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LOWER TO MIDDLE TOARCIAN FROM THE COIMBRA REGION (LUSITANIAN BASIN, PORTUGAL): SEQUENCE STRATIGRAPHY, CALCAREOUS NANNOFOSSILS AND STABLE-ISOTOPE EVOLUTION

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Abstract. This multidisciplinary study (facies analysis, sequence stratigraphy, calcareous nannofossils and carbon stable isotopes) focuses on the Lower to Middle Toarcian succession cropping out in the Coimbra region (Northern sector of the Lusitanian Basin), Portugal. Deposited on homoclinal carbonate ramp, the sampled hemipelagic series, consisting of marl/limestone alternations, can be subdivided into three third-order depositional sequences (ST1, ST2 and ST3) characterised by different vertical facies arrangements and paleontological contents. The sequence boundaries lie within the Polymorphum Zone, around the Polymorphum/Levisoni Zone boundary and in the Bifrons Subzone (Bifrons Zone). The calcareous nannofossils provide a continuous succession of age-significant assemblages, and a useful set of nannobiohorizons that include the LO of *Calcivascularis jansae*, the LOs of *Biscutum grande* and *Biscutum finchii*, and the FOs of *Carinolithus cantaluppi*, *Carinolithus superbus*, *Discorhabdus striatus* and *Discorhabdus ignotus*. The evolution of the $\delta^{13}C$ agrees with the sequential developments of the series because the positive excursions roughly coincide with transgressive depositional phases, whereas a negative trend is observed during regressive phases.

Riassunto. Questo studio multidisciplinare (analisi di facies, stratigrafia sequenziale, nannofossili calcarei ed isotopi stabili del carbonio) si focalizza sulla successione del Toarciano da inferiore a medio che affiora nella regione di Coimbra (settore settentrionale del Bacino Lusitanico), Portogallo. Depositata su una rampa carbonatica omoclinalica, la serie emipelagica campionata, costituita da alternanze marne/calcari, può essere suddivisa in tre sequenze deposizionali di terzo ordine (ST1, ST2 ed ST3), caratterizzate da differenti organizzazioni verticali di facies e contenuti paleontologici. I limiti di sequenza giacciono nella Zona a Polymorphum, intorno al limite di Zona Polymorphum/Levisoni, e nella Sottozona a Bifrons (Zona a Bifrons). I nannofossili calcarei forniscono una successione continua di associazioni tempo-significative, ed un'utile serie di nannobioorizzonti che includono la LO di *Calcivascularis jansae*, le LO di *Biscutum grande* e *Biscutum finchii*, e le FO di *Carinolithus cantaluppi*, *Carinolithus superbus*, *Discorhabdus striatus* e *Discorhabdus ignotus*. L'evoluzione del $\partial^{13}C$ concorda con gli sviluppi sequenziali della serie, perché le escursioni positive coincidono pressappoco con le fasi deposizionali trasgressive, mentre si osserva un andamento negativo durante le fasi regressive.

Introduction

The Upper Liassic of the Lusitanian Basin is dominated by marl/marly limestone and limestone alternations, usually characterized by a rich and diverse necktonic and benthic macrofauna (Duarte 1995, 1997). The Toarcian succession is thicker and more hemipelagic in the Coimbra region (Duarte 1997). The continuous and nicely exposed lithological record is useful to study the paleoenvironmental conditions that controlled the sedimentation of this distal sector of the Lusitanian Basin, not affected during the Toarcian by anoxic deposition.

Based on facies analysis, calcareous nannofossils and stable (oxygen and carbon) isotopes, the aim of this study is to improve the sequence stratigraphy of the early-middle Toarcian of the Coimbra region, and hence of the northern sector of the Lusitanian Basin. Facies analysis and stable isotopes, in particular, are useful tools to identify the major transgressive-regressive cycles and sequence evolution, mainly based on the recognition of the main discontinuities (sequence boundaries) and maximum flooding surfaces. Calcareous nannofossils are used to refine the biostratigraphic frame, based either ammonite biostratigraphy recovered from the literature (El-

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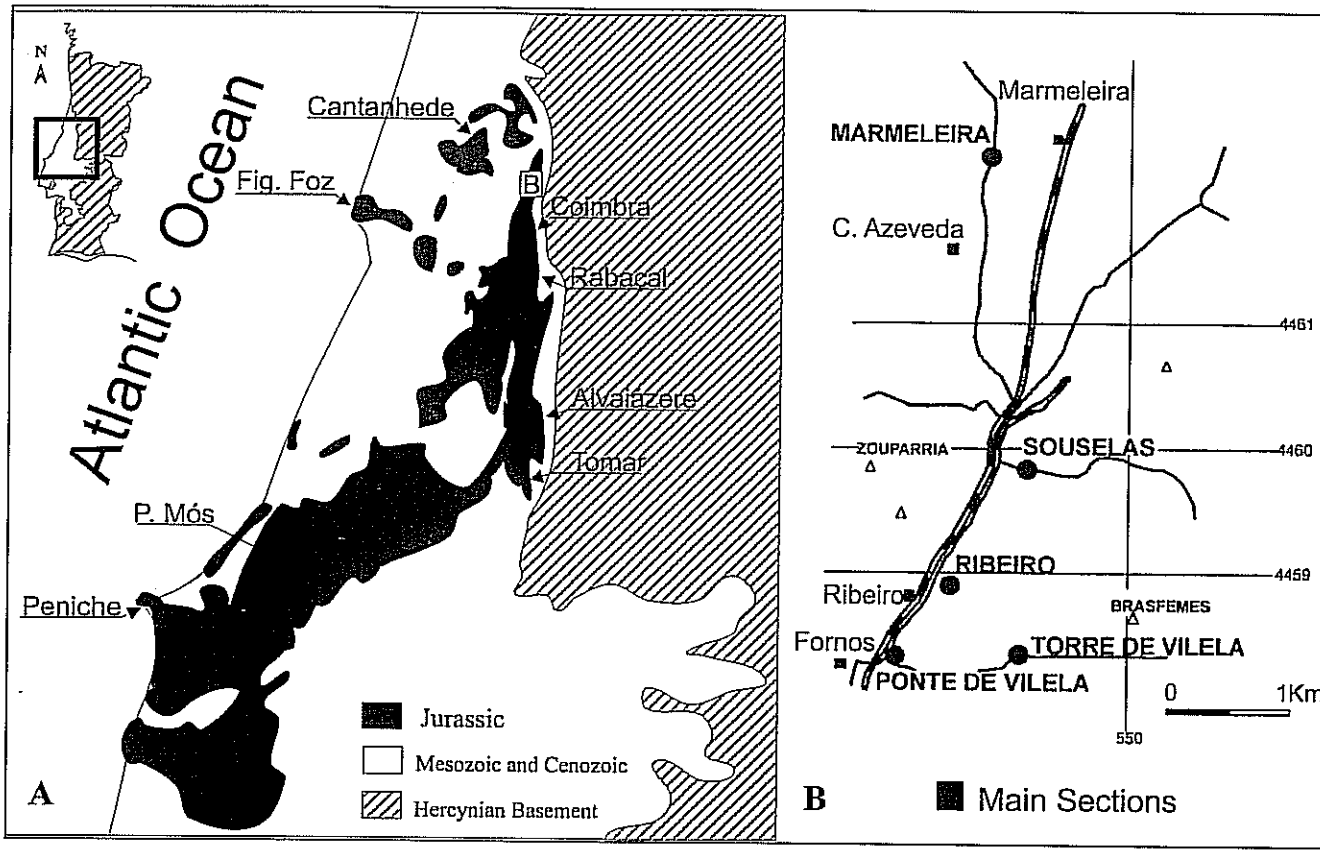


Fig. 1 - A: Location of the main Lower Toarcian successions in the Lusitanian Basin; B: Location map of the studied sections.

mi et al. 1989; Rocha et al. 1996) and from the personal communications of S. Elmi, R. Mouterde and R. Rocha during field trips.

The achieved results are compared with the previous studies on sequence analysis of the Toarcian succession cropping out in other sectors of the Lusitanian Basin (Duarte 1995, 1997).

Geological setting and studied sections

Although in the Coimbra region (Fig. 1), the Upper Liassic succession is expanded and shows well-developed hemipelagic characteristics, up to now, few papers focused on it. The earlier published works deal with ammonite biostratigraphy and regional geology (Choffat 1880; Charnay 1962; Courbouleix 1972; Courbouleix et al. 1974; Soares et al. 1985; Duarte 1995). This lack of detailed study is probably related to the widespread anthropogenic activities and tectonics; the dominance of marly lithotypes that characterize the Toarcian portion undoubtedly favoured both anthropogenic activities (mainly agriculture) and growth of vegetation. Nevertheless, an initial refined sequence and sedimentological analysis of the Toarcian succession, cropping out in this region, has been developed (Duarte 1995). The composite section of the Lower-Middle Toarcian succession is based on the Ribeiro/Fornos, Marmeleira and Cabeço da Azeveda sub-sections (Fig. 2), and is useful to illustrate the stratigraphy and sequence analysis of the Lower to Middle Toarcian succession exposed in the northern sector of the Lusitanian Basin.

Lithostratigraphy and sedimentology

The studied succession belongs to the S. Gião Formation, ranging in age from the Early Toarcian (Polymorphum Zone) up to Late Toarcian (Meneghinni Zone) (Duarte & Soares 2002). Based on the vertical facies arrangement, between marl and limestone beds, and the stratigraphical distribution of the macrofauna, the studied succession (Lower-Middle Toarcian) could be divided into four members (Fig. 2), easily recognizable across a large area of the Lusitanian Basin.

Marly limestones with Leptaena facies Member (MLLF). Correlatable with the MST1 of Duarte (1995, 1997), it belongs to the Polymorphum Zone and is characterized by greyish alternations of decimetric to metric marly beds, recording a large variability of carbonate content (26 to 63%), with centimetric marly limestones. It contains a very rich benthic and necktonic macrofauna, characterized by the significant presence of tiny brachiopods (*Koninckella liasiana* and *Nannirhynchia pygmoea*), belemnites, pyritized ammonites (Dactylioceratids), bivalves (essentially *Plicatula* sp.) and small gastropods (*Pleurotomaria* sp.). The bioturbation is very strong, with some limestone levels particularly rich in *Zoophycos* and ferruginous tubular burrows. The member is 20 m thick.

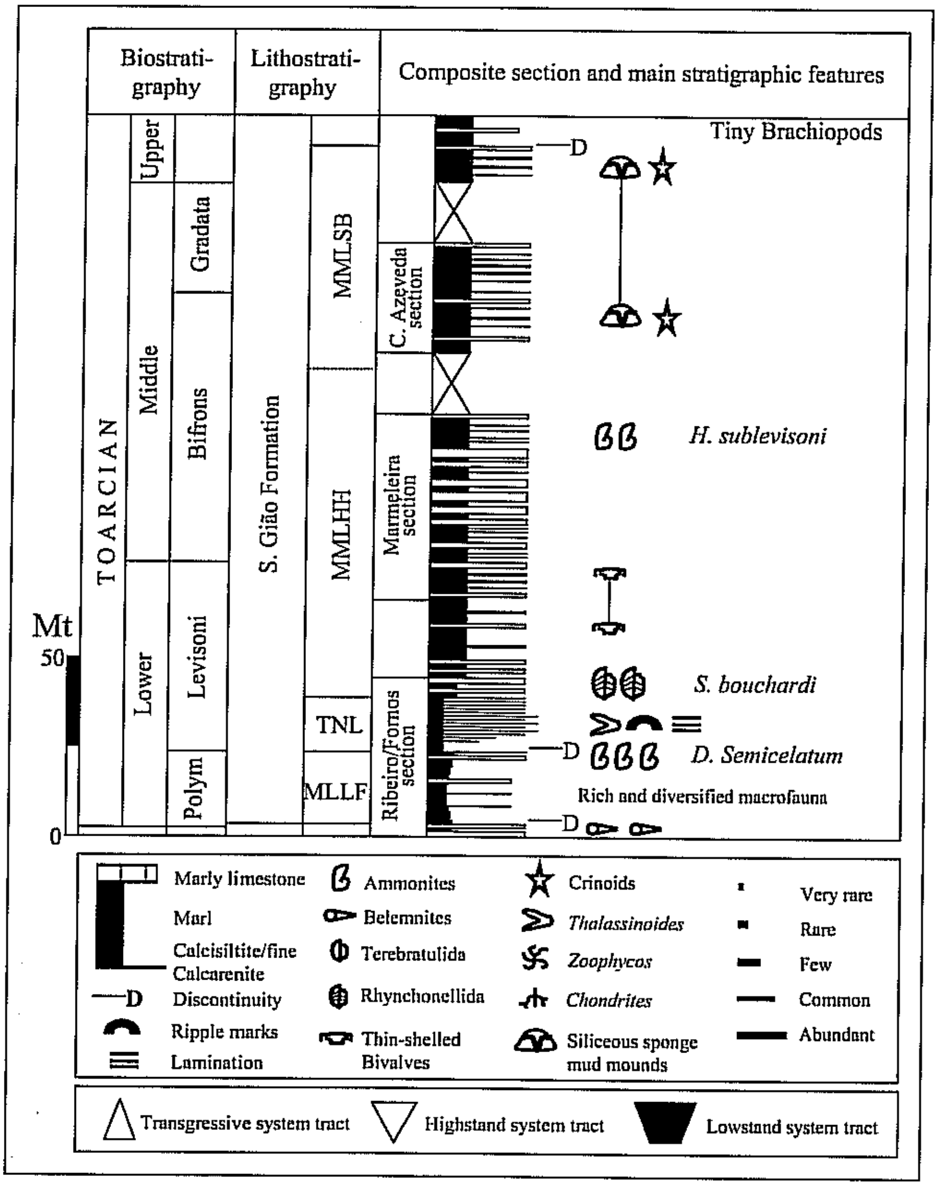


Fig. 2 - Compostite section and synthetic stratigraphic chart for the Lower-Middle Toarcian of the Coimbra region.

Thin Nodular Limestones Member (TNL). Corresponding to the MST2A of Duarte (1995, 1997), this member, referable to the lowermost Levisoni Zone, is characterised by thin (centimetric) bedded alternations of limestones and marlstones (grey to brownish). The basal part of this unit is composed (about 3/4 m) of barren brownish clays (carbonate content less than 10%) and marls. The limestones include calcilutites to fine calcarenites, with irregular surfaces (amalgamated structures), locally with lamination, cross-bedding, symmetrical and current ripples. The thin (<14 cm thick) calcareous levels are usually strongly bioturbated; *Thalassinoides*, *Chondrites* and ferruginous tubular burrows are common. Unfortunately the entire 14 m thick succession belonging to this member yields only few and scattered macrofaunal remains such as ammonites belonging to the *Hildaites* genus.

Marls and marly limestones with Hildaites and Hildoceras Member (MMLHH). This very thick member, correlatable with the MST2B of Duarte (1995, 1997), reaches in this region nearly 95 m in thickness. Spanning from uppermost Levisoni to middle-upper part of the Bifrons Zone, is made up of decimetric to metric alternations of marls, marly limestones and limestones (mudstones), with the latter increasing towards the top of this unit. The necktonic (ammonites) and benthic (brachiopods and bivalves) faunal association is a persistent feature of this unit, but always with low diversity. The brachiopods, essentially rhynchonellids (*Soaresirhynchia*) and terebratulids (*Telothyris jauberti*) are very rich at the base of the member, referable to the Levisoni Zone; whilst some horizons of the uppermost part of this ammonite Zone are very rich in thin-shelled bivalve (like *Bositra*). These features are observed in other sections of the northern sector of the Lusitanian Basin (Duarte 1997).

Marls and marly limestones with sponge bioconstructions Member (MMLSB). This 60 m thick unit, ranging from the uppermost Bifrons Zone to the lower part of the Bonarelli Zone, is correlatable with the MST3 of Duarte (1995, 1997). Although it discontinuously crops out, it shows a similar monotonous feature throughout the Lusitanian Basin (Duarte 1997). With the exception of the marly base, the unit is composed of regular alternations of decimetric to metric marly beds with centi- to decimetric marly limestones. Throughout the entire member the occurrence of small siliceous sponge mud mounds, preferentially associated with calcareous lithofacies, is a typical and dominant feature of this unit (Duarte et al. 2001). The macrofauna shows a large diversity, locally with high concentrations of ammonoids, rhynchonellids, crinoids and bivalves.

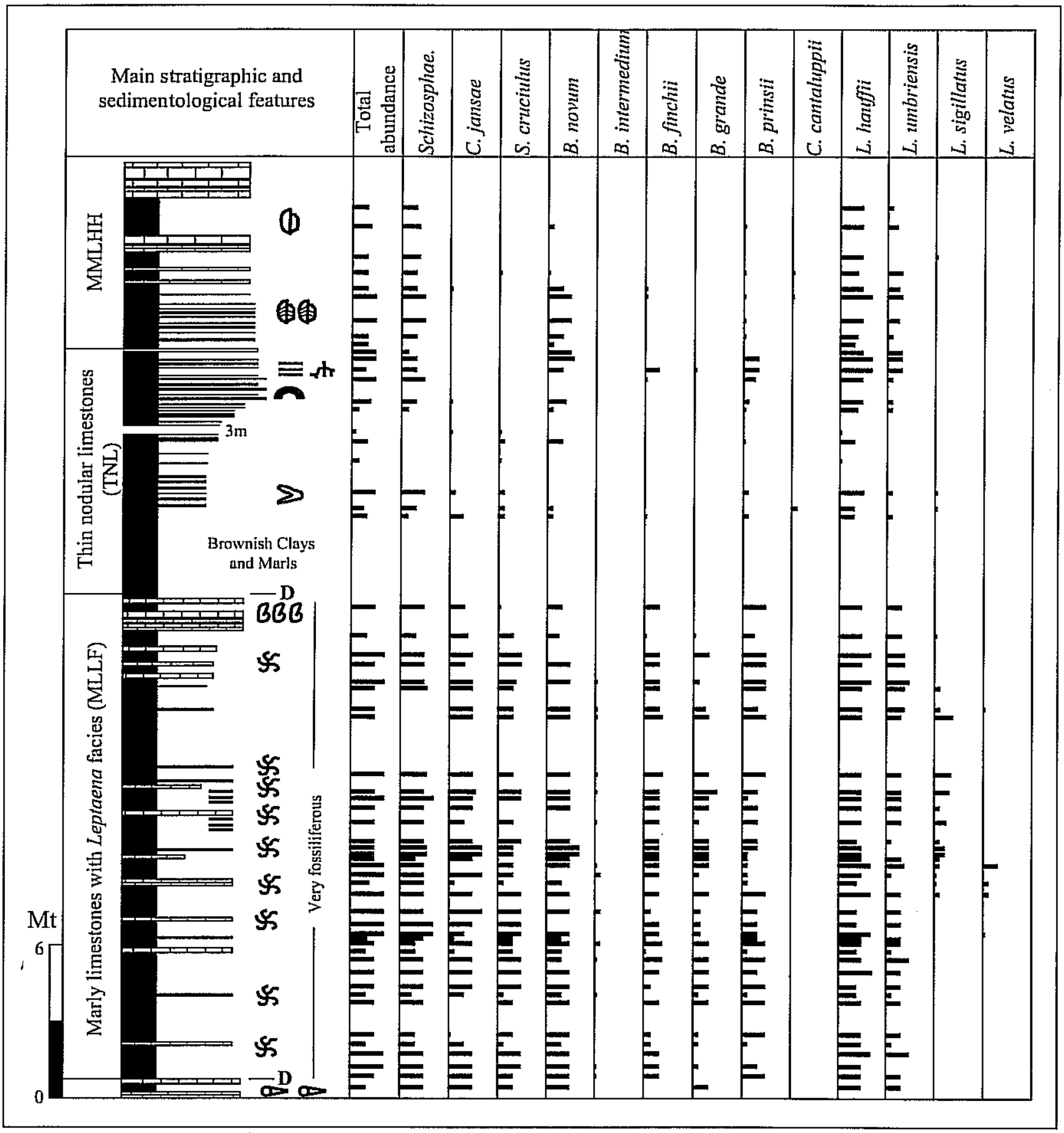


Fig. 3 - Stratigraphic distribution of the main nannofossil taxa in the Ribeiro/Fornos composite section (Polymorphum Zone to lowermost Levisoni Zone).

Calcareous nannofossils

Methods. A total of 180 closely spaced samples were collected. Because the limestones have been strongly affected by diagenesis, mostly marly or marly limestone intervals have been sampled. In order to retain the original ratio between nannofossils and other fragments, neither centrifugation nor ultrasound were applied. Semiquantitative analysis was performed with a light microscope using 1250X magnification. A total of 1000 fields of view for each sample were observed to estimate the total and relative abundance classes and the degree of preservation. Special attention was paid to smear slide sets corresponding to critical stratigraphic intervals (e.g. beginning and ending range of age-significant taxa) or to poor and bad by preserved assemblages; in both cases more than 2000-2500 fields of view have been observed. Smear slide preparation and semiquantitative analysis were adopted because an additional purpose of our investigation was to develop a reliable and easily reproducible biostratigraphic framework.

Assemblages. The studied samples yielded 32 different nannofossil taxa (listed in Appendix 1). The stratigraphic ranges of selected species are outlined for each section in Figs. 3-5 and a summary scheme of their range is reported in Fig. 6. The bulk of the assemblages are characterized by abundant *Schizosphaerella* and *Lotharingius*, along with the genera *Biscutum* and *Crepidolithus*. The diagenesis-resistant genera *Schizosphaerella* and *Lotharingius* frequently represent a large amount (up to 90-95%) of the depleted assemblages, and frequently they are the only taxa present, with a low abundance.

The great abundance and diversity of the assemblages from the lowermost Toarcian Polymorphum Zone (correlatable with the Tenuicostatum Zone) is most likely related to their high clay contents (Fig. 3). These assemblages are dominated by *Schizosphaerella* spp., *L. hauffii*, *C. jansae*, *B. novum*, *B. prinsii* and *S. cruciulus*, along with *C. crassus*, *B. grande*, *B. finchii* and *L. umbriensis*. The assemblages are also characterized by the occurrence of *L. sigillatus* and very rare specimens of *L. velatus*. Across the Polymorphum-Levisoni Zone boundary the assemblage composition changes remarkably due to the abundance decrease of *C. jansae* and *S. cruciulus*. Unfortunately, the lowermost part of the Levisoni Zone is represented by thin nodular limestone lithofacies that are usually barren or provide few and badly preserved nannofossil specimens. However, the few fossiliferous samples collected at the Fornos sub-section furnish age significant-assemblages that allow us to recognize the lowermost part of the Levisoni Zone as the level of disappearances of *B. grande*, *B. finchii* and of *C. jansae* as well as the appearance of the genus *Carinolithus* (*C. cantaluppii*).

Even the overlying samples belonging to the upper part of the Levisoni, Bifrons and Gradata *p.p.* Zones, collected at the Marmeleira and Cabeço da Azeveda sub-sections, furnish a continuos succession of age-significant assemblages, although the majority of them are scarce and badly preserved. In the middle of the upper part of the Levisoni Zone the first appearance and the relative abundance increase of *C. superbus* is readily detectable. Likewise, the first occurrence of *Discorhabdus*, with *D. ignotus* and *D. striatus*, is observed around the Levisoni-Bifrons Zone boundary, even if both species are extremely rare up to the middle part of the Bifrons Zone. Consequently, the assemblages referable to the upper part of the Levisoni Zone and Bifrons Zone are quite similar and are characterized by the common occurrence of *Schizosphaerella* and *L. haufii* together with *C. cantaluppii* and *C. superbus* (from the upper part of the Levisoni Zone), *D. ignotus* and *D. striatus* (from the upper part of the Bifrons Zone) and extremely rare specimens of *Lotharingius velatus*. Across the Bifrons-Gradata Zone boundary the assemblages further change due to the remarkable abundance decrease of *Lotharingius hauffii*, which almost disappears within the Gradata Zone.

Nannofossil bioevents

As mentioned above, only the samples belonging to the Polymorphum Zone provide well-preserved and diverse nannofossil assemblages, whereas those from the overlying ammonite zones are frequently depleted by diagenesis. Nevertheless, the biostratigraphic signal is not completely overshadowed, and all the main early-middle Toarcian nannofossil events, utilized in both Boreal and Tethyan sections, have been identified. Therefore, based on a closely spaced sampling of the sequential units cropping out in the Coimbra region, they are correctly placed with respect to the available ammonite biostratigraphy (Elmi et al. 1989; Rocha et al. 1996).

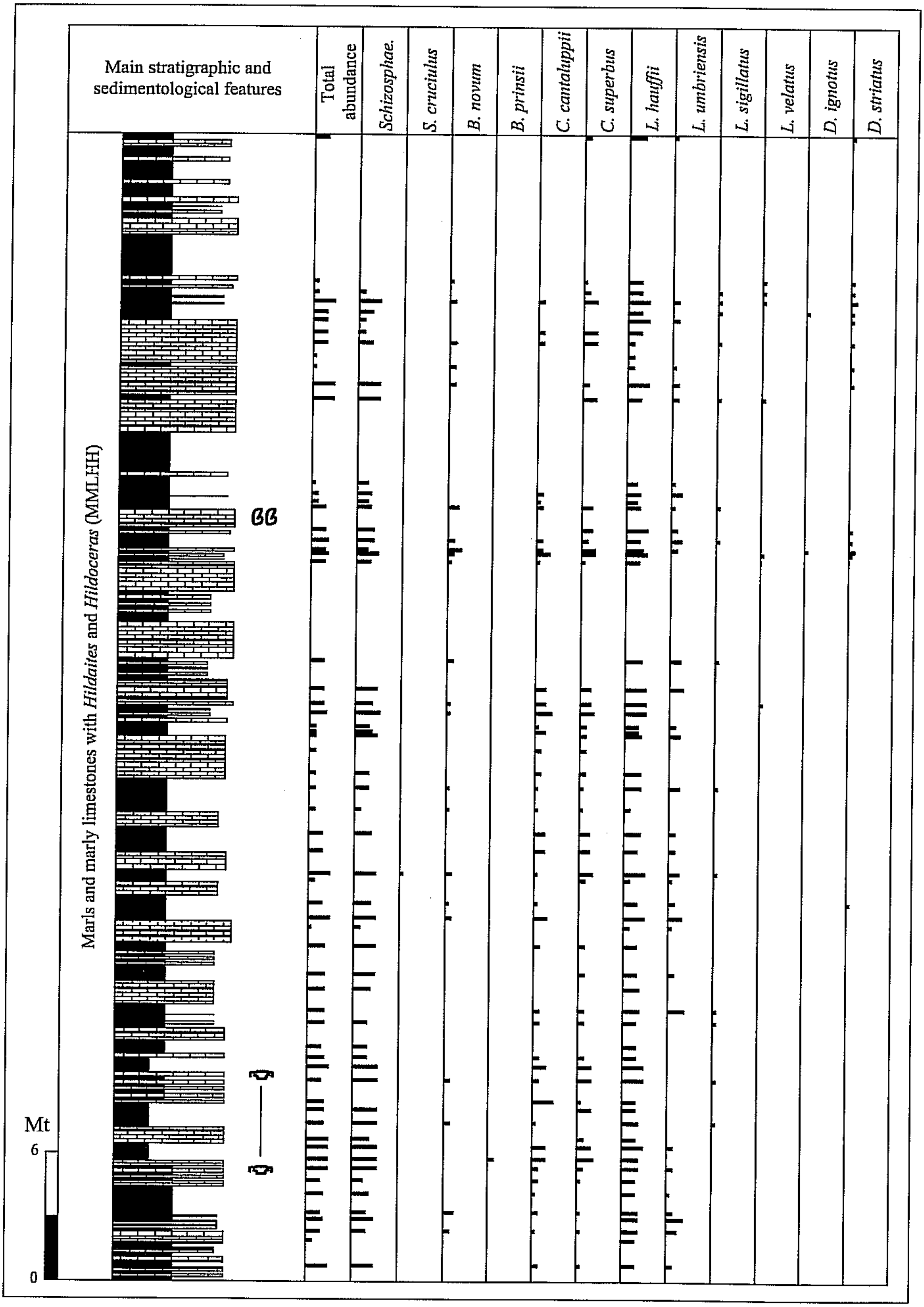
LO of *Calcivascularis jansae*. This taxon disappears within the TNL Member, slightly above its sharp abundance decrease that roughly coincides with the MLLF/TNL (i. e. DT2) boundary. Hence, *C. jansae* is useful to date both the first intra-Toarcian discontinuity (DT1) (nearly coincident with its sharp abundance decrease) and DT2 (lying below its disappearance). A sharp abundance decrease of *C. jansae* as well as the LO of *C. jansae* have also been recognized in the same stratigraphic position in the Peniche section (Perilli & Duarte in progress).

FO of *Carinolithus cantaluppiii*. Although the few fossiliferous samples collected within the TNL Member provide scarce and badly preserved assemblages, the appearance of the genus *Carinolithus*, with the FO of *C. cantaluppi*, is readily detectable just above the MLLF/TNL boundary. This biohorizon has been recognized above this boundary in both Peniche and Figueira da Foz sections (Perilli & Duarte in progress); in this latter sections it lies within the TNL Member.

LOs of *Biscutum grande* and *Biscutum finchii*. Both taxa are significantly present within the MMLF Member, whereas they are extremely rare in the TNL Member. Because only few and scattered *B. finchii* are present in the overlying basal portion of the MMLHH Member, both biohorizons should be placed in the lower part of the Levisoni Zone. With respect to depositional sequence and ammonite zones, the LOs of *Biscutum grande* and *Biscutum finchii* lie in the same stratigraphic position in the Peniche and Figueira da Foz sections (Perilli & Duarte in progress).

FO of *Carinolithus superbus*. Common to both Tethyan and Boreal sections, in the investigated succession *C. superbus* is present from the base of the Marmeleira section, where the middle part of the MMLHH Member crops out. Consequently the FO of *Carinolithus superbus* lies within the Levisoni Zone, as observed in the Peniche and Figueira da Foz section (Perilli & Duarte in progress). Nevertheless, due to its low and scattered occurrence in its initial range, a lower first appearance of this taxon is not excluded.

FO of *Discorhabdus striatus* and *Discorhabdus ignotus*. Although both taxa are extremely rare in their initial range, their appearance is nicely recognizable in the


Main stratigraphic and sedimentological features
Total abundance
Schizosphae.
S. cruciulus
B. novum
B. prinsii
C. cantaluppii
C. superbus
L. hauffii
L. umbriensis
L. sigillatus
L. velatus
D. ignotus
D. striatus
Marls and marly limestones with Hildaites and Hildoceras (MMLHH)
Mt
6
0

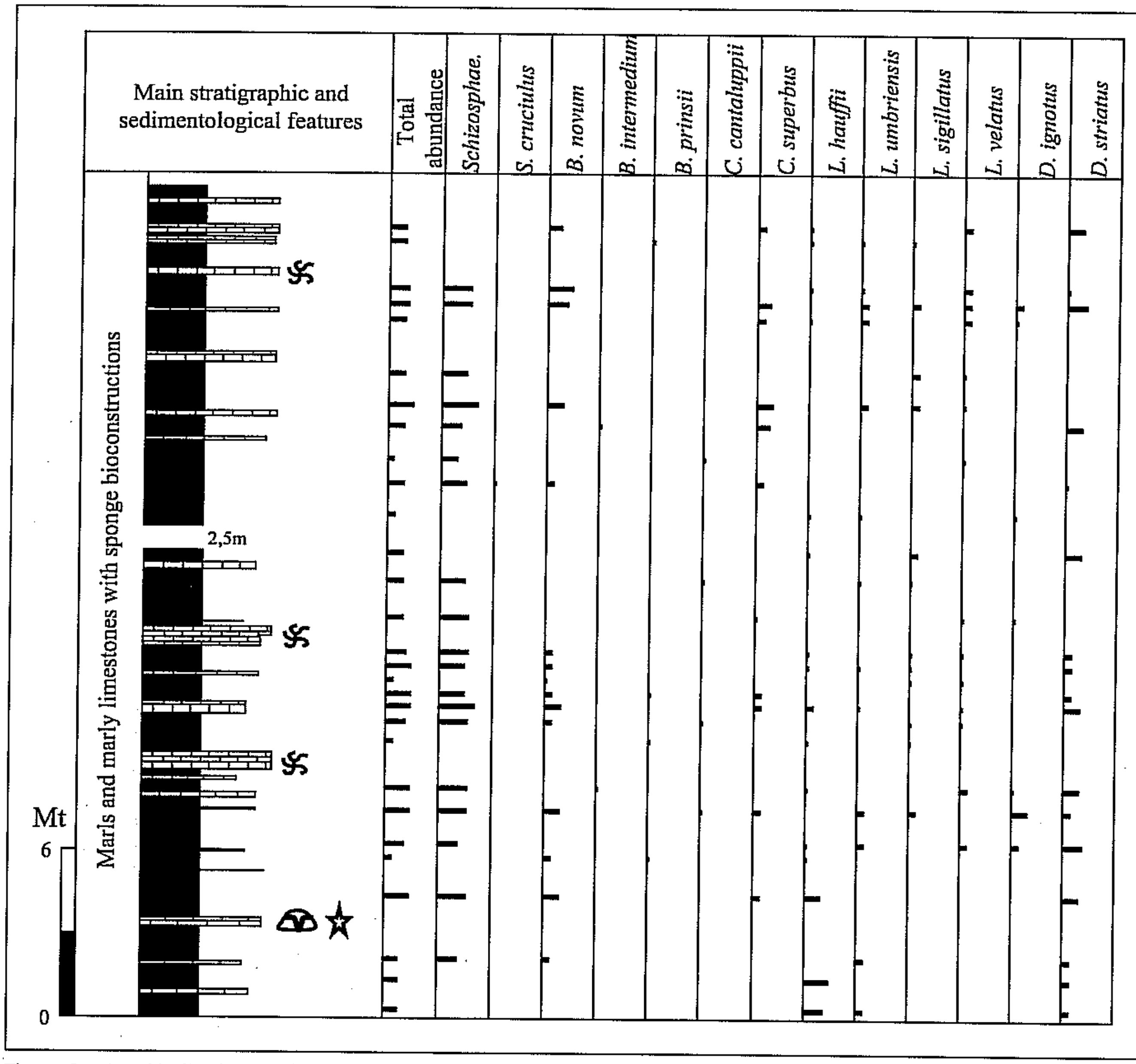


Fig. 5 - Stratigraphic distribution of the main nannofossil taxa in the Cabeço da Azeveda section (uppermost Bifrons Zone to lowermost Gradata Zone).

middle-upper part of the Marmeleira section that correspond to the middle part of the MMLHH Member. Both biohorizons are referable to the lower part of the Bifrons Zone, because their appearance lies below the Sublevisoni Subzone. The FO of *Discorhabdus striatus* has been identified slightly above the Levison/Bifrons Zone boundary of both Peniche and Figueira da Foz sections (Perilli & Duarte, in progress).

Fig. 4 - Stratigraphic distribution of the main nannofossil taxa in the Marmeleira section (uppermost Levisoni Zone to Bifrons Zone).

Carbon and oxygen stable isotopes

In the studies of carbonate sediments, particularly in pelagic environments, carbon and oxygen stable isotopes have been widely used as an important stratigraphic tool or as an important paleoceanographic/paleoclimatic indicator (Scholle & Arthur 1980; Renard 1984, 1986; Shackleton & Hall 1984; Weissert 1989; Follmi et al. 1994; Weissert et al. 1998; Jenkyns et al. 2002). The hemipelagic nature (marl/limestone alternations) of the Toarcian sediments, supported by ammonite and nannofossil biostratigraphy, constitutes a good context for isotope study.

Methods. To investigate both $\delta^{13}C$ and $\delta^{18}O$ stable isotopes, 29 samples of bulk-rock micritic carbonate sediments from calcareous levels belonging to the Lower-Middle Toarcian members were analysed. The

UNITS	Samples	$\delta^{13}C$	$\delta^{18}O$
MMCB Member	SS 45	1.19	-3.56
MMLSB Member	SS 38	0.48	-4.76
MMLSB Member	SS 32	0.8	-3.46
MMLSB Member	SS 20	0.68	-4.99
MMLSB Member	MB 76	1.84	-2.95
MMLSB Member	MB 57	1.63	-3.49
MMLSB Member	MB 40B	1.83	-3.04
MMLSB Member	MB 01	1.89	-3
MMLHH Member	MM 95	1.79	-4.48
MMLHH Member	MM 91	2.01	-3.27
MMLHH Member	MM 77	2.38	-3.55
MMLHH Member	MM 71	2.21	-3.37
MMLHH Member	MM 69	1.37	-3.46
MMLHH Member	MM 64	2.66	-3.59
MMLHH Member	MM 58	2.24	-4.57
MMLHH Member	MM 54	2.73	-3.76
MMLHH Member	MM 50	3.1	-3.41
MMLHH Member	MM 44	3.02	-3.58
MMLHH Member	MM 40	2.84	-3.77
MMLHH Member	EP336	1.7	-2.78
TNL Member	EP249	0.2	-2.75
TNL Member	R 60	-0.24	-3.19
MLLF Member	R 56	2.6	-3.79
MLLF Member	R 52	2.08	-3.8
MLLF Member	R 41	0.94	-4.45
MLLF Member	R 33	1.26	-4.43
MLLF Member	R 18	1.41	-3.63
MLLF Member	R 09	0.56	-3.43
Lemede Formation	R 01	0.49	-4.04

Tab. 1 - List of the isotopic results (‰) in the Lower-Middle Toarcian succession of the Coimbra region. MMCB Member - Marls and Marly Limestones with Brachiopods Member in Duarte & Soares (2002).

total carbonate content of each sample was analysed through the Bernard calcimeter. The final isotopic composition of carbon and oxygen, was obtained using a Finnigan MAT 252 mass spectrometer at Petrobras Research Center (Cenpes, Brazil), following the traditional procedures (McCrea 1950). All the values are reported in parts per mil (‰) notation (δ) relative to the PDB (Pee Dee Belemnite) international standard (Craig 1957). Carbon-and oxygen-isotope ratios are listed in Tab. I and plotted along the stratigraphic composite section in Fig. 6.

Results

$\delta^{13}C$: the carbon-isotope ratio shows a large variation within the Lower-Middle Toarcian succession, with values ranging between -0.24‰ and +3.1‰. Despite the low number of analysis, significant oscillations are observed within and between each member. The isotopic variation curve of $\delta^{13}C$ roughly agrees with the trends observed in other sections of the Lusitanian Basin, as pointed out by Duarte (1995, 1998); the achieved results also support the $\delta^{13}C$ as a good stratigraphic marker.

As outlined in Fig. 6, the lower part of the succession is characterized by two positive trends observed within the MLLF (0.56 to 2.6‰) and TNL (-0.24 to 0.2‰) separated by a minimum values found in the TNL Member (R60 and EP249). Besides, the greatest Toarcian change occurs at the boundary between those units (from 2.6 to –0.24‰). Unfortunately, the trend observed within the overlying MLLF Member is not uniform, showing in this member some important variations (positive and negative excursions) and a big difference between the values obtained for the same unit (more than 2.00‰) (Fig. 6).

However, it is in the middle part of the MMLHH Member (Levisoni Zone) that the maximum values, reaching 3.00 ‰ (MM44 and MM50), are observed. Fluctuations in $\delta^{13}C$ are generally negative in the upper part of the MMLHH Member (Bifrons Zone; from 3.1 to 1.79‰) and throughout the MMLSB Member (uppermost Bifrons Zone to Bonarellii Zone; 1.89 to 0.48‰). These trends have been previously observed by Duarte (1995, 1998) in the Rabaçal and Porto de Mós regions, located southern of Coimbra region (Fig. 1).

$\delta^{18}O$: ranging from -4.99‰ to -2.75‰, the oxygen-isotope values agree with the results obtained by Duarte (1998) in other sections (e. g. Rabaçal, Brenha and Porto de Mós) of the Lusitanian Basin. Compared with the $\delta^{13}C$ trends, the oxygen-isotope values are highly variable (Fig. 6); nevertheless, several interesting trends can be pointed out, particularly between MLLF and TNL Members. The maximum value is obtained at the top of TNL Member, whilst the minimum value is observed at the top of MMLSB Member. Because of the thermodependence of oxygen isotopes (McRea 1950; Epstein et al. 1953), a diagenetic modification during burial may have occurred.

Discussion

Sequence stratigraphy and depositional system

The composite section of the Lower-Middle Toarcian of the Coimbra region is organised into three depositional sequences (ST1 to ST3). These sequences are correlatable with the MST1-MST3 sequential units of Duarte (1995, 1997) and they are bounded by four (DT1 to DT4) isochronous regional discontinuities (Figs. 2 and 6), particularly remarkable in the southeast part of the basin (Tomar region; Fig. 1). Based on ammonite and calcareous nannofossil biostratigraphic data, the duration of each sequence agrees with the time range estimated by Vail et al. (1991) for the third-order depositional sequences (0,5 to 3 My).

According to Duarte (1995, 1997), these characteristic trends are quite similar to those observed in other classical sections of the Lusitanian Basin (i.e. Alvaiázere, Porto de Mós, Rabaçal and Figueira da Foz; Fig. 1). However, several particular sedimentary features are observed only in the Coimbra region. The ST1-ST3 sequences have been deposited in the differentiated context of a homoclinal carbonate ramp system dipping towards the northwest (Duarte 1997). The thickness of each sequence increases in this direction, favoured by a great subsidence-controlled accommodation. In fact, the Lower-Middle Toarcian succession is 170 m thick in the distal part of the basin (Figueira da Foz and Coimbra), whereas in the southern proximal sectors (Tomar) it reaches only 50 m (Duarte 1997).

DT1: this first Toarcian discontinuity is located in the lowermost Polymorphum Zone. This surface coincides with the boundary between the Lemede and S. Gião Formations (Fig. 2), and corresponds to the first Toarcian flooding surface. Compared with the much more calcareous uppermost part of the underlying Spinatum Zone, the base of ST1 is interpreted as a deepening phase, a large scale event observed in many other Boreal and Tethyan sections at the base of Toarcian.

ST1: this sequence corresponds to the MLLF Member, and is the most argillaceous unit of the entire Toarcian succession. The marl/marly limestone alternations show an interesting rhythmicity at various scales (parasequences and parasequence groups). Usually, several sedimentological and stratinomic aspects show an elementary rhythmic sequential organisation (parasequence), beginning with marl grading to marly limestone. This sequence is very asymmetric, and a large part of it, is interpreted as a transgressive system tract. Hence it is quite difficult to identify the maximum flooding surface although this probably corresponds to a thick limestone bed (0.80 m), very rich in Dactylioceratids (a good event horizon easily recognizable in all the Lusitanian Basin). However, the transgressive trend is well documented by the $\delta^{13}C$ values because a maximum excursion (2.6‰) has been obtained for this Dactylioceratid-rich horizon (Figs. 2, 3 and 6).

DT2: this unconformity corresponds to the MLLF/TNL Member boundary. Defines the most important sedimentological and palaeontological change observed in whole the Lower Jurassic succession of the Lusitanian Basin, and reflects significant tectonic activity (Duarte & Soares, 1993; Duarte 1997). Roughly corresponding to the Polymorphum-Levisoni Zone boundary (Duarte 1997), it lies between the sharp abundance decrease of *C. jansae* and the appearance of *C. cantaluppiii*. In the distal facies of the Coimbra region, the great change observed between the MLLF and TLN Members, corresponds to an abrupt decrease in the $\delta^{13}C$ (Figs. 2 and 6).

ST2: this sequence begins with brownish clays and marls that characterize the base of TNL Member. These facies, exclusive to the northern part of the Lusitanian Basin, are usually unfossiliferous, providing only scarce nannofossil assemblages strongly depleted by diagenesis (Fig. 2). Upwards, this sequence grades into thin silty to sandy limestone alternations with marly clay interbeds that corresponds to the typical TNL Member in whole the basin. Several patterns can characterise the sequential organisation (microsequences), but all of them are fining upward and can shows a millimetric-scale bioclastic lag, composed of echinoid fragments. These facies show tempestitic-turbiditic features (Duarte 1997), observed in the other sections of the Lusitanian Basin, and related to tectonic trigger mechanisms (Wright & Wilson 1984; Duarte & Soares 1993; Duarte 1997). The carbon-isotope evolution in these levels shows an abrupt decrease, which support the lowstand system tract interpretation, through the increase of lighter continental ^{12}C in the depositional system.

The overlying part of ST2, coincident with the MMLHH Member, is composed of marl/limestone decimetric to metric alternations. The alternations are not so rhythmic as other sectors of the Lusitanian Basin, like Rabaçal (Duarte 1994), and it has been difficult to discern the elementary sequences (parasequences). The limestone beds are composed of thin (centimetric) limestone levels alternating with centimetric marls. Despite the similarities with the TNL Member, the facies at the base of the MMLHH Member are exclusively lutitic and particularly rich in brachiopods (rhynchonellids and terebratulids). The base of this thick unit corresponds to a transgressive event (transgressive system tract), shown by an increase in marly deposits and a positive carbon-isotope excursion (values above 3.00 ‰) (Fig. 6). This event ends with some evidence of pelagic deposition (top of the Levisoni Zone). In fact, the maximum flooding surface is shown by thin-shelled bivalve-rich (*Bositra* sp.) horizons (Figs. 2, 4, and 6). The transgressive system tract is overlain by a thick agrading/prograding package. The series become progressively more calcareous and the vertical facies association, compared with the evolution recognised in other points of the basin (Duarte 1997), illustrate a shallowing-upward evolution (highstand system tract). This trend is corroborated by the $\delta^{13}C$ record, showing a negative excursion (Fig. 6), interpreted as the result of an increase in continental ^{12}C than a decrease in marine productivity. With exception of TNL Member, the vertical distribution and diversity of calcareous nannofossils is very similar in whole ST2 (in MMLHH Member).

DT3: this unconformity is easily recognizable in the superbly exposed Rabaçal section (located 15km at south of Coimbra), has been not recognized in the studied composite section, due to the bad exposures in the Coimbra region. However, the major facies change, corresponding to a flooding surface, occurs between the MMLHH and MMLSB Members (Bifrons Subzone; Duarte 1997), and lies below the sharp abundance decrease of *L. hauffii*. The AE (Acme End) of *L. hauffii* in other sections such as Rabaçal and Peniche (Perilli & Duarte, in progress) took place above the Bifrons-Gradata Zone boundary.

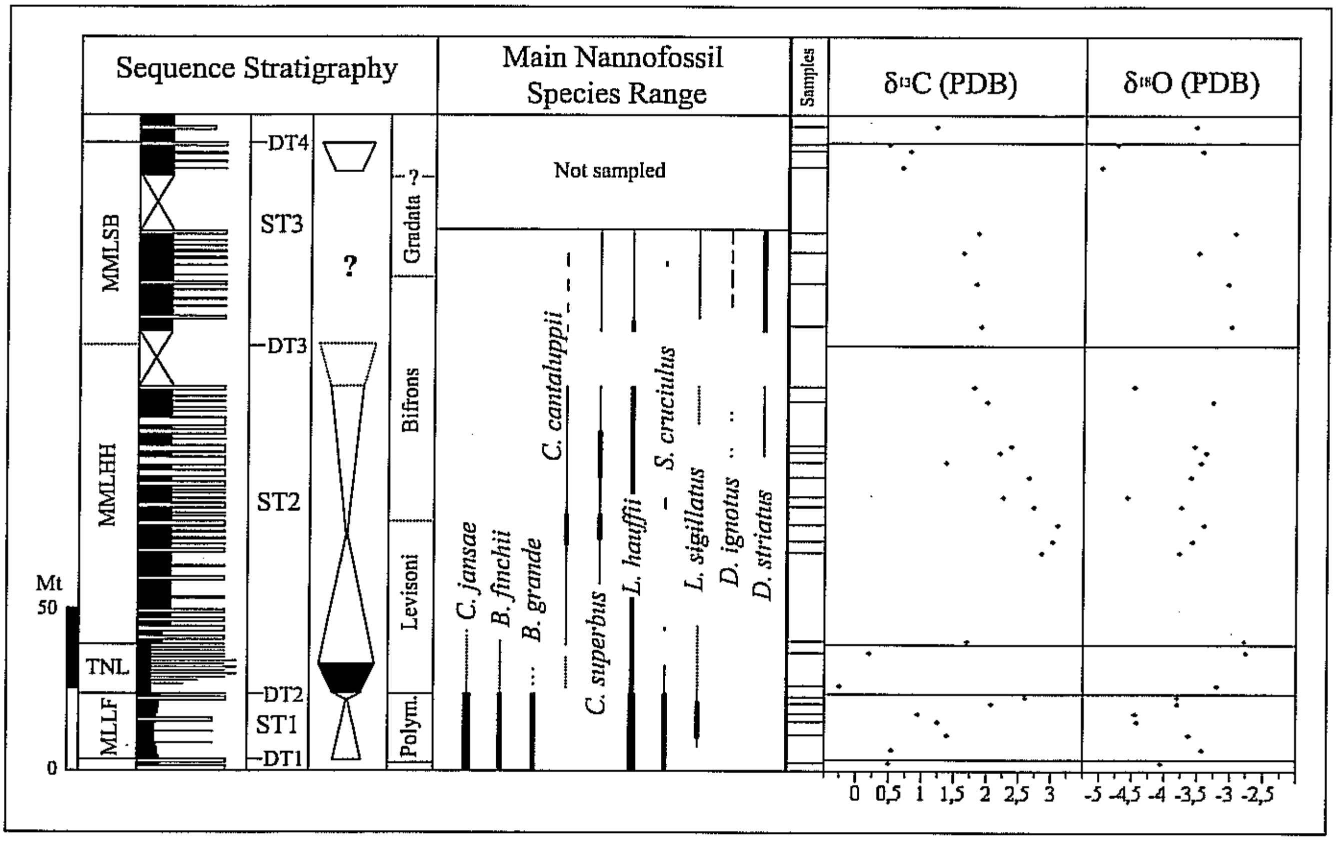


Fig. 6 - Sequence stratigraphy, stratigraphic distribution of the main nannofossil taxa and carbon-isotopic record for the Lower-Middle Toarcian of Coimbra region (see legend in Fig. 2).

ST3: the base of the MMLSB Member corresponds to a thick and widespread marl deposit. The elementary sequential organisation of ST3 shows regular alternations, composed of deci- to metric marls bed that evolve to centi- to decimetric marly limestones towards the top. The asymmetry of these parasequences is well illustrated at the top of the limestone beds by the small sponge mud mounds (Duarte et al. 2001). The increase of bioclastic remains at the top of this sequence, easily recognizable in the eastern part of the basin (Duarte 1997), suggests an important regressive phase (highstand system tract). Despite this apparent uniformity of lithofacies associations, the marl/limestone couplets are often affected by small-scale syndepositional structures, characterized by lenticular and tabular bioclastic build-ups, particularly rich in crinoids and brachiopods (Fig. 2). In the ST3 of Coimbra section, the regressive trend is correlative of a slight negative trend in the $\delta^{13}C$ record (Fig. 6).

$\delta^{13}C$ as a Sequence Stratigraphic and Palaeoceanographic Tool

The carbon-isotope ($\partial^{13}C$) record shown herein confirms the trends illustrated in Duarte (1998), for other regions of the Lusitanian Basin. The first main conclusion of the observed variations is that the link with the sequence analysis previously established, should indicate a mechanism of a primary nature. The isotopic variation curve clearly shows remarkable changes at the boundaries between several depositional sequences. The large (fundamentally abrupt) positive fluctuations correspond to transgressive periods. With the exception of ST1, which is truncated at the top (erosional surface), the uppermost part of ST2 and ST3 shows gradual negative shifts, associated with regressive phases (Fig. 6). These results confirm that $\delta^{13}C$ may be important indicator of palaeodepth (Letolle & Renard 1980) and, indirectly, changes in sea level: for instance, positive oscillations occur during transgressive events (Föllmi et al. 1994, Weissert et al. 1998). This evidence can be corroborated here: according to several authors (Weissert 1989; Jenkyns et al. 1994), the two main reasons that control this parameter in oceanic environment are burial of organic carbon and productivity. If the low levels of organic matter present in the sediments do not seem to agree the possibility of carbon transfer, fixed to the organic matter of marine sediments, the productivity factor does not seem to be sufficient to justify all the variability of the carbon-isotope curve. Thus, the decrease of $\delta^{13}C$ cannot be due to a simple break in productivity. As demonstrated in previous work (Duarte 1998), the good correlation between the sequence development and the carbon-isotope variation can be explained by the interplay of ^{12}C of continental origin. In fact, the increase of lighter carbon-isotope in the carbonate sediments confirms the continental influence on deposition and consequently a regressive phase. A good example can be seen at the base of ST2 (TNL Member), where the lowest values of $\delta^{13}C$ are observed (Fig. 6). As demonstrated above, the detrital facies and other features present in the TNL Member indicate lowstand deposition.

This characteristic shallowing event, observed at the base of Levisoni (Falciferum/Serpentinum) Zone in the whole Lusitanian Basin, is related with local tectonics (Duarte 1997). It is coeval of the well-known global anoxic event (Jenkyns & Clayton 1986; Jenkyns 1988; Jenkyns et al. 1991; Röhl et al. 2001, among others), related to a widespread deepening phase (Hallam 1988; Haq et al. 1988; Hardenbol et al. 1998). Excluding some areas (e.g. Rosales et al. 2001), a rapid negative carbon-isotope excursion characterizes the marine carbonates of lowermost Levisoni Zone in some European basins (Jenkyns et al. 2002). This event, well recognized in the Lusitanian Basin, was recently explained as the result of large methane gas-hydrate dissociation (Hesselbo et al. 2000; Beerling et al. 2002).

On the other hand, the highest values of $\delta^{13}C$, recorded in the Lusitanian Basin, within the middle-upper part of Levisoni Zone, and the gradual decrease up to the Bifrons Zone is consistent with the trends observed in other Boreal and Tethyan basins (Jenkyns & Clayton, 1986; Baudin 1989; Jenkyns et al. 1991, 2002; Jiménez et al. 1996; Rosales et al. 2001).

Conclusions

The Lower-Middle Toarcian succession of the Coimbra region in the northern sector of the Lusitanian Basin is dominated by monotonous marl/marly limestone and limestone alternations, usually characterised by rich and diverse necktonic and benthic macrofauna. Based on facies analysis, calcareous nannofossils and stable isotopes, the following conclusions should be emphasized.

The series can be subdivided into three depositional sequences (ST1, ST2 and ST3), bounded by three discontinuities: at base of Polymorphum Zone (DT1), across the Polymorphum/Levisoni Zone boundary (DT2) and within the Bifrons Subzone (DT3), respectively. The most significant sedimentological change is observed at the ST1/ST2 boundary, where the facies of the base of Levisoni Zone are interpreted as a result of a strong shallowing in the deposition (lowstand).

Although only the samples collected at the Ribeiro sub-section provide well preserved and diverse nannofossil assemblages, the samples collected from the overlying Levisoni, Bifrons and Gradata p.p. Zones furnish age-significant assemblages that provide a useful set of nannobiohorizons. They include the disappearances of *B. grande*, *B. finchii* and *C. jansae*, and the first appearances of the *C. cantaluppii*, *C. superbus*, *D. ignotus* and *D. striatus*, and the sharp abundance decrease of *L. hauffii*. These events support and refine the available ammonite biostratigraphy.

The $\delta^{13}C$ is an important tool in sequence stratigraphic interpretation. Two main positive carbon-isotope excursions are observed: at the top of Polymorphum Zone (2.6‰) and in the upper part of Levisoni Zone (3.1‰). Both peaks are interpreted as deepening phases. The late early Toarcian inferred deepening phase is supported by the presence of thin-shelled bivalve (like *Bositra*) horizons. Between these two peaks, the minimum value (-0.24‰), observed at the base of Levisoni Zone (base of ST2), is interpreted as induced by an abrupt increase of continental ^{12}C in the carbonate sediments.

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REFERENCES

Baudin F. (1989) - Caracterisation geochimique et sedimentologique de la matière organique du Toarcien tethysien (Mediterranee, Moyen-Orient). Significations paleogeographiques. *Unpublished PhD, Université Pierre et Marie Curie, Paris*, 246 pp., Paris.

Beerling D. J., Lomas M. R. & Gröcke D. R. (2002) - On the nature of methane gas-hydrate dissociation during the Toarcian and Aptian Oceanic Anoxic events. *Am. J. Science*, 302: 28-49, New Haven.

Bown P. R. & Cooper M. K. E. (1998) - Jurassic. In: Bown P. R. (ed.) - Calcareous Nannofossil Biostratigraphy, 34-85, Cambridge.

Charnay C. (1962) - Contribution à l'étude géologique de la région du Nord de Coimbra (Portugal). *Dipl. d'Et. Sup., Faculté des Sciences de Lyon*, 173 p., Lyon.

Choffat P. (1880) - Étude stratigraphique et paléontologique des terrains jurassiques du Portugal. Première livrasion - Le Lias et le Dogger au Nord du Tage. *Mem. Sec. Trab. Géol. Portugal*, 22: 72 pp., Lisboa.

Courbouleix S. (1972) - Étude géologique des régions de Anadia et de Mealhada au Nord de Coimbra (Portugal). *Dipl. d'Et. Sup. Sc. Nat., Fac. Sc. Lyon*, 342 p., Lyon.

Courbouleix S., Mouterde R. & Ruget C. (1974) - Étude géologique des régions de Anadia et de Mealhada, III - Le Lias. *Com. Serv. Geol. Portugal*, 68: 47-89, Lisboa.

Craig H. (1957) - Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbonate dioxide. *Geochim. Cosmochim. Acta*, 12: 133, Oxford.

Duarte L. V. (1994) - La sédimentation cyclique marne-calcaire dans le Toarcien du Bassin Lusitanien (Portugal Central). *Geobios*, M.S. 17: 663-669, Lyon.

Duarte L. V. (1995) - O Toarciano da Bacia Lusitaniana. Estratigrafia e Evolução Sedimentogenética. *Unpublished PhD, Centro de Geociências, Departamento de Ciências da Terra, Universidade de Coimbra*, 349 pp., Coimbra.

Duarte L. V. (1997) - Facies analysis and sequential evolution of the Toarcian-Lower Aalenian series in the Lusitanian Basin (Portugal). *Com. Inst. Geol. e Mineiro*, 83: 65-94, Lisboa.

Duarte L. V. (1998) - Clay minerals and geochemical evolution in the Toarcian Lower Aalenian of the Lusitanian Basin. *Cuad. Geol. Iberica*, 24: 69-98, Madrid.

Duarte L. V., Krautter M. & Soares A. F. (2001) - Bioconstructions à spongiaires siliceux dans le Lias terminal du Bassin lusitanien (Portugal): stratigraphie, sédimentologie et signification paléogéographique. *Bull. Soc. Géol. France*, 172: 637-646, Paris.

Duarte L. V. & Soares A. F. (1993) - Eventos de natureza tempestítica e turbidítica no Toarciano inferior da Bacia Lusitaniana (Sector Norte). *Cadernos de Geografia*, F.L.U.C., 12: 89-95, Coimbra.

Duarte L. V. & Soares A F. (2002) - Litostratigrafia das séries margo-calcárias do Jurássico inferior da Bacia Lusitânica (Portugal). *Com. Inst. Geol. Mineiro*, 89: 135-154, Lisboa.

Elmi S., Goy A., Mouterde R., Rivas P. & Rocha R. (1989) - Correlaciones biœstratigraficas en el Toarciense de la Peninsula Iberica. *Cuad. Geol. Iberica*, 13: 265-277, Madrid.

Epstein S., Buchsbaum R., Lowestam H. & Urey H. C. (1953) - Revised carbonate water isotopic temperature scale. *Geol. Soc. Am. Bull.*, 64: 1315-1326, San Antonio.

Föllmi K., Weissert H., Bisping M. & Funk H. (1994) - Phosphogenesis, carbon-isotope stratigraphy and carbonate-platform evolution along the Lower Cretaceous northern Tethyan margin. *Geol. Soc. Amer. Bull.*, 106: 729-746, San Antonio.

Hallam A. (1988) - A reevaluation of Jurassic eustasy in the light of new data and the revision Exxon curve. In: Wilgus C., Hastings B., Kendall C. G., Posamentier H. W., Ross C. A. & Van Wagoner J. C. (eds.) - Sea-level changes: an integrated approach. *SEPM Sp. Publ.*, 42: 261-273, Tulsa.

Haq B. U., Hardenbol J. & Vail, P. R. (1988) - Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level changes. In: Wilgus C., Hastings B., Kendall C. G., Posamentier H. W., Ross C. A. & Van Wagoner J. C. (eds.) - Sea-level changes: an integrated approach. *SEPM Sp. Publ.*, 42: 71-108, Tulsa.

Hardenbol J., Thierry J., Farley M., Jacquin T., De Graciansky, P.-C. & Vail P. R. (1998) - Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins. In: De Graciansky P.-C., Hardenbol J., Jacquin T. & Vail P. (eds.) - Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. *SEPM Sp. Publ.*, 60: 3-13, Tulsa.

Hesselbo S. P., Gröcke D. R., Jenkyns H. C., Bjerrum C. J., Farrimond P., Morgans Bell H. & Green O. (2000) - Massive dissociation of gas hydrate during a Jurassic Oceanic Anoxic Event. *Nature*, 406: 392-395, London.

Jenkyns H. C. (1988) - The early Toarcian (Jurassic) anoxic event: stratigraphic, sedimentary, and geochemical evidence. *American Journal of Science*, 288: 101-151, New Haven.

Jenkyns H. C. & Clayton C. J. (1986) - Black shales and carbon isotopes in pelagic sediments from the Tethyan Lower Jurassic. *Sedimentology*, 33: 87-106, Oxford.

Jenkyns H. C., Gale A. S. & Corfield R. M. (1994) - Carbon- and oxygen-isotope stratigraphy of the English Chalk and Italian Scaglia and its palaeoclimatic significance. *Geol. Mag.*, 131 (1): 1-34, Cambridge.

Jenkyns H. C., Géczy B. & Marshall J. D. (1991) - Jurassic manganese carbonates of Central Europe and the Early Toarcian anoxic event. *J. Geol.*, 99: 137-149, Chicago.

Jenkyns H. C., Jones C. E., Gröcke D. R., Hesselbo S. P. & Parkinson D. N. (2002) -Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. *J. Geol. Soc. London*, 159: 351-378, London.

Jiménez A. P., Cisneros C. J., Rivas P. & Vera J. A. (1996) - The Early Toarcian anoxic event in the westernmost Tethys (Subbetic): Paleogeographic and paleobiogeographic significance. *J. Geol.*, 104: 399-416, Chicago.

Letolle R. & Renard M. (1980) - Évolution des teneurs en 13C des carbonates pélagiques aux limites Crétacé/Tertiaire et Paléocène/Éocène. *C. R. Acad. Sci. Paris*, 290: 827-830, Paris.

McCrea J. M. (1950) - On the isotopic chemistry of carbonates and a paleotemperature scale. *J. Chem. Phys.*, 18 (6): 849-857, Amsterdam.

Renard M. (1984) - Géochimie des carbonates pélagiques. Mise en évidence des fluctuations de la composition des eaux océaniques depuis 140Ma. Essai de chimiostratigraphie. *Mém. Sci. Terre. Univ. P. et M. Curie*, 84-16: 650 pp., Paris.

Renard M. (1986) - Pelagic carbonate chemostratigraphy (Sr, Mg, 18O, 13C). *Marine Micropaleontology*, 10: 117-164, Amsterdam.

Rocha (General Coordinator) (1996) - The 1st and 2nd rifting phases of the Lusitanian Basin: stratigraphy, sequence analysis and sedimentary evolution. Final report, CEC, Project MILUPOBAS, Contract no JOU-2-CT94-0348, 4 vols, Lisboa.

Röhl H.J., Schmid-Röhl A., Oschmann W., Frimmel A. & Schwark L. (2001) - The Posidonia Shale (Lower Toarcian) of SW-Germany: an oxygen-depleted ecosystem controlled by sea level and palaeoclimate. *Palaeogeog., Palaeoclim., Palaeoecol.*, 165: 27-52, Amsterdam.

Rosales I., Quesada S. & Robles S. (2001) - Primary and diagenetic isotopic signals in fossils and hemipelagic carbonates: the Lower Jurassic of northern Spain. *Sedimentology*, 48: 1149-1169, Oxford.

Scholle P. & Arthur M. A. (1980) - Carbon isotopic fluctuations in pelagic limestones: potential stratigraphic and petroleum exploration tool. *AAPG Bull.*, 64: 67-87, Tulsa.

Shackleton N. J. & Hall, A. (1984) - Carbon isotope data from Leg 74 sediments. In: Moore, T. C. et al. (eds.) - I, Init. Report D.S.D.P., U.S. Gov. Printing Office, Washington, 74: 613-644.

Soares A. F., Marques J. F. & Rocha R. B. (1985) - Contribuição para o conhecimento geológico de Coimbra. *Memórias e Notícias*, Pub. Mus. Lab. Geol. Univ. Coimbra, 100: 41-71, Coimbra.

Vail P. R., Audemard F., Bowman S.A., Eisner P. N. & Perez-Cruz G. (1991) -The stratigraphic signatures of tectonics, eustacy and sedimentology. An overview. In: Einsele et al. (eds.) - Cycle and Events in Stratigraphy. Springer-Verlag, Berlin, 617-659.

Weissert H. (1989) - C-Isotope stratigraphy, a monitor of paleoenvironmental change: a case study from the Early Cretaceous. *Surveys in Geophysics*, 10: 1-61, Dordrecht.

Weissert H., Lini A., Follmi K. B. & Kuhn O. (1998) - Correlation of Early Cretaceous carbon isotope stratigraphy and platform drowning events: a possible link. *Palaeogeog., Palaeoclim., Palaeoecol.*, 137: 189-203, Amsterdam.

Wright V. P & Wilson R.C.L. (1984) - A carbonate submarine-fan sequence from the Jurassic of Portugal. *J. Sed. Petrol.*, 54: 394-412, Tulsa.

Taxonomic Appendix

Calcareous nannofossil species recognized.
Bibliography references for citated taxa can be found in Bown & Cooper (1998).

Biscutum dubium (Noël, 1965) Grün in Grün et al. 1974
Biscutum finchii (Crux, 1979) Bown, 1987
Biscutum grande Bown, 1987
Biscutum intermedium Bown, 1987
Biscutum novum (Goy, 1979) Bown, 1987
Bussonius prinsii (Noël, 1973) Goy, 1979
Calcivascularis jansae (Wiegand, 1984) Bown & Young in Young et al. 1986
Calyculus spp. indet.
Calyculus noelae depressa (Goy in Goy et al. 1979) Crux, 1987
Calyculus noelae recondita (Goy in Goy et al. 1979) Crux, 1987
Carinolithus spp. indet.
Carinolithus cantaluppiii Cobianchi, 1990
Carinolithus poulnabronei Mattioli, 1996
Carinolithus superbus (Deflandre, 1954) Prins in Grün et al. 1974
Crepidolithus cavus Rood, Hay & Barnard, 1973
Crepidolithus crassus (Deflandre, 1954) Noël, 1965
Crepidolithus granulatus Bown, 1987
Discorhabdus ignotus (Gorka, 1957) Perch-nielsen, 1968
Discorhabdus striatus Moshkovitz & Ehrlich, 1976
Lotharingius barozii Noël, 1973
Lotharingius crucicentralis (Medd, 1971) Grün & Zweili, 1980
Lotharingius hauffii Grün & Zweili in Grün et al. 1974
Lotharingius sigillatus (Stradner, 1961) Prins in Grün et al. 1974
Lotharingius velatus Bown & Cooper, 1989
L. umbriensis Mattioli, 1996
Mitrolithus lenticularis Bown, 1987
Parabdolithus liasicus Deflandre, 1952
Schizosphaerella spp. indet.
Similiscutum cruciulum de Kaenel & Bergen, 1993
Tubirhabdus patulus Prins ex Rood, Hay & Barnard, 1973
Zeugrhabdotus choffatii Rood, Hay & Barnard, 1973
Zeugrhabdotus erectus (Deflandre, 1954) Reinhardt, 1965