogeographic reconstructions. The studied area was located close to the sea coast during the Early Miocene. Marine incursions occurred during the middle Aquitanian and from late Burdigalian to Early Serravallian. These are characterized by tidal facies as well as dinocysts and benthic foraminifera occurrences. These marine incursions are better recorded in the eastern part of the Châteauredon Dome arguing for a northern or a southern connection with the Miocene sea in relation to the foreland basin evolution.

These new results on the stratigraphy, paleoenvironment and paleogeography of the Miocene Châteauredon Dome underline the high potential of multidisciplinary studies on coastal and continental series.

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