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Base of the Toarcian Stage of the Lower Jurassic defined by the Global Boundary Stratotype Section and Point (GSSP) at the Peniche section (Portugal)

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The Global Stratotype Section and Point (GSSP) for the base of Toarcian Stage, Lower Jurassic, is placed at the base of micritic limestone bed 15e at Ponta do Trovão (Peniche, Lusitanian Basin, Portugal; coordinates: 39º22'15"N, 9º23'07"W), 80km north of Lisbon, and coincides with the mass occurrence of the ammonite Dactylioceras (Eodactylites). *The Pliensbachian/Toarcian boundary (PLB/TOA) is contained in a continuous section forming over 450m of carbonate-rich sediments. Tectonics, syn-sedimentary disturbance, metamorphism or significant diagenesis do not significantly affect this area. At the PLB/TOA, no vertical facies changes, stratigraphical gaps or hiatuses have been recorded. The base of the Toarcian Stage is marked in the bed 15e by the first occurrence of* D. (E.) simplex, *co-occurring with* D. (E.) pseudocommune *and* D. (E.)

polymorphum. *The ammonite association of* D. (Eodactylites) *ssp. and other species e.g.* Protogrammoceras (Paltarpites) *cf.* paltum, Lioceratoides *aff.* ballinense *and* Tiltoniceras *aff.* capillatum *is particularly significant for the boundary definition and correlation with sections in different basins. Ammonites of the PLB/TOA are taxa characteristic of both the Mediterranean and Northwest European provinces that allow reliable, global correlations. The PLB/TOA is also characterized by other biostratigraphical markers (brachiopods, calcareous nannofossils, ostracods and benthic foraminifers) and by high-resolution stable carbon and oxygen isotopes, and* $^{87}Sr/^{86}Sr$ *ratios that show distinctive changes just above the PLB/TOA, thus providing additional, powerful tools for global correlations. The PBL-TOA lies at the end of a second (and third) order cycle of sea-level change, and the top of bed 15e is interpreted as a sequence boundary. Cyclostratigraphy analysis is available for the Lower Toarcian of Ponta do Trovão. Detailed correlations with the Almonacid de la Cuba section (Iberian Range, Spain) provide complementary data of the ammonite succession in the Northwest European Hawskerense and Paltum Subzones, and magnetostratigraphical data that allow supra-regional correlations. The proposal was voted on by the Toarcian Working Group in June, 2012, and by the International Subcommission on Jurassic Stratigraphy in September, 2012, approved by the ICS in November, 2014, and ratified by the IUGS in December, 2014. With this Toarcian GSSP, all international stages of the Lower Jurassic have been officially defined.*

Introduction

The Toarcian is the highest stage in the Early Jurassic. D'Orbigny in 1852 designated "étage Toarcien", from the town of Thouars (*Toarcium*) (Deux-Sèvres, France), but the boundary Pliensbachian - Toarcian is marked by an important unconformity in this locality, and a big question stands: what is missing at the base of the Toarcian (or at the top of the Pliensbachian)? This well-known problem has prevented easy correlations since the beginning of the use of the Toarcian stage. The lower limit of the stage has to be selected elsewhere.

Several groups of ammonites of primary importance for chronostratigraphy of the Jurassic System underwent significant turnover during the Late Pliensbachian and Early Toarcian (Harries and Little, 1999; Macchioni and Cecca, 2002; Cecca and Macchioni, 2004; Guex et al., 2012), enabling very fine biochronological subdivision and precise correlation of strata of this age. The base of the Toarcian has been usually assigned as the base of the Tenuicostatum Zone (Buckman, 1910; index species *Dactylioceras (Orthodactylites) tenuicostatum*), which is drawn at the first abundant appearance of *Dactylioceras* after the disappearance of *Pleuroceras*. The custom of using the Tenuicostatum Zone has been maintained, in spite of the restricted biogeographical extent of the index species and of the difficulties inherent to its identification. In the Tethyan "standard" the Toarcian begins with the Polymorphum Zone (index species *Dactylioceras (Eodactylites) polymorphum*). Thus, the primary marker for the base of the Toarcian, placed at 182.7±0.7 Ma (Gradstein et al., 2012), is provided by the evolution of *Dactylioceras* (*Eodactylites*) sp. However, the ammonite turnover was associated with some endemism and provincialism (Dera et al., 2011). Within most of the classical areas of Europe and North Africa, the provincialism did not lead to a complete isolation, so that correlations among areas showing mixed faunas are feasible.

The Toarcian Working Group was established in 1984 (1st International Symposium on Jurassic Stratigraphy in Erlangen, Germany), in order to improve the geological knowledge of the Pliensbachian/Toarcian boundary (PLB/TOA). Detailed studies of the ranges of all major fossil groups in well-studied sections subsequently were addressed. By considering the different advances of knowledge in various domains, the Toarcian Working Group intensified local investigations, with the aim of producing local standards (Fischer, 1984). Over the following fifteen years, the Toarcian Working Group has carried out fieldwork or scientific meetings in several selected sections before finally choosing Peniche (central-west Portugal; Fig. 1a, b) as the formal candidate for the GSSP of the Toarcian Stage. A final consensus was obtained in June, 2005, when the Toarcian Working Group accepted the Peniche section as the best section currently available (Elmi et al., 2005).

This report presents the GSSP for the Toarcian Stage at the base of the Polymorphum Zone in the Peniche section. It also presents in detail all the biostratigraphical (ammonites, brachiopods, calcareous nannofossils, ostracods, palynomorphs, and benthic foraminifers) and chemostratigraphical (carbon and oxygen stable isotope, strontium isotopes) data acquired for the Peniche section. A detailed comparison of the Peniche with the Almonacid de la Cuba section in the Iberian Range is then presented. The latter section is particularly interesting because magnetostratigraphy has been successfully applied (Comas-Rengifo et al., 2010). An indirect correlation of the Peniche section to the magnetic record of the Karoo basalts (South Africa) was then possible.

The Pliensbachian and the Toarcian stages in the Lusitanian Basin

Geological setting and lithostratigraphy

The Lower Jurassic is well represented in the Lusitanian Basin (Fig. 1c). The lithological succession corresponds to a thick carbonate series (over 450m), and is composed of shallow-marine dolomites to deep-marine limestones and argillaceous limestones (Mouterde et al., 1972; Soares et al., 1993; Duarte and Soares, 2002; Azerêdo et al., 2003; Duarte et al., 2004b, 2010; Duarte, 2007a; Kullberg et al., 2013). The Lower Pliensbachian recorded the opening of the basin to marine influence, with basin-wide occurrence of ammonoids. The Pliensbachian and Toarcian are dominated by hemipelagic deposits composed of marlstone-limestone alternations very rich in nektonic (ammonite and belemnite) and benthic (bivalve, brachiopod, crinoid and siliceous sponge) macrofauna. Ammonite biostratigraphy provides

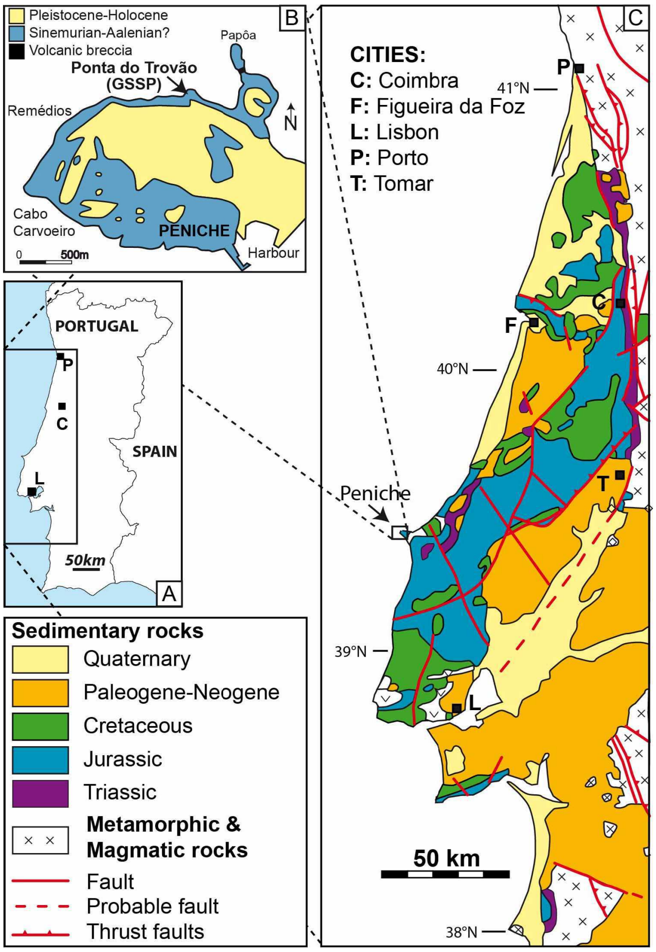


Figure 1. A. Geographic map of Portugal and position of main cities (L = Lisbon; C = Coimbra; P = Porto; T = Tomar). B. Geological map of Peniche peninsula and location of Ponta do Trovão. C. Schematic geological map of Portugal.

a good resolution throughout basin (Mouterde, 1967; Mouterde et al., 1972; Phelps, 1985; Rocha et al., 1987, 1996; Dommergues, 1987; Elmi, 2006; Elmi et al., 2007; Mouterde et al., 2007). In Portugal, the PLB/TOA outcrops in several localities and yields Tethyan ammonites associated with some classically NW European taxa. These assemblages provide good markers for worldwide correlations. Moreover, although condensation occurs at some levels, the transition beds commonly indicate continuous sedimentation, in contrast to the widespread significant gaps recorded in sections from NW Europe (Pittet et al., 2014).

The Peniche peninsula, located some 80km north of Lisbon (Fig. 1b) shows the most representative Lower Jurassic succession for the Lusitanian Basin. Cropping out along the Atlantic coast, the Peniche section (>450m thick; Fig. 2a) ranges in age from the Early Sinemurian (Coimbra Fm) to the early Middle Jurassic (Aalenian (?); top of Cabo Carvoeiro Fm; França et al., 1960; Duarte and Soares, 2002; Duarte et al., 2004b). Good exposure and detailed biostratigraphical data (Mouterde, 1955, 1967; Phelps, 1985; Dommergues, 1987; Elmi, 2006; Elmi et al., 2007) allowed the definition of three formations with type localities in Peniche: Vale das Fontes, Lemede and Cabo Carvoeiro (Duarte and Soares, 2002). The whole succession dips gently to the south.

In the Ponta do Trovão section, the PLB/TOA (coordinates: 39º22'15"N, 9º23'07"W) is included in the uppermost part of the Lemede Fm, just below the base of Cabo Carvoeiro Fm (Fig. 2b). The Lemede Fm is composed of bioturbated, cm-thick marlstones alternating with dm-thick limestones, rich in belemnites, ammonites, bivalves and brachiopods. The formation age ranges from the top of Margaritatus Zone to the lowermost part of Polymorphum Zone (Duarte et al., 2014), attaining in Peniche a thickness of around 24m. The Cabo Carvoeiro Fm consists of a thick, carbonate-rich succession; an increase in siliciclastic sandstones and oolitic/peloidal limestones is recorded towards the top of the formation (Wright and Wilson, 1984; Duarte, 1997). This unit, more than 150m thick, is subdivided into five members (CC1 to 5; Duarte and Soares, 2002; Fig. 2a). The first member, around 11m thick, is dated as Polymorphum Zone, and consists of dm-thick alternations of marls and cm-thick limestones. The macrofauna is very abundant and diverse, being particularly rich in brachiopods, bivalves, belemnites and pyritised ammonites (dactylioceratids), but benthic fauna decreases upwards in terms of number of individuals and of species. *Zoophycos*, *Planolites* and pyritised burrows are very common. Member CC1 is the lateral equivalent of the Marly limestones with “Leptaena” fauna (MLLF) Member of S. Gião Fm, showing very similar sedimentary characteristics.

The uppermost part (top ~1m) of the Lemede Fm described by Choffat (1880) and Mouterde (1955) shows a progressive sedimentary evolution from carbonate- to marl-dominated sediments and is named *Couches de passage* (Transition beds, 15a-e; Fig. 3). These beds have yielded a continuous and diversified fossil record. Shells are commonly concentrated, forming irregular heaps. Some chaotically oriented belemnite accumulations have been interpreted as coprolite remains. *Plicatula* and serpulids are attached to ammonite shells or casts. Because of these features, the *Couches de passage* are interpreted as being deposited under a low sedimentation rate, although there is no evidence for the occurrence of a hiatus. The uppermost bed (15e; Fig. 3) has yielded a characteristic association of dactylioceratids that is classically interpreted as marking the base of the Toarcian. As a consequence, the chronostratigraphical boundary is distinct from the lithological boundary, the latter being situated between the *Couches de passage* (beds 15, topmost part of Lemede Fm) and the base of the Cabo Carvoeiro Fm (bed 16, base of Cabo Carvoeiro CC1; Fig. 3).

Sequence stratigraphy and cyclostratigraphy

In the Lusitanian Basin, the Pliensbachian and Toarcian series are included in an Upper Triassic (Norian?)–Callovian sedimentary cycle (Hallam, 1971; Wright and Wilson, 1984; Wilson et al., 1989; Soares et al., 1993; Azerêdo et al., 2003, 2014). This cycle begins with coarse, red siliciclastic sediments from the base of the Upper Triassic, and ends with bioclastic limestones of Late Callovian age (Athleta Zone). In this cycle, the Pliensbachian and Toarcian deposits correspond to the maximum transgressive interval and the strata are subdivided into two second-order sequences, equivalent to transgressive-regressive facies cycles of de Graciansky et al. (1998) (Fig. 2a; Soares et al., 1993; Duarte, 1997, 2007a; Duarte et al., 2004b; Azerêdo et al., 2014). The sequence boundary of the second sequence is dated to the lowermost Polymorphum Zone (intra-Mirabile Subzone, at the top of bed 15e; Fig. 2b) at the top of the Lemede Formation that shows a regressive trend (Duarte et al., 2010) well constrained in the proximal part of the Lusitanian Basin (Tomar region;

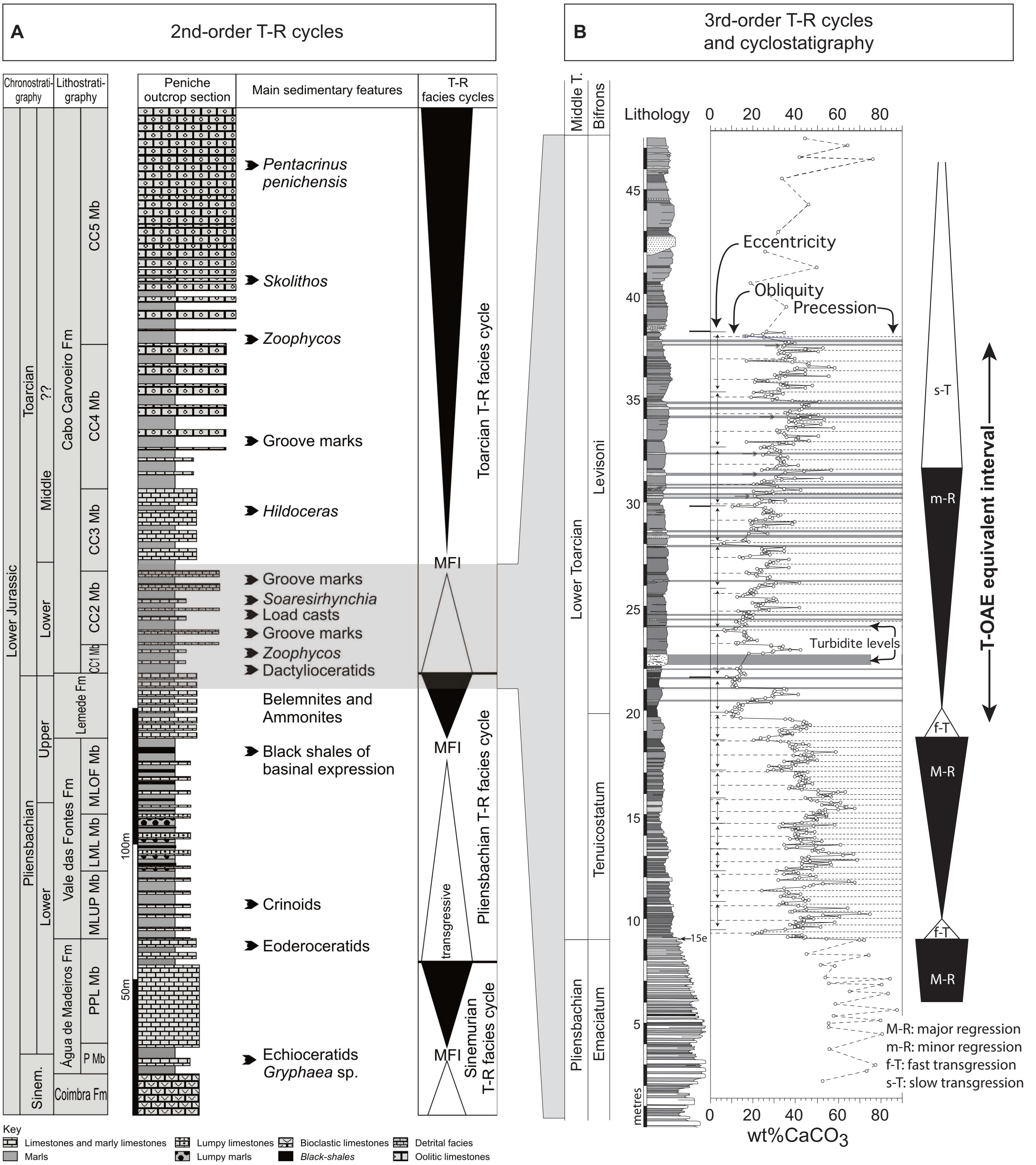


Figure 2. A. Stratigraphical log of the Late Sinemurian – Aalenian (?) succession at Peniche: lithostratigraphy, sequence stratigraphy (second-order Transgressive (T) – Regressive (R) cycles) and main sedimentary features (adapted from Duarte et al., 2004b). PMb – Polvoeira Member; PPLMb – Praia da Pedra Lisa Member; MLUP Mb - Marls and limestones with Uptonia and Pentacrinus member; LML Mb - Lumpy marlstones and limestones member; MLBF Mb – Marly limestones with bituminous facies member; CC1 to CC5 Mb – Cabo Carvoeiro members 1 to 5. B. The PLB/TOA interval at Peniche with high-resolution wt%CaCO$_3$ data. Fluctuations of the wt%CaCO$_3$, related to eccentricity, obliquity and precession, are shown. Also are shown the fluctuations in wt%CaCO$_3$ not related to cycles (doubled-tipped arrows), but likely corresponding to values measured on samples collected in or just below turbiditic layers (shaded zones). Low-resolution wt%CaCO$_3$ data in the Emaciatum and uppermost Levisoni Zones are also displayed to characterize the long-term evolution of the lithology (Suan et al., 2008b). 3rd order transgressive-regressive sequences are based upon Pittet et al. (2014). The stratigraphic position of the T-OAE equivalent interval is displayed. Even if this log shows only two meters of uppermost Pliensbachian (a part of its uppermost ammonite subzone), there is a more complete Upper Pliensbachian in the Ponta do Trovão section.

Fig. 1) by coarse calcarenites deposited in coastal environments (Suan et al., 2010). This level was immediately followed by a fast transgression at the onset of Early Toarcian in the Lusitanian Basin and the installation of a clay-rich sedimentation (Fig. 2b). The transgression is locally materialized by a condensed interval on top of bed 15e (Mouterde, 1955) and in the lowermost marls of the Cabo Carvoeiro Formation (Pittet et al., 2014).

The Lemede Fm (Upper Pliensbachian) is formed by lithological alternations where marlstones have a calcium carbonate content of 50–60wt% and limestones of 75–85wt% (Fig. 2b; Suan et al., 2008a). The Polymorphum Zone in the Cabo Carvoeiro Fm displays more variable $CaCO_3$ content. Some 30 cm above the Pliensbachian-Toarcian boundary, a 15 cm-thick marly interval has a $CaCO_3$ content of 20–25wt%. This clay-rich interval is also recorded in other sections of the Lusitanian Basin. Above, carbonate content fluctuates between 25 and 75wt%, and a decrease in the average carbonate content is recorded in the uppermost Polymorphum Zone. Spectral analysis of the carbonate content has been undertaken for most of the Lower Toarcian (Suan et al., 2008b), which demonstrates a dominant control of eccentricity and precession in the lower part of the Polymorphum Zone, of eccentricity alone in the upper part of this zone, and of eccentricity and obliquity in most of the Levisoni Zone, with precessional pacing being well-resolved in the upper part of the latter zone (Fig. 2b). The change from precession to obliquity dominance for the shorter term orbital control on sedimentation passing from the Pliensbachian to the Toarcian has also been recorded in other sedimentary sequences (Hinnov and Park, 1999), which suggests that the Pliensbachian of the Lemede Fm was also formed in tune with precession. The marlstone-limestone alternations display an average thickness (~27 cm in the upper part of the Emaciatum Zone, Fig. 2b) comparable to the precession-related carbonate content fluctuations recorded in the Polymorphum Zone (two cyclicities at 23 and 33 cm; Suan et al., 2008b). Similar results were obtained by Huang and Hesselbo (2014) who applied spectral analysis to the high-resolution $\delta^{13}C_{carb}$ record of the Peniche section.

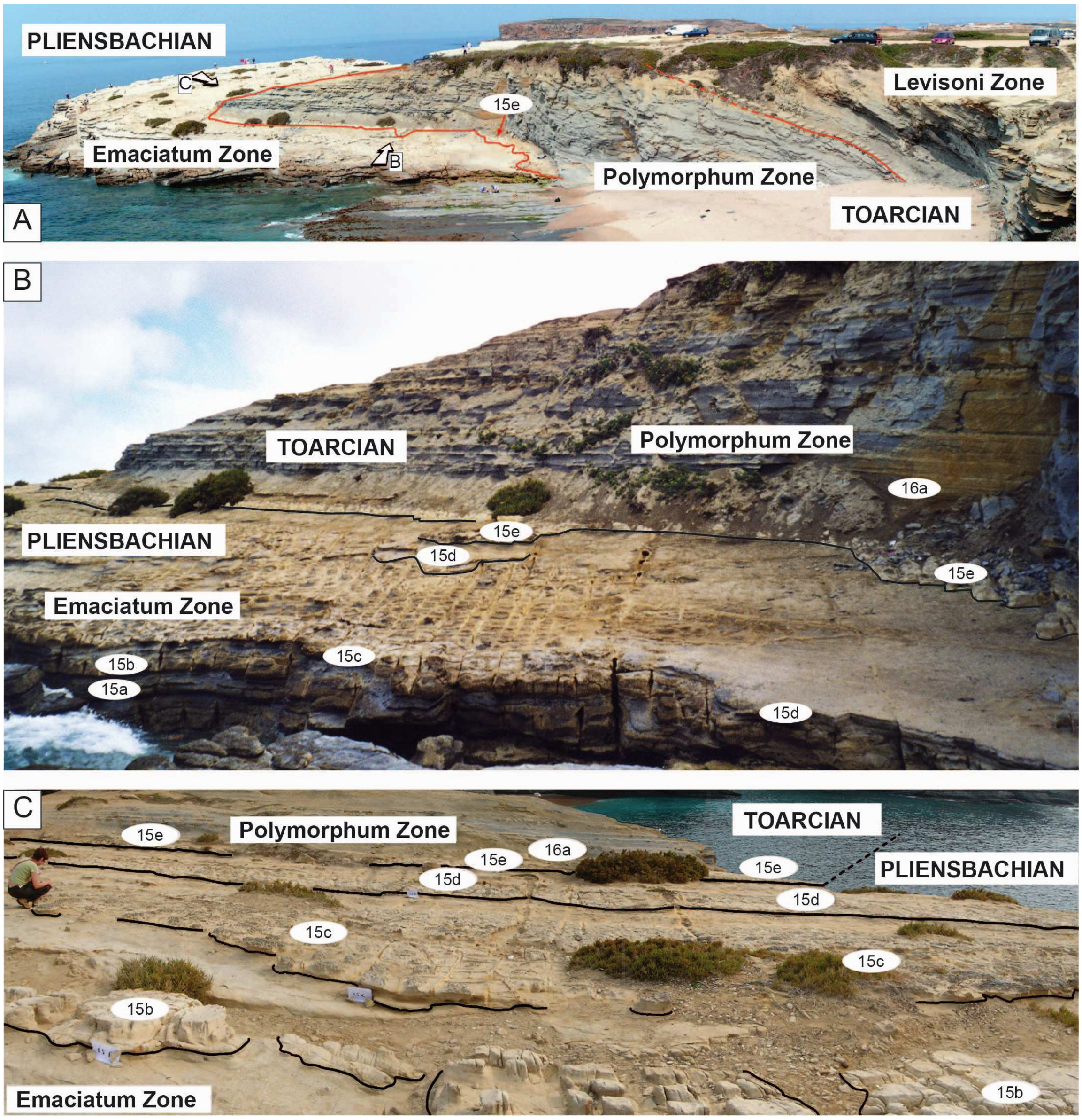


Figure 3. A. General view of the outcrop at Ponta do Trovão section, Peniche peninsula (Portugal). B. The PLB/TOA boundary, with the Transition beds ("Couches de passage") defined by Mouterde (1955). C. Detail of the Transition beds.

Fossil content of the Transition beds

Ammonites

The Peniche section, first mentioned by Choffat (1880), is one of the most important settings in Europe for establishing the ammonite zones succession of the Pliensbachian and Toarcian stages (Mouterde, 1955, 1967; Phelps, 1985; Rocha et al., 1987, 1996; Dommergues, 1987; Elmi, 2006, 2007; Elmi et al., 2007; Mouterde et al., 2007). The detailed description of the *Couches de passage* (Transition beds) succession marking the PLB/TOA interval is presented here, from the bottom to the top (Figs. 4A and 5):

Emaciatum Zone, Elisa Subzone

Bed 15a (0.15m) also named *Canavaria* bed: bioturbated, micritic limestone containing some irregular, nodular lumps. *Canavaria zancleana* (Fucini) is associated with *Emaciaticeras emaciatum* (Catullo), *E. lotti* (Fucini) and *Lioceratoides* aff. *ballinense* (Haas).

Bed 15b (0.25/0.30m): no ammonites recorded in these calcareous laminated marls, which bear brachiopods (*Zeilleria* sp.), belemnites, gastropods and bivalves (*Plicatula* (*P.*) *spinosa* (Sowerby) var. *pectinoides* (Lamarck)).

Bed 15c (0.25/0.30m) also known as *Taurومeniceras* bed: formed of bioturbated micritic limestones, with *Taurومeniceras elisa* (Fucini), *T. disputandum* Dubar, *T.* gr. *nerina* (Fucini), *Lioceratoides aradasi* (Fucini), *L.* aff. *ballinense* (Haas), *Tiltoniceras* aff. *capillatum* (Denckmann), *Pleuroceras* cf. *buckmani* Moxon, *Protogrammoceras* (*Paltarpites*) sp., *Spiriferina* gr. *rostrata* Schlotheim and *P.* (*P.*) *spinosa* var. *pectinoides* (Lamarck).

Bed 15d (0.20/0.30m): marly limestone enriched in belemnites and spiriferinids. *Taurومeniceras mazetieri* (Dubar), *Neolioceratoides* aff. *hoffmanni* (Gemmellaro), *Spiriferina* gr. *rostrata* Schlot., *Zeilleria* sp. and *P.* (*P.*) *spinosa* var. *pectinoides* (Lamarck) are commonly recorded.

Polymorphum Zone, Mirabile Subzone

Bed 15e (0.20m) also named *Eodactylites* bed: micritic limestone bearing numerous ammonites. Ammonites generally correspond to oxidized-pyrite internal moulds. *Eodactylites* are abundant and diversified: *Dactylioceras* (*Eodactylites*) *simplex* (Fucini), *D.* (*E.*) *pseudocommune* Fucini, *D.* (*E.*) *polymorphum* Fucini. According to Elmi et al. (1994), the Mirabile Subzone is defined on the basis of the presence of *D.* (*E.*) *simplex*. The association of *D.* (*E.*) *simplex* with *D.* (*E.*) *pseudocommune* may indicate a slight condensation. Upper Pliensbachian specimens, like *Tiltoniceras* aff. *capillatum* (Denckmann) and *Lioceratoides* aff. *ballinense* (Haas), are also associated. The presence of *Protogrammoceras* (*Paltarpites*) cf. *paltum* (Buckman) is especially important for correlations with NW Europe. Brachiopods (*Spiriferina* sp., *Zeilleria* sp. and *Rhynchonella* sp.), belemnites and bivalves (*P.* (*P.*) *spinosa* var. *pectinoides* (Lamarck)) are also common. This bed marks the beginning of the Toarcian (Paltus/Mirabile Subzone of the Tenuicostatum/Polymorphum Zone), also characterized by the disappearance of arieticeratinids (*Emaciaticeras*, *Canavaria*, *Taurومeniceras*) and hildoceratids (*Neolioceratoides*).

Polymorphum Zone, Semicelatum Subzone

Bed 16a (1.70m): base of the Cabo Carvoeiro Fm. The lowest two metres of this marl-dominated unit contain small pyritized internal moulds of specimens attributed to NW European *Orthodactylites* namely, *D.* (*O.*) *crosbeyi* (Simpson), *D.* (*O.*) *clevelandicum* Howarth, associated with *Protogrammoceras* (*Paltarpites*) sp. The base of the Semicelatum Subzone is defined on the basis of the occurrence of *D.* (*O.*) *crosbeyi* and *D.* (*O.*) *clevelandicum*, whilst *D.* (*O.*) *semicelatum* (Simpson) is recorded from the bed 16c. The record of these specimens allows a tentative correlation with the Crosbeyi/Clevelandicum Subzones of Britain, and supports the hypothesis that the absence of *Eodactylites* in many classic NW European sections is due to a sedimentary gap, rather than to a palaeogeographically controlled distribution of this genus. This bed also yields an abundant assemblage of belemnites, gastropods and brachiopods. Brachiopods are small and perhaps indicative of dwarfism, related to poorly oxygenated, organic matter-rich environments. Bioturbation is widespread (*Zoophycos* and pyritised tubular burrows). The upper part of Bed 16c contains several fossiliferous layers yielding mainly *D.* (*O.*) *semicelatum*. These ammonites are commonly randomly orientated, probably as a result of bioturbation.

In the Lusitanian Basin, the successive fossil assemblages of the PLB/TOA mainly contain genera characteristic of the Mediterranean Province (*Lioceratoides*, *Neolioceratoides*, *Dactylioceras* (*Eodactylites*)) and of the Northwest European Province (*Protogrammoceras* (*Paltarpites*), *Dactylioceras* (*Orthodactylites*); Figs. 4, 5). The occurrence of taxa from both provinces in the Peniche section is extremely helpful in improving correlations between different areas.

For the definition of the base of the Toarcian, the ammonite assemblage includes (Figs. 4A, 5):

Dactylioceras (*Eodactylites*) *polymorphum* Fucini,
D. (*E.*) *pseudocommune* Fucini,
D. (*E.*) *simplex* (Fucini),
Protogrammoceras (*Paltarpites*) cf. *paltum* (Buckman),
Lioceratoides aff. *ballinense* (Haas),
Tiltoniceras aff. *capillatum* (Denckmann).

This assemblage well characterizes the Mirabile Subzone, although the zonal index (*D.* (*E.*) *mirabile* Fucini 1935, p. 85, tav. VIII, fig. 1-4) is not present in the Peniche section but in the Almonacid de la Cuba section, well correlated to Peniche (see below). *Lioceratoides* aff. *ballinense* and *Tiltoniceras* aff. *capillatum* are found below and above the boundary. The latter species differs from the *Tiltoniceras antiquum* of Britain (Howarth, 1992) in having a more open umbilicus, and its stratigraphical range is also different, being confined to the Polymorphum Zone (Dommergues et al., in Cariou and Hantzpergue, 1997).

Brachiopods

The early work of Choffat (1880) mentioned in the upper part of the "Couches de passage" (beds with *Ammonites spinatus*), *Terebratula* cf. *punctata* Sow., *T. davidsoni* Haime, *Zeilleria darwini* Desl., *Z.* cf. *cornuta* Sow., *Z. resupinata* Sow., *Kingena deslongchampsi* Dav., *Rhynchonella* cf. *bidens* Sow., *R.* cf. *serrata* Sow., *R. amalthei* Qu., *R. rimosa* Buch, *R. moorei* Dav., *Spiriferina rostrata* Schl. In the "Couches à *Leptaena*", are mentioned: *Terebratula davidsoni* Haime, *Zeilleria darwini* Desl., *Kingena*

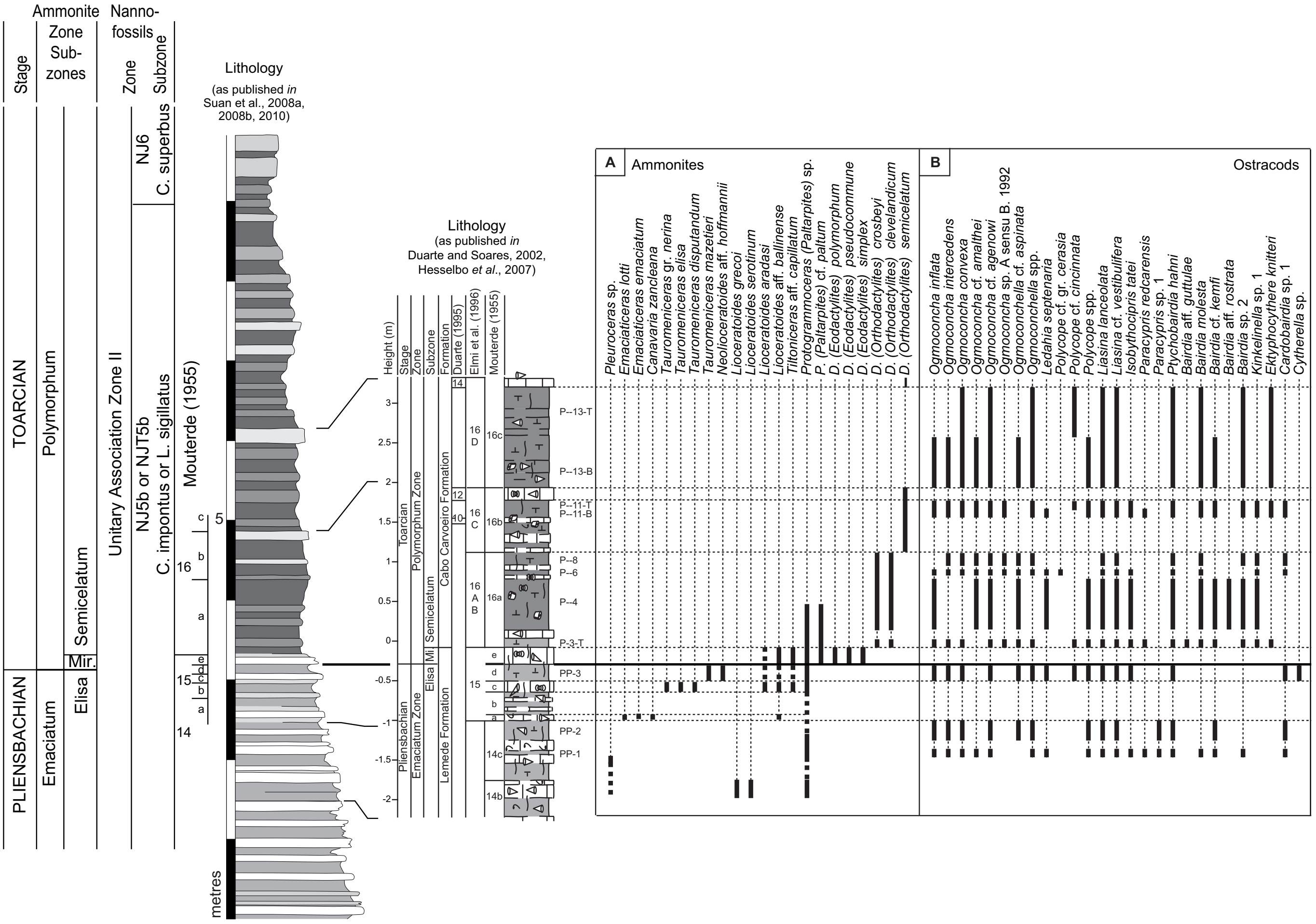


Figure 4. Comparison between the stratigraphig logs published by Suan et al. (2008a and b; 2010), and by Duarte and Soares (2002) and Hesselbo et al. (2007). Even if these logs show only two meters of uppermost Pliensbachian (a part of its uppermost ammonite subzone), there is a more complete Upper Pliensbachian in the Ponta do Trovão section. A. Distribution chart of ammonites. B. Distribution chart of ostracods.

deslongchampsi Dav., *Rhynchonella pygmaea* Sow., *R. amalthei* Qu., *R. moorei* Morr., *R.* cf. *bouchardi* Dav., *R.* cf. *frontalis* Desl., *Spiriferina rostrata* Schl., *Leptaena liasina* Bouch., *Thecidea sinnata* Desl. Choffat (1947, posthumous publication coordinated by C. Teixeira) figured *Zeilleria conocolis* Rau (Charmouthian, "couches à *Am. spinatus*"), *Terebratula ovulum* Qu., *Zeilleria* sp. ind., *Z. cornuta* Sow., *Z. darwini* Desl. (Lower Toarcian, "Couches de passage"), *Terebratula ovulum* Qu. var. *penichensis* Chof. ("Couches à *Leptaena*").

Mouterde (1955) described *Spiriferina* gr. *S. rostrata* Schl., *S. sicula* Canav., *Aulacothyris* aff. *walfordi* Dav., *Zeilleria* gr. *darwini* Desl., *Zeilleria* sp., *Rhynchonella* sp. from the upper part of the Spinatum Zone (beds 14a-c, 15 a-d). At the base of the Toarcian (bed 15e), he recorded *S. rostrata* Schl. var. *madagascariense* Thév., *S. apenninica* Canav., *Zeilleria* sp., *Rhynchonella* sp., and in the overlying beds 16a-b *R. pygmaea* Morr., *Koninkella liasina* Desl., *K. deslongchampsi* Dav., *S. apenninica* Canav. and *Rhynchonella* cf. *fallax* Desl. The most abundant species in bed 16c is *R. pygmaea* Sow.

More recently, many authors have mentioned the presence of Upper Pliensbachian and Lower Toarcian brachiopods from the Peniche section, but there are few detailed studies (Alméras et al., in Rocha and Soares, 1988; Alméras et al., 1995; Comas-Rengifo et al., 2015) where the most representative species of Emaciatum Zone (Elisa Subzone) are illustrated, namely: *Liospiriferina* cf. *rostrata* (Schl.), *L.* aff. *nicklesi* (Corroy), *Prionorhynchia serrata* (Sow.), *Gibbirhynchia northamptonensis* (Dav.), *Quadratirhynchia quadrata* Buck., *Homoeorhynchia acuta* (Sow.), *Lobothyris punctata* (Sow.), *L. subpunctata* (Dav.). These papers also report the specimens from the Elisa Subzone and the lower part of Semicelatum Subzone: *Liospiriferina* cf. *falloti* (Corroy), *Cisnerospira* n. sp., *Gibbirhynchia* aff. *reyi* Alméras and Fauré, *Gibbirhynchia cantabrica* García Joral and Goy, *Zeilleria quadrifida* (Lamarck), *Zeilleria culeiformis* (Rollier), *Lobothyris* cf. *arcta* (Dubar). Alméras et al. (in Rocha and Soares, 1988), Alméras et al., (1995) and Comas-Rengifo et al. (2015) also document the brachiopods recorded only from the Polymorphum Zone (Semicelatum Subzone): *Liospiriferina subquadrata* (Seguenza), *Cirpa fallax* (Desl.), *Nannirhynchia pygmaea* (Morris), *Pseudokingena deslongchampsi* (Dav.) and *K. liasina* (Bouchard).

Below the PLB/TOA, the recorded taxa are very similar to the Southern England faunas and enable correlation with the basins of Western Europe and North Africa outside the Alpine Belt. In the Mirabile Subzone of the Lower Toarcian, taxa show a more restricted palaeobiogeographic distribution, allowing correlation with several neighboring European basins. At the base of the Semicelatum Subzone, an important environmental change took place with

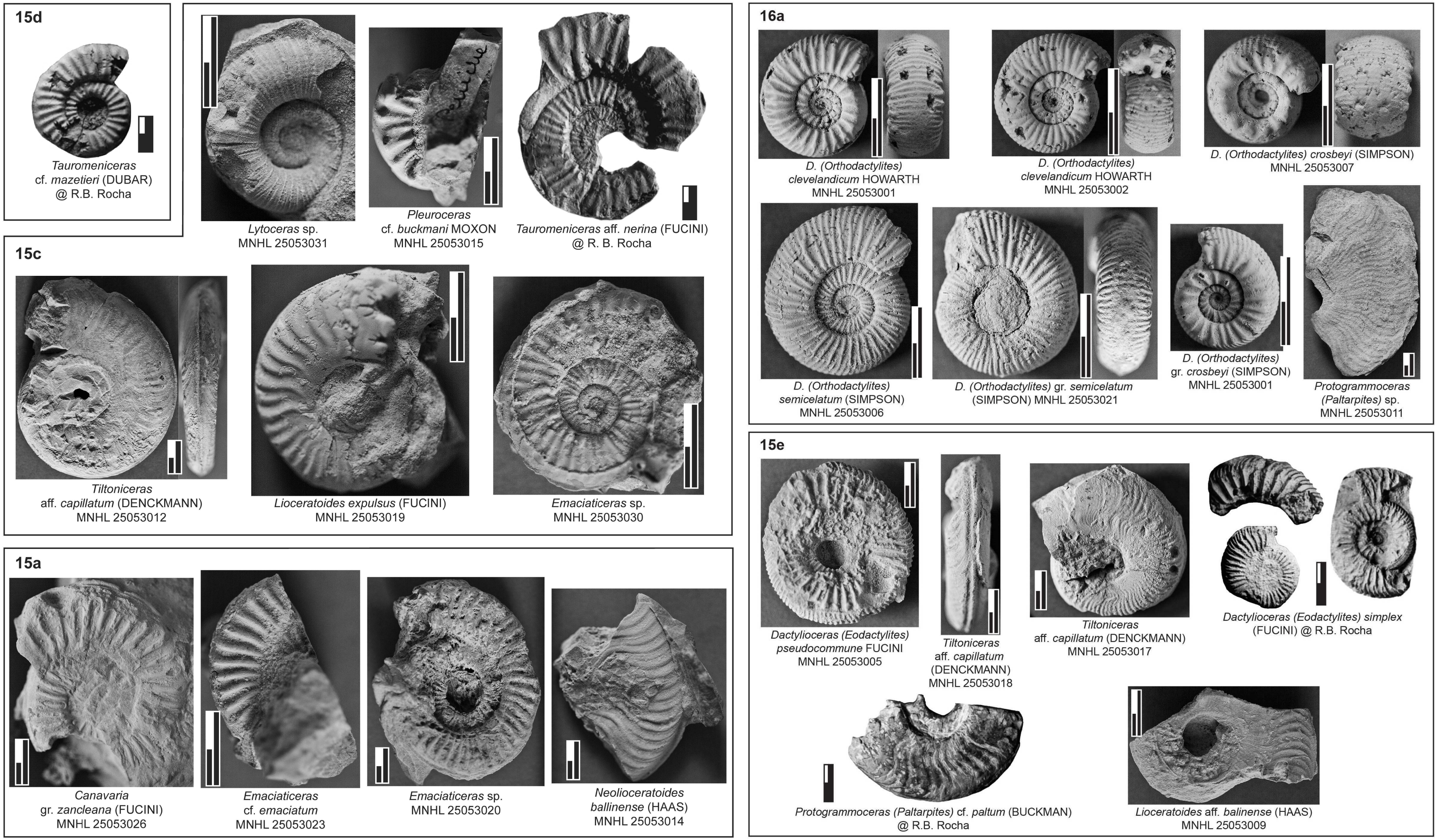


Figure 5. Ammonites from Ponta do Trovão (Peniche) section. Specimens are from the René Mouterde's collection, by the courtesy of David Besson curator of the Musée des Confluences Lyon (MNHL). Photos by Emmanuel Robert (curator, Collections de Géologie de Lyon) unless for bed 15e and for* Protogrammoceras (Paltarpites) *cf.* paltum *and* Dactylioceras (Eodactylites) simplex *that are from Elmi et al. (2007). Scale is 1 cm. A. Specimens from beds 15a, 15c and 15d. B. Specimens from beds 15e and 16a.

development of probable dysoxic conditions. Brachiopods are rather small in size, polymorphs, very abundant and with a low diversity assemblage. They are represented by Athyridida, Koninckinidae (*K. liasina*), Terebratulida, *incertae sedis* (*P. deslongchampsi*) and Rhynchonellida, Norellidae (*N. pygmaea*), which represent the lower beds of the Koninckella fauna, equivalent to the Leptaena fauna described in England and Normandy (Davidson and Morris, 1847; Deslongchamps, 1853).

In Peniche, as in other Western Tethys areas, a major extinction episode affected brachiopods during the Polymorphum–Levisoni Zones, with the complete disappearance of the orders Athyridida and Spiriferida, the renewal of many of the specimens of the order Rhynchonellida, and a negative impact on the Terebratulida (García Joral and Goy, 2000; Alméras and Fauré, 2000; Gahr, 2002; Vörös, 2002; Gómez et al., 2008). The reappearance of the group took place subsequently and is marked by the presence of the widely distributed species *Soaresirhynchia bouchardi* (Davidson).

Calcareous nannofossils

Calcareous nannofossils represent a powerful biostratigraphic tool for the Lower Jurassic series. Events and assemblages of Peniche have already been described (Comas-Rengifo et al., 2004; Oliveira et al., 2005; 2007b; Perilli and Duarte, 2006; Mailliot et al., 2007; Suan et al., 2008a; Mattioli et al., 2008; 2013). The majority of the samples analyzed here display a good to moderate preservation of nannofossils (Fig. 7), with the Upper Pliensbachian marlstone/limestone alternations of Peniche (Emaciatum Zone) showing a moderate preservation, whereas the basal Toarcian marlstone/limestone alternations (Polymorphum Zone) generally display a better preservation where delicate forms of coccoliths are commonly observed.

A gradual diversification of coccoliths is observed at Peniche (Mattioli et al., 2013) and this trend is consistent with the diversification pattern documented within the western Tethys (Bown and Cooper, 1998). Species richness significantly increases across the PLB/TOA. Nannofossil diversification mainly concerned placoliths (coccoliths with two sub-horizontal shields separated by a tube, Bown and Young, 1998). Thus, assemblages in the Pliensbachian were dominated by muroliths (coccoliths having a wall-like, sub-vertical rim; Bown and Young, 1998), whereas placoliths became more common in the Toarcian (Fig. 6). Just above the PLB/TOA, absolute abundance progressively increases up to the highest value recorded in the section (Suan et al., 2008a). This increase parallels a significant decrease of *Schizosphaerella* spp. size from 12 µm on average to <9 µm (Suan et al., 2010).

The presence of *Calyculus* spp., *Crepidolithus cavus/impontus*, *Lotharingius sigillatus* and *Lotharingius crucicentralis* is recorded from the base of the interval studied here (Fig. 6). *Lotharingius* aff. *L. velatus* (having the same diagnostic characters of *Lotharingius velatus* but smaller in size and with a thinner rim; Fig. 7.17) first occurs within the Emaciatum Zone at the very base of the studied interval (Oliveira et al., 2007b; Mattioli et al., 2013). Slightly higher, we report the First Occurrences (FOs) of *Biscutum intermedium L. velatus* and *Discorhabdus ignotus* (1.20 m and 2.95 m, respectively; Fig. 6). In particular, the FO of *Discorhabdus* genus at the very base of the Toarcian is a new datum. A similar record is documented in the Amellago (Morocco; Bodin et al., 2010) and Valdorbia (central Italy; Mattioli et al., 2013) sections. A possible explanation for this new record relies on the presence of a hiatus affecting several Tethyan areas at the PLB/TOA, when *Discorhabdus* first occurs, and a subsequent Lazarus behaviour of this taxon during the Toarcian Oceanic Anoxic Event (T-OAE; for more discussion, see Mattioli et al., 2013). Also, the FO of *B. intermedium* was previously referred to as Middle Toarcian (Bown, 1987; Bown and Cooper, 1998). The Peniche record represents, therefore, significant new evidence of nannofossil events. The FOs of *Diductius constans* and *Carinolithus superbus* are recorded in the basal Toarcian (8.1 m; Fig. 6), and this record is consistent in the literature (Bown, 1987).

The PLB/TOA at Peniche is within the NJT5b *L. sigillatus* nannofossil subzone of Mattioli and Erba (1999; South Tethyan margin) or in the NJ5b *C. impontus* Subzone of Bown and Cooper (1998; NW Europe). Because the Peniche nannofossil assemblages show characters intermediate between the N and S Tethyan assemblages, both biostratigraphical schemes can be used. Finally the FO of *Carinolithus superbus* (reported as the FO of *Carinolithus* spp. by Oliveira et al., 2007b) is very important because it marks the base of the NJ6 Nannofossil Zone, which encapsulates the T-OAE. The PLB/TOA is in the nannofossil Unitary Association Zone UA-Z II, spanning the Upper Pliensbachian to the Lower Toarcian interval (Mailliot et al., 2006). This zone is characterized by the co-occurrence of *Similiscutum precarium* and 22 other nannofossil species. Among these taxa, *Similiscutum finchii* represents the oldest FO within the UA-Z II, while *Discorhabdus ignotus* represents the youngest.

Peniche nannofossils show some peculiar features. Over-calcified specimens of *L. frodoi* are observed in various samples (Fig. 7.14), displaying higher birefringence colours. These specimens are probably transitional between *Lotharingius* and *Watznaueria britannica*, as the FO of *W. britannica* is commonly reported at the Aalenian/Bajocian boundary (Mattioli and Erba 1999). The presence of these transitional forms, similar to *W. britannica*, may explain the presence of *Ellipsagelosphaera* (=*Watznaueria*) *britannica* (that are very likely over-calcified *L. frodoi*) from the Toarcian of the Lusitanian Basin (Hamilton, 1979). The presence of over-calcified, robust coccoliths seems to be a common pattern in Peniche, mainly in the uppermost Pliensbachian interval. Robust specimens of *Similiscutum* aff. *S. finchii*, named here *S. giganteum* (Fig. 7.9-10), and *C. granulatus*, are also recorded sporadically. Conversely, in the Lower Toarcian under-calcified, tiny coccoliths are observed, including *L. velatus* (Fig. 7.18), *L. barozii*, and *Similiscutum finchii*. These taxa do not show reduced dimensions (i.e., coccolith length and width) with respect to holotype descriptions, but instead have a very thin ring and an enlarged central area.

Ostracods

Ostracod data from Peniche have previously been published in part in Pinto et al. (2007). Ostracods are present in all the analysed samples with poor preservation (recrystallized and worn specimens). Species richness is high in the interval from the top of Emaciatum to the top of Polymorphum zones, with 13 genera and at least 28 marine species. Ostracods from the top of Emaciatum Zone are dominated by *Ogmoconcha*, *Ogmoconchella* and *Liasina*, associated with *Polycope*, *Paracypris* and *Ledahia*. Ostracods from the Polymorphum Zone are represented by *Ogmoconcha*, *Ogmoconchella* and *Liasina* genera, which are dominant, and by heavily ornamented species of *Kinkelinella* and *Ektyphocythere*. Of the 28 ostracod species, 19 are common to the topmost Pliensbachian and Lower Toarcian. Most of

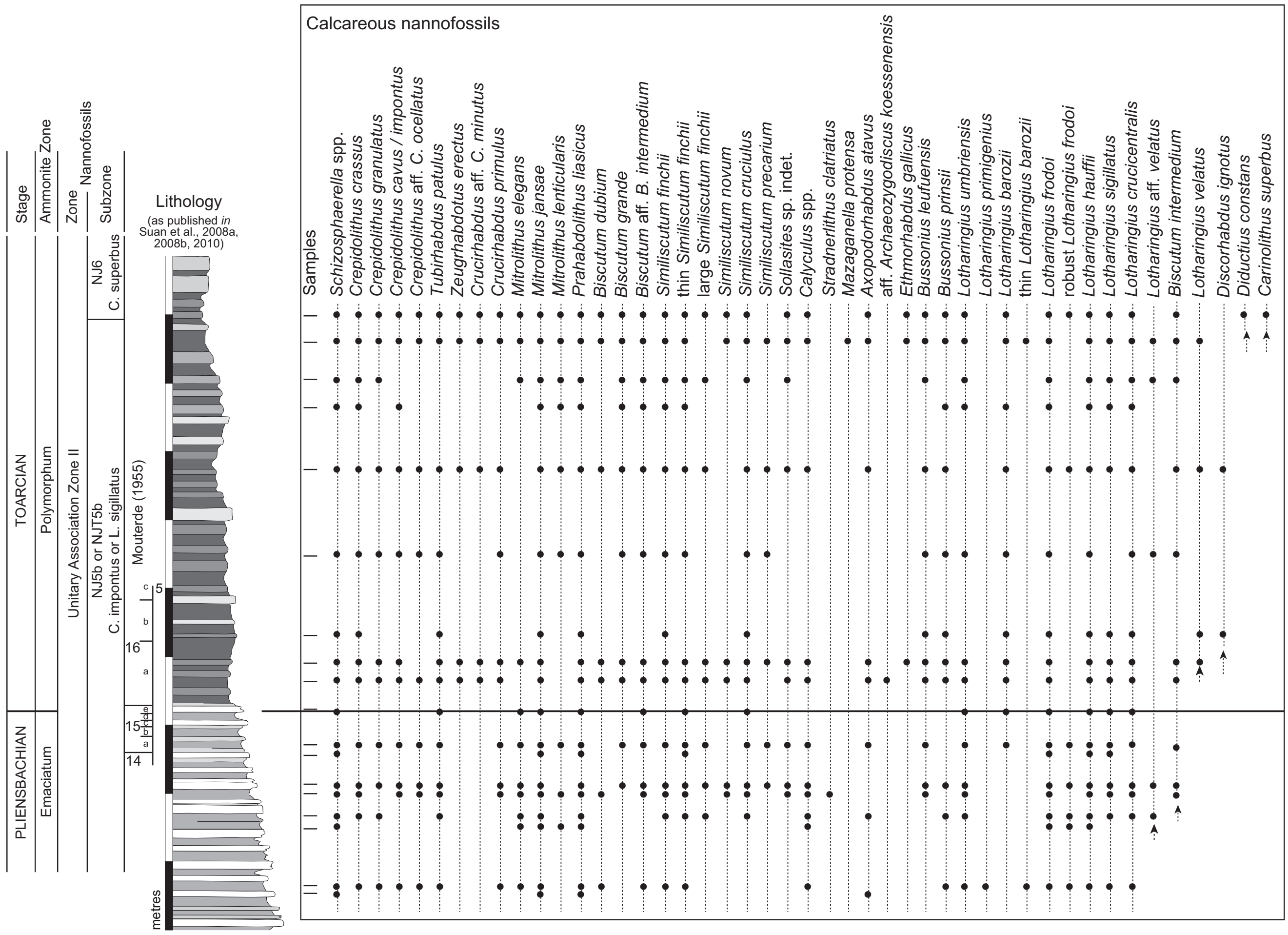


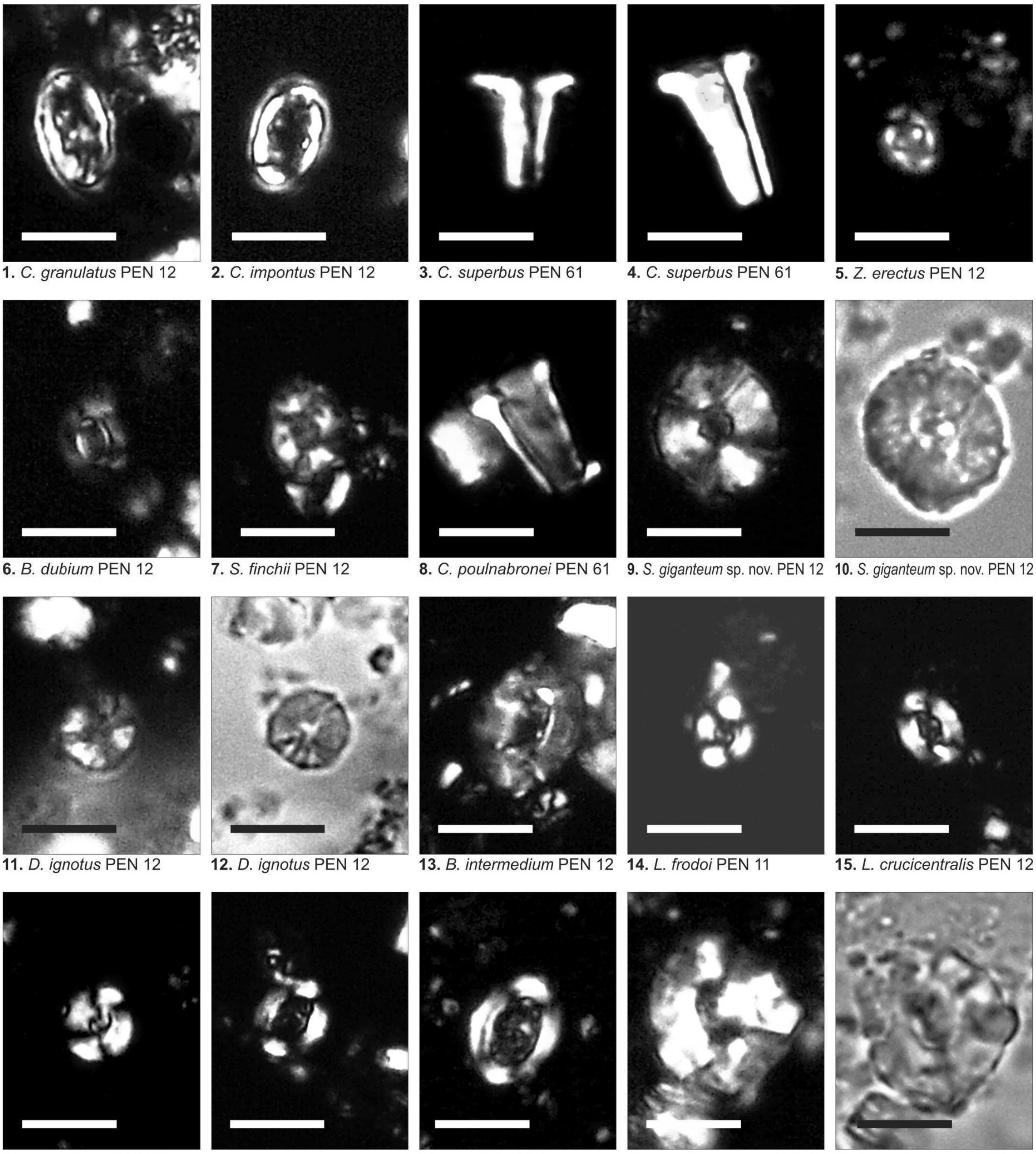
Figure 6. Distribution chart of calcareous nannofossils across the PLB/TOA boundary of Peniche section. Arrows indicate the first occurrences (FO) recorded in the studied interval. Even if this log shows only two meters of uppermost Pliensbachian (a part of its uppermost ammonite subzone), there is a more complete Upper Pliensbachian in the Ponta do Trovão section.

the Lower Toarcian species extend into the Middle and Upper Toarcian (unpublished data from Boca da Mata and Rabaçal/Zambujal sections, Lusitanian Basin). In the Peniche section, the first appearance of *Kinkelinella* sp. 1 and of *Ektyphocythere knitteri* (Riegraf 1984) marks the PLB/TOA. The disappearance of several species of *Ogmoconcha*, *Ogmoconchella* and *Isobythocypris* aff. *ovalis* Bate and Coleman 1975, together with the appearance of *Cytherella* cf. *toarcensis* Bizon 1960 and *Kinkelinella* gr. *sermoisensis* (Apostolescu 1959), occurs at the transition from Polymorphum to Levisoni zones. The main biological changes in ostracod assemblages are observed at the top of the Polymorphum Zone, just below the major C-isotope negative excursion coinciding with the T-OAE (Hesselbo et al., 2007). A strong reduction in ostracod diversity and abundance, and the disappearance of *Ogmoconcha*, *Ogmoconchella* and *Ledahia* genera occurs at this level. The disappearance of these three genera is also observed at a global scale, related to the global extinction of Metacopina (Cabral et al., 2013). The studied assemblages show strong similarities with those described from other European areas (see Arias and Whatley, 2005). The data reported here are also similar to previous works on the Peniche section (Lord, 1982).

Benthic foraminifers

Foraminifera of the PLB/TOA at Peniche are very similar to the fauna recorded in other Portuguese sites. The microfauna of Beds 16a and 16b (lowermost Toarcian) is clearly dominated by typical Upper Pliensbachian species. These assemblages consist of *Lenticulina* morphogenus *Lenticulina* and rare morphogenera of *Planularia* or *Marginulinopsis*, although the morphogenus *Falsopalmula* is also present in very small numbers. The specimens collected from the Polymorphum Zone are: *Lenticulina praeobonensis* morphogenus *Planularia* (Boudchiche et al., 1994). Numerous specimens of *Marginulina prima* d'Orbigny, *M. spinata* Terquem, *M. interrupta* Terquem, ornamented forms, are found. In level 16b, arenaceous forms are present, accompanied by smooth *Pseudoglandulina* and by *Pseudonodosaria multicostata* (Bornemann).

From Bed 16c upwards, a clear reduction in the number of individuals of *Marginulina prima* group is observed. The only abundant forms are *Dentalina terquemi* d'Orbigny, *D. obscura* Terquem and *D. arbuscula* Terquem. The *Lenticulina s.s.* group (coiled specimens) assemblage different in Bed 16c differs with respect to the Upper Pliensbachian assemblages. The umbilicus of the specimens recorded in Bed 16c is higher, the keels are more acute and wider, and the body chambers are more numerous. These forms are morphologically close to those from the basal Toarcian that have been described in France, Spain and Morocco (e.g., Bassoullet, in Cariou and Hantzpergue, 1997; Ruget and Nicollin, in Cariou and



1. *C. granulatus* PEN 12 **2.** *C. impontus* PEN 12 **3.** *C. superbus* PEN 61 **4.** *C. superbus* PEN 61 **5.** *Z. erectus* PEN 12

6. *B. dubium* PEN 12 **7.** *S. finchii* PEN 12 **8.** *C. poulnabronei* PEN 61 **9.** *S. giganteum* sp. nov. PEN 12 **10.** *S. giganteum* sp. nov. PEN 12

11. *D. ignotus* PEN 12 **12.** *D. ignotus* PEN 12 **13.** *B. intermedium* PEN 12 **14.** *L. frodoi* PEN 11 **15.** *L. crucicentralis* PEN 12

16. *L. sigillatus* PEN 11 17. *L.* aff. *velatus* PEN 12 **18.** *L. velatus* PEN 11 **19.** *Calyculus* sp. indet., PEN 11 **20.** *Calyculus* sp. indet. PEN 11

Figure 7. Micrograph of selected calcareous nannofossil specimens from the PLB/TOA boundary of Peniche section. White/black bar = 5 µm.

Hantzpergue, 1997; Mailliot et al., 2009). Level 16d also yields *L. praeobonensis*, which usually occurs in the Lower Toarcian (Polymorphum Zone). In these two beds, numerous Holothurian sclerites are also present.

Palynomorphs

A rich but poorly preserved palynoflora was documented by Oliveira et al. (2007a) from the PLB/TOA of Peniche. Terrestrial palynomorphs (spores and pollen grains) dominate the assemblage (see also Barrón et al., 2013). Bisaccate and monosulcate pollen grains are rare components of the assemblage. The most common spores belong to *Dictyophyllidites* and *Deltoidospora*, and the pollen grains are dominated by *Corollina torosa*, *Spheripollenites scabratus*, *Exesipollenites scabratus*, and other small inaperturate pollen grains. Dinoflagellate cysts are common in the Upper Pliensbachian and are mainly represented by *Mancodinium* and *Nannoceratopsis*. Other marine microplankton (acritarchs and microforaminifer lining) are common.

The palynoflora is mainly represented by relatively long-ranging species. The most conspicuous component of the palynoflora is *Nannoceratopsis gracilis*, which ranges from the late Pliensbachian to Bajocian (see compilation in Bucefalo-Palliani and Riding, 2003) and shows a wide geographical distribution in the Northern Hemisphere. Davies (1985) correlated the first occurrence of *N. gracilis* to the *Luehndea* sp. A biozone. He considered this palynozone to encompass the Spinatum and Tenuicostatum (Polymorphum) ammonite zones. *Mancodinium semitabulatum* is considered to have

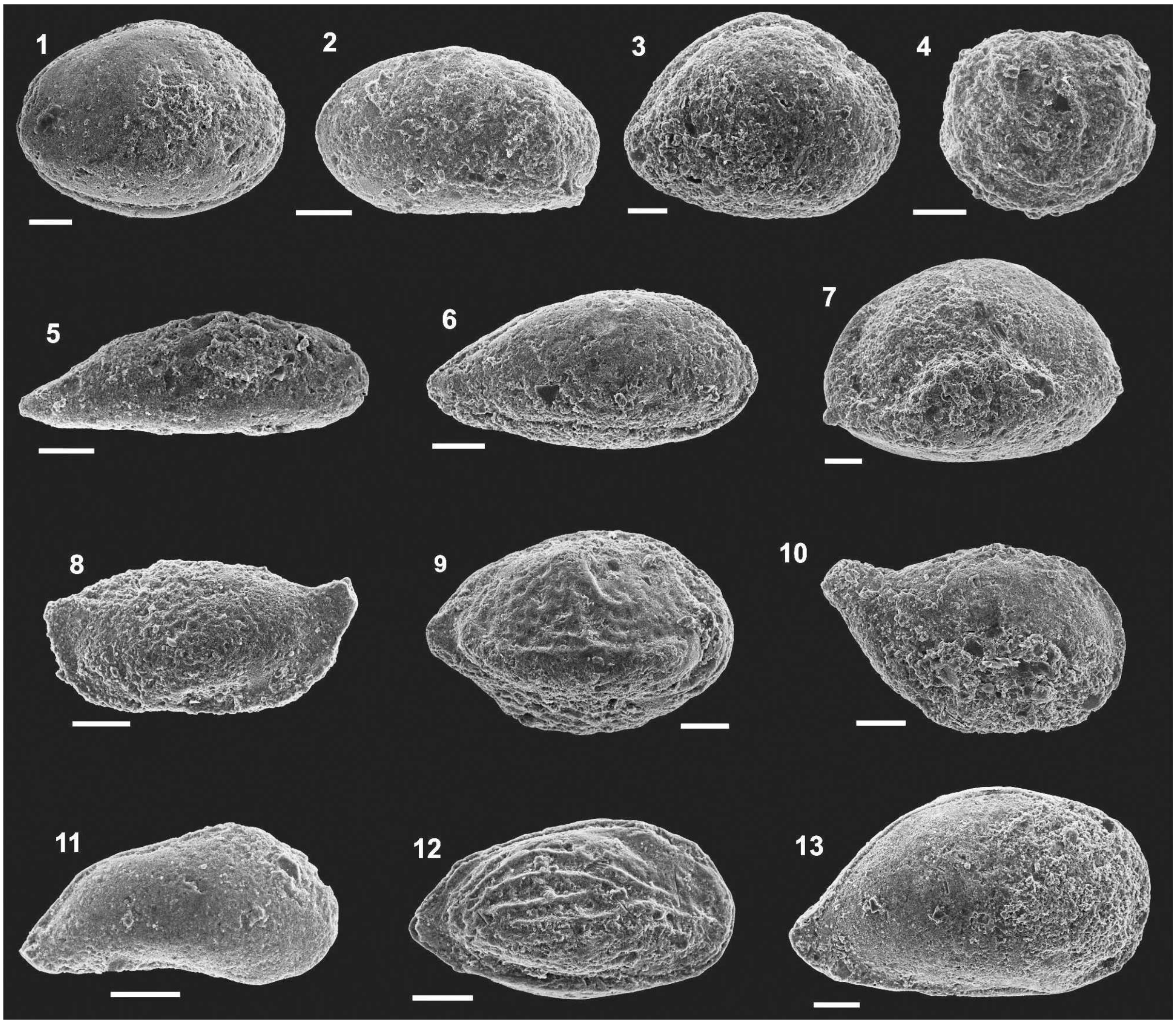


Figure 8. Selected ostracod specimens from the PLB/TOA. Legend: Cp = carapace; RV = right view; LV = left view. Bar = 100 µm. 1. **Ogmoconcha** ***cf.*** **hagenowi** ***Drexler, 1958, Cp, RV, sample PP-1, Emaciatum Zone. 2.*** **Ledahia septenaria** ***Gründel, 1964, Cp, LV, sample P-6, Polymorphum Zone. 3.*** **Bairdia** ***cf.*** **kempfi** ***Ainsworth, 1989, Cp, RV, sample P-4, Polymorphum Zone. 4.*** **Polycope** ***cf.*** **cincinnata** ***Apostolescu, 1959, Cp, RV, sample PP-3, Emaciatum Zone. 5.*** **Paracypris** ***sp. 1, Cp, RV, sample PP-2, Emaciatum Zone. 6.*** **Liasina lanceolata** ***(Apostolescu, 1959), Cp, RV, sample P-6, Polymorphum Zone. 7.*** **Ogmoconcha inflata** ***(Ainsworth, 1987), Cp, RV, sample P-4, Polymorphum Zone. 8.*** **Ptychobairdia hahni** ***(Lord & Moorley, 1974), Cp, LV, sample P-6, Polymorphum Zone. 9.*** **Kinkelinella** ***sp. 1, Cp, RV, sample P-8, Polymorphum Zone. 10.*** **Bairdia** ***aff.*** **rostrata** ***Issler, 1908, Cp, RV, sample P-4, Polymorphum Zone. 11.*** **Paracypris redcarensis** ***(Blake, 1876), Cp, RV, sample P-11-B, Polymorphum Zone. 12.*** **Ektyphocythere knitteri** ***Riegraf, 1984, Cp, RV, sample P-13-B, Polymorphum Zone. 13.*** **Bairdia** ***sp. 2, Cp, RV, sample P-11-T, Polymorphum Zone.***

ranged from the Pliensbachian to the Bajocian (Bucefalo-Palliani and Riding, 2003). In the palynomorph assemblages of Peniche, a Tethyan influence is indicated by the presence of *M. semitabulatum* and *N. gracilis* (Bucefalo-Palliani and Riding, 2003).

Isotope stratigraphy (C, O and Sr)

In recent years, large quantities of geochemical data have been published from the Pliensbachian-Toarcian succession at Peniche (Jenkyns et al., 2002; Oliveira et al., 2005; 2006; Hesselbo et al., 2007; Hermoso et al., 2009; Suan et al., 2008a; 2010; Silva et al., 2011). These include carbon and oxygen stable isotopes ($\delta^{13}C$, $\delta^{18}O$), strontium isotopes ($^{87}Sr/^{86}Sr$), and total organic carbon (wt% TOC) data. Isotopic data have been derived from bulk carbonate, belemnites, brachiopods, and fossil wood. Some of the isotopic data span the Toarcian oceanic anoxic event (T-OAE) and have demonstrated the importance of the Peniche section for understanding of this global phenomenon (Hesselbo et al., 2007; Suan et al., 2008a; 2010).

Across the PLB/TOA, TOC values are generally low, around 0.2wt% in the Emaciatum Zone and around 0.5 wt% in the Polymorphum Zone (Oliveira et al., 2006; Hesselbo et al., 2007). In the marlstone/limestone succession across the PLB/TOA, a prominent negative carbon-isotope excursion has been recognized. The $\delta^{13}C$ values of bulk carbonate decrease through the upper Emaciatum Zone, with the most negative values observed in the lowermost part of the Polymorphum Zone (0.65m above the PLB/TOA boundary; base of Semicelatum Subzone), representing an overall decrease of about 2.0‰ (Oliveira et al., 2005; Hesselbo et al., 2007; Fig. 9). The same trend has been documented in carbon isotopes of belemnites and brachiopods from Peniche, as well as in fossil wood (Hesselbo et al., 2007; Suan et al., 2008a; 2010). This negative shift in $\delta^{13}C$ is also recorded in other sections in the Lusitanian Basin (Pittet et al., 2014). Littler et al. (2010) also detected a very similar negative carbon-isotope excursion, centred at the Hawskerense–Paltum Subzone boundary, in bulk organic matter from Yorkshire (England), and Bodin et al. (2010) documented a significant negative excursion in bulk carbonate at the base of the Polymorphum Zone in a section from Morocco. Although less precisely dated and smaller in amplitude, such a boundary negative excursion in carbon stable isotopes (both bulk rock and organic matter) was further recorded in the Ionian zone (Kafousia et al., 2014). These records demonstrate the potential importance of the $\delta^{13}C$ excursion as a chemostratigraphical marker for the PLB/TOA. The morphology of the negative spike at Peniche with respect to the expanded sections in Yorkshire and Morocco is further evidence for the continuous sedimentary record at Peniche across the PLB/TOA boundary.

In the Polymorphum Zone, the $\delta^{13}C_{\text{bulk-carb}}$ data show a positive shift of +2.0‰, reaching maximum values in the middle–upper part of the Polymorphum Zone (Hesselbo et al., 2007). The same shift was observed in $\delta^{13}C$ values from of belemnites, brachiopods and wood (Hesselbo et al., 2007; Suan et al., 2008a; 2010). This positive excursion was also recognized in the Coimbra area and other distal sectors of the Lusitanian Basin (Duarte et al., 2007; Pittet et al., 2014). Above this level, the trend is reversed and an abrupt large negative carbon-isotope excursion is observed in the Lusitanian Basin at the base of the Levisoni Zone, which is considered as a characteristic feature of the T-OAE (Duarte, 1998; Jenkyns et al., 2002; Duarte et al., 2004a, 2007; Oliveira et al., 2005; Hesselbo et al., 2007; Suan et al., 2008a; Pittet et al., 2014). According to cyclostratigraphy, the negative shift in $\delta^{13}C$ values characterizing the T-OAE occurred ~860 kyr after the PLB/TOA (Suan et al., 2008b; Huang and Hesselbo, 2014).

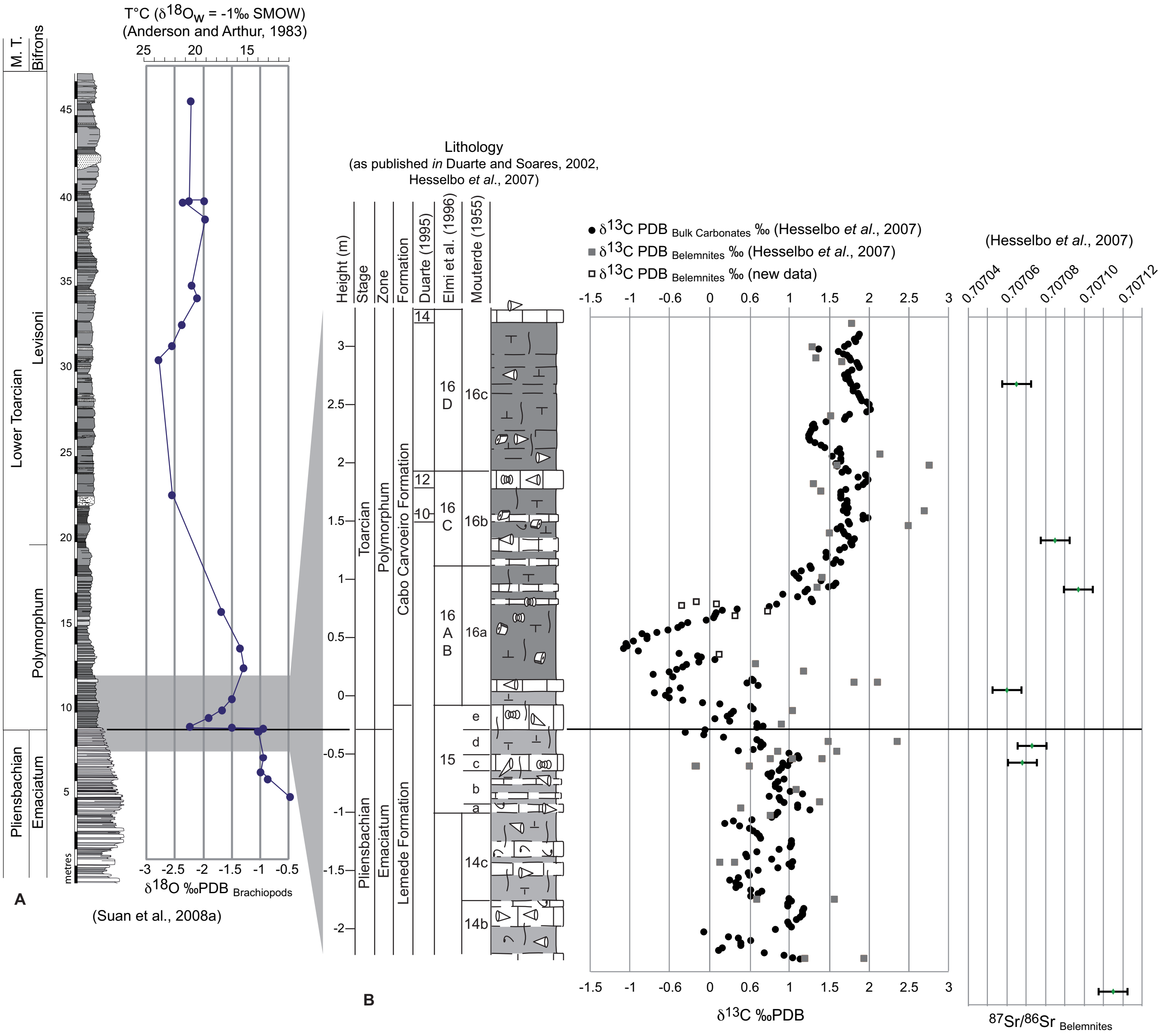


Figure 9. A. Oxygen isotopes measured on calcite brachiopod shells in the interval corresponding to the Emaciatum – Levisoni Zones (Suan et al., 2008a). B. High-resolution C-isotopes of bulk rock, C-isotope values of belemnites and $^{87}Sr/^{86}Sr$ around the PLB/TOA at Peniche (Hesselbo et al., 2007).

Oxygen-isotope values of bulk carbonates through the Upper Pliensbachian and Lower Toarcian interval fluctuate considerably. However, around the PLB/TOA a negative excursion is observed in bulk rock, and both belemnite and brachiopod calcite, with several low $\delta^{18}O$ values observed at the base of the Polymorphum Zone (20–30 cm above the PLB/TOA) suggesting a sharp warming event occurred at the base of the Toarcian (Oliveira et al., 2005; Suan et al., 2008a; Hermoso et al., 2009). The $\delta^{18}O$ values of belemnites and brachiopods increase gradually until the middle part of the Polymorphum Zone, then decrease towards the Polymorphum/Levisoni zones boundary (Fig. 9). Strontium-isotope data have been generated from belemnites at Peniche (Fig. 9; Jenkyns et al., 2002; Hesselbo et al., 2007), although the uncertainties associated with these analyses are large in comparison to equivalent determinations from the sections in Yorkshire (McArthur et al., 2000). However, it is notable that the lowest strontium-isotope ratios inferred for Early Jurassic seawater occur at the PLB/TOA.

Correlation of Peniche to other relevant areas based on ammonites and other fossil groups

Ammonites are the most relevant taxonomic group for global biochronological correlation of the PLB/TOA. Upper Pliensbachian and Lower Toarcian ammonites are found worldwide in the two major marine, palaeogeographical realms, Boreal and Tethyan, and a few biogeographical provinces (Arkell, 1956; Hallam, 1969; Stevens, in Hallam, 1973; Howarth, in Hallam, 1973; Cariou, in Hallam, 1973; Enay, 1980; Enay and Mangold, 1982; Cariou et al., 1985; Smith et al., 1988; Hillebrandt et al., in Westermann, 1992; 2000; Enay and Cariou, 1997; Page, 2004, 2008). The classical biogeographical schemes for the Early Jurassic usually do not recognize an Austral ammonite fauna or an Austral Province that is known for the Late Jurassic. In fact, the Lower Jurassic Austral and Tethyan ammonite faunas show a less marked contrast than the Tethyan and Boreal Realms (Enay and Cariou, 1997).

Figure 10 shows standard zonations for the three ammonite biogeographical provinces present in Western Europe, namely the Subboreal, the NW European and the Mediterranean, as compared to the Peniche section ammonite zonation. Ammonites of the Tenuicostatum/Polymorphum zones have a wide distribution through the various ammonite provinces and allow for easy correlation. Data shown here clearly demonstrate that, in spite of palaeoprovincialism, the first (mass) occurrence of *Dactylioceras* (*Eodactylites*) is a solid event that allows reliable, worldwide correlations.

Several authors have proposed various biozonations for the Upper Pliensbachian and Lower Toarcian based on different taxonomic groups of macroinvertebrates: brachiopods (Tchoumatchenco, 1972; Goy et al., 1984; Manceñido and Dagis, in Westermann, 1992; Alméras and Fauré, 2000; Alméras et al. in Cariou and Hantzpergue, 1997; Alméras et al., 2007; García Joral and Goy, 2000), belemnites (Stoyanova-Vergilova, 1977; Doyle, 1990; Challinor et al., in Westermann, 1992; Doyle and Bennett, 1995; Combémorel, in Cariou and Hantzpergue, 1997), bivalves (Shopov, 1970; Sato, in Westermann, 1992; Hallam, 1994; Damborenea, 2002; Ruban, 2006), echinoderms (Thierry et al., in Cariou and Hantzpergue, 1997), and corals (Beauvais, in Westermann, 1992).

The following taxonomic groups of microfossils are also of biochronostratigraphical relevance: benthic foraminifera (Ruget and Nicollin, in Cariou and Hantzpergue, 1997); ostracods (Bodergat, in Cariou and Hantzpergue, 1997); dinoflagellate cysts (Davies, 1985; Fauconnier, in Cariou and Hantzpergue, 1997; Bucefalo Palliani and Riding, 2003); radiolarians (Carter et al., 1988; Pessagno and Mizutani, in Westermann, 1992; Sato, in Westermann, 1992); and calcareous nannofossils (Bown, 1987; de Kænel and Bergen, 1993; Bucefalo Palliani and Mattioli, 1998; Mattioli and Erba, 1999; Perilli et al., 2010; Mailliot et al., 2006, 2007; Oliveira et al., 2007b). Palaeobotanical and palynological data have been published by Rogalska (1974), Cernjavska (1986), Guy-Ohlson (in Rocha and Soares, 1988), Kimura et al. (in Westermann, 1992), Sarjeant et al. (in Westermann, 1992), Vijaya (2000), and Shenghui and Fen (2000).

In synthesis, the base of the Toarcian, primarily defined by means of ammonites, can be characterised by several other fossil groups. In particular, a succession of calcareous nannofossils' FOs (*B. intermedium L. velatus*, *B. intermedium*, *D. ignotus* and *C. superbus*) encapsulates the PLB/TOA (Fig. 6). Also, ostracod assemblage significantly changes passing from the Amalthei Zone in the Pliensbachian to the Tenuicostati Zone in the Toarcian. Although dinoflagellate and foraminifera data are studied in a lesser detail, some

<table>
<tr><th rowspan="2">TIME SCALE (My)
Gradstein <i>et al.</i> (2012)
181.7</th><th rowspan="2">SUBSTAGE</th><th colspan="3">SUBBOREAL PROVINCE
(Howarth <i>in</i> Dean <i>et al.</i>, 1961; Howarth, 1973, 1992; Page, 2003)
(Northern England, Scotland)</th><th colspan="3">NORTHWEST EUROPEAN PROVINCE
(Dean <i>et al.</i>, 1961; Elmi <i>et al.</i>, 1994, 1997; Dommergues <i>et al.</i>, 1997)
[=Submediterranean Province (Page, 2003)]
(Southern England, Germany, France, Iberic Ranges, Romania, Bulgaria)</th><th colspan="3">MEDITERRANEAN PROVINCE
(Dean <i>et al.</i>, 1961; Braga, 1983; Elmi <i>et al.</i>, 1994, 1997; Dommergues <i>et al.</i>, 1997)
(Betic Ranges, Italy, North Africa, Alpine Belt)</th><th>NORTH AMERICA
(Smith <i>et al.</i>, 1988; Jakobs, 1997)</th><th>SOUTH AMERICA
(Hillebrandt, 2006)</th><th>JAPAN
(Sato <i>in</i> Westermann, 1996)</th><th>NE-ASIA
(Repin, 1988; Kalacheva, 1988)</th></tr>
<tr><th>Zone</th><th>Subzone</th><th>Horizon</th><th>Horizon</th><th>Subzone</th><th>Zone</th><th>Zone</th><th>Subzone</th><th>Horizon</th><th>Zone</th><th>Zone</th><th>Zone</th><th>Zone</th></tr>
<tr><td rowspan="7">182.7</td><td rowspan="7">Lower Toarcian</td><td rowspan="7">Tenuicostatum</td><td rowspan="2">Semicelatum (<i>sensu</i> Howarth, 1973)</td><td>Antiquum</td><td rowspan="2">Semicelatum</td><td rowspan="5">Semicelatum (<i>sensu</i> Mouterde, 1967)</td><td rowspan="7">Tenuicostatum</td><td rowspan="7">Polymorphum</td><td rowspan="5">Semicelatum (<i>sensu</i> Mouterde, 1967)</td><td rowspan="5"></td><td rowspan="7">Kanense</td><td rowspan="7">Tenuicostatum</td><td rowspan="10">Nipponicum (<i>partim</i>)
?</td><td rowspan="7">Propinquum</td></tr>
<tr><td>Semicelatum</td></tr>
<tr><td>Tenuicostatum</td><td>Tenuicostatum</td><td>Tenuicostatum</td></tr>
<tr><td rowspan="2">Clevelandicum</td><td>Clevelandicum</td><td rowspan="2">Crosbeyi</td></tr>
<tr><td>Crosbeyi</td></tr>
<tr><td rowspan="2">Paltum</td><td rowspan="2">Paltum</td><td rowspan="2">Paltum</td><td rowspan="2">Paltum</td><td rowspan="2">Mirabile</td><td>Mirabile</td></tr>
<tr><td>Simplex</td></tr>
<tr><td rowspan="7">184.2</td><td rowspan="7">Upper Pliensbachian</td><td rowspan="7">Spinatum</td><td rowspan="4">Hawskerense</td><td rowspan="2">Hawskerense</td><td rowspan="2">Hawskerense</td><td rowspan="4">Hawskerense</td><td rowspan="7">Spinatum</td><td rowspan="5">Emaciatum</td><td rowspan="4">Elisa</td><td>Elisa</td><td rowspan="7">Carlottense (<i>partim</i>)</td><td rowspan="7">Disciforme (<i>partim</i>)</td><td rowspan="7">Viligaensis</td></tr>
<tr><td rowspan="2">Emaciatum</td></tr>
<tr><td rowspan="2">Elaboratum</td><td rowspan="2">Emaciatum</td></tr>
<tr><td>Imitator</td><td rowspan="4">Fontanellence (<i>partim</i>)</td></tr>
<tr><td rowspan="3">Apyrenum</td><td>Solare</td><td>Solare</td><td rowspan="3">Apyrenum</td><td>Solare</td><td>Solare</td></tr>
<tr><td>Transiens</td><td>Transiens</td><td rowspan="2">Algovianum (<i>partim</i>)</td><td>Levidorsatum</td><td rowspan="2"></td></tr>
<tr><td>Salebrosum</td><td>Salebrosum</td><td>Meneghinii</td></tr>
</table>

Figure 10. Lower Toarcian subdivisions and correlations: Subboreal, Northwest European and Mediterranean Provinces. Comparisons are also made with North America and circum-Pacific zonations, namely South America, Japan and NE Asia. Absolute ages are after Gradstein et al. (2012).

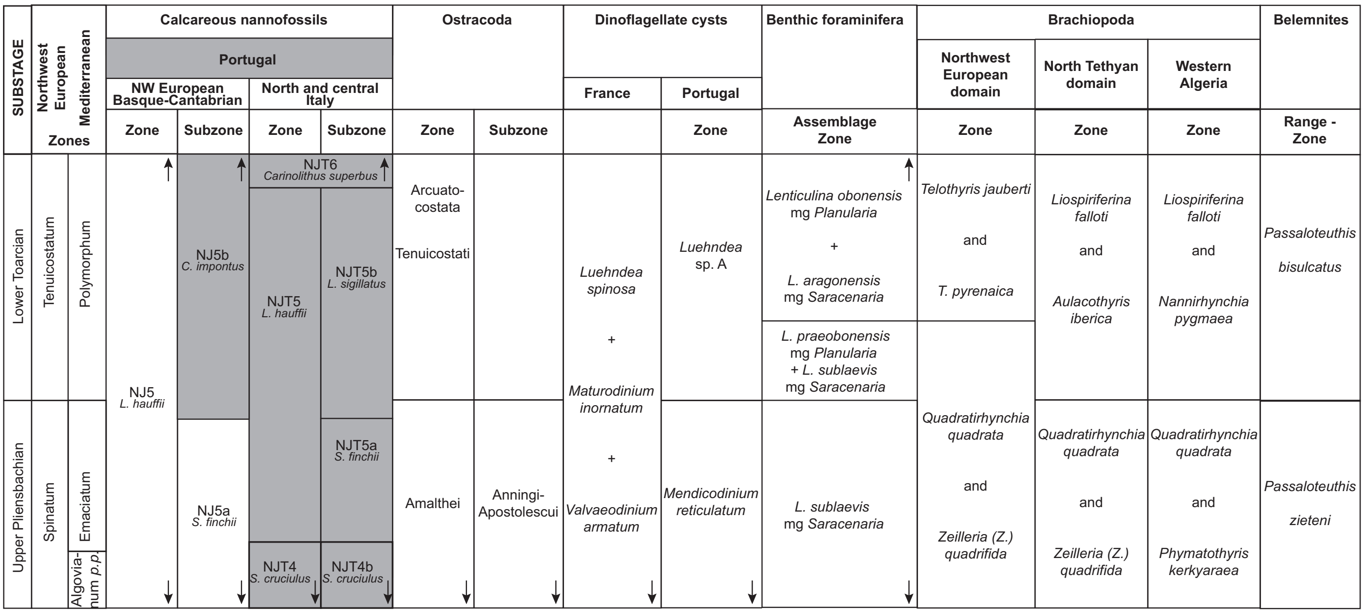


Figure 11. Zonations based upon calcareous nannofossils (Bown and Cooper, 1998; Mattioli and Erba, 1999; Perilli and Comas-Rengifo, 2002; Comas-Rengifo et al., 2004; Perilli et al. 2004; 2010; Mailliot et al., 2007; Mattioli et al., 2013), ostracods (Bodergat, in Cariou and Hantzpergue, 1997), dinoflagellate cysts (Davies, 1985; Fauconnier, in Cariou and Hantzpergue, 1997) and foraminifera (Ruget and Nicollin, in Cariou and Hantzpergue, 1997). Concerning calcareous nannofossils, the zones used for Peniche are shown in grey. Both NJ5b and NJT5b Subzones defined in NW Europe and Basque-Cantabria area, and in Northern and Central Italy, respectively, can be used at Peniche, as the markers of the two subzones (*Crepidolithus impontus *and* Lotharingius sigillatus*) are commonly recorded there. Comparison of brachiopod and belemnite zones from various domains (Alméras et al., in Cariou and Hantzpergue, 1997; Combémorel, in Cariou and Hantzpergue, 1997).

significant change did occur across the PLB/TOA. Within the dinoflagellates, *N. gracilis* and *Luhendea* sp. A first occur. Benthic foraminifera also display an important renewal (Fig. 11). All these events are fundamental for correlating Peniche to other marine sections that do not contain a detailed ammonite biostratigraphy.

Comparisons with the Almonacid de la Cuba section (Iberian Range, Spain)

A reference section for the base of the Toarcian Stage is located near the Almonacid de la Cuba town, 35 km South of Zaragoza (Aragonese branch of the Iberian Range, Spain) where magnetostratigraphy is available (Fig. 12). The Pliensbachian” Toarcian succession and the fossil content have been studied in detail (Goy et al., 2006; Comas-Rengifo et al., 2010 and references therein). The PLB/TOA boundary is recorded in the marlstone/limestone alternations of the Turmiel Fm, which was deposited in an open-marine, external platform environment (Gómez, 1991; Gómez and Goy, 2005). The Almonacid de la Cuba section contains an excellent record of the PLB/TOA, where no evidence of major sedimentary breaks was found. Four ammonite assemblages characterized, respectively, by the presence of *Pleuroceras*, *Canavaria*, *Dactylioceras* (*Eodactylites*) and *Dactylioceras* (*Orthodactylites*) have been distinguished. The base of the Toarcian is located at level CU35.2, based on the first occurrence of *Dactylioceras* species (Fig. 12).

Based upon comparison of ammonite assemblages in the two sections, a bed-by-bed correlation is possible. The Upper Pliensbachian Beds 15a–15b of the Peniche section are the equivalent of the levels 15–22 of the Almonacid de la Cuba section (Figs. 4a and 12). Level 15c of Peniche is the equivalent of levels 23–28 of Almonacid de la Cuba. Bed 15d of Peniche is the equivalent of levels 29–35 of Almonacid de la Cuba. The Lower Toarcian Bed 15e of Peniche, containing *Dactylioceras* (*Eodactylites*) *simplex, D.* (*E.*) *pseudocommune*, *D.* (*E.*) *polymorphum, Protogrammoceras* (*Paltarpites*) cf. *paltum*, *L.* aff. *ballinense* and *T.* aff. *capillatum*, is the equivalent of levels 35.2–42 of Almonacid de la Cuba, characterized by *D.* (*E.*) *simplex*, *D.* (*E.*) *mirabile*, *D.* (*E.*) *polymorphum*, *Protogrammoceras* sp. and *P.* cf. *paltum.* Level 16a of Peniche is the equivalent of level 46 and younger levels of Almonacid de la Cuba. Level 16c of Peniche, which includes the first record of *D.* (*Orthodactylites*) *semicelatum*, can be correlated with level 62 of Almonacid de la Cuba, which contains the same record.

The Almonacid de la Cuba magnetostratigraphy (Fig. 12) shows the N3 magnetozone also observed in the Iznalloz section (Betic Cordillera, southern Spain; Galbrun et al., 1990) and in the Sierra Palomera and Ariño sections (Iberian Range, Central Spain; Osete et al., 2007). The R2 magnetozone corresponds to the reversed polarity observed in the lower part of the Iznalloz section. R2 and R1 were also recorded in the Breggia section, southern Switzerland (Southern Alps; Horner and Heller, 1983), but the N2 magnetozone was not detected there. The Lower Toarcian is only poorly represented in the Alpine section (the Tenuicostatum Zone is around 30 cm thick) and probably there is a gap at the PLB/TOA (Comas-Rengifo et al., 2010). These authors also report the magnetostratigraphy of the Amonacid de la Cuba section as the most complete record for the PLB/TOA. The $^{87}Sr/^{86}Sr$ values obtained at Almonacid de la Cuba (Fig. 12) match well with previously published data (McArthur et al., 2000; Hesselbo et al., 2007). Upper Pliensbachian $^{87}Sr/^{86}Sr$ values generally decrease during the Hawskerense Biochron, reaching a first minimum value below 0.70705 in the late portion of this time interval. $^{87}Sr/^{86}Sr$ values

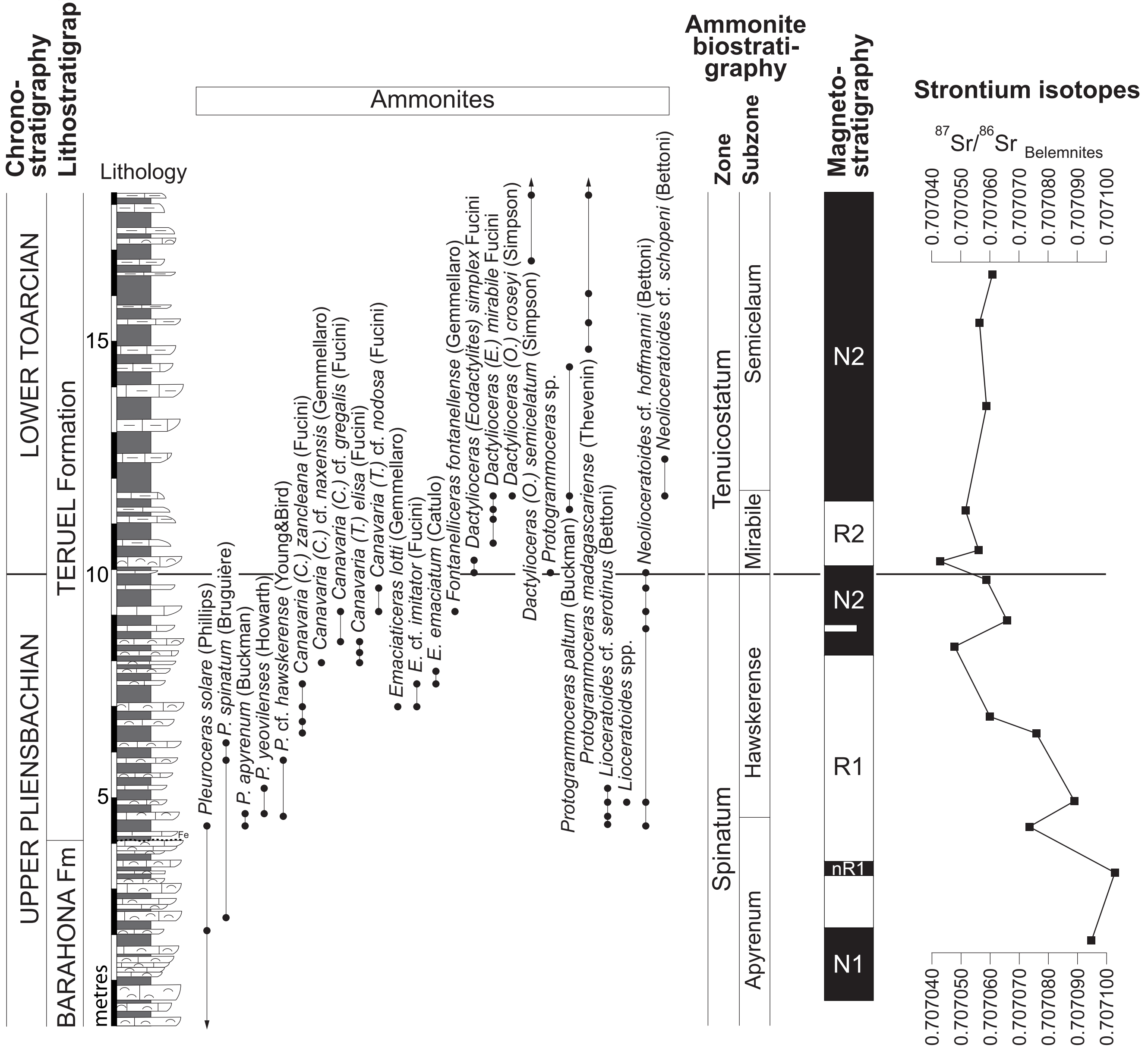


Figure 12. Lithological succession of the Almonacid de la Cuba section with ammonite distribution, magnetostratigraphy, and $^{87}Sr/^{86}Sr$ isotope ratio (modified from Comas-Rengifo et al., 2010).

slightly increase in the latest part of Hawskerense Biochron. Minimum values are recorded at the base of the Toarcian, and ^{87}Sr/^{86}Sr slowly recovers during the Tenuicostatum Zone.

Comparisons between Peniche, Almonacid de la Cuba and the magnetic record of the Karoo volcanic province

The very tight correlation of Peniche to the Almonacid de la Cuba magnetostratigraphy allows discussion of the magnetic record and correlation with the Karoo volcanic reversed/normal polarity succession, and hence the possible projection of Karoo ages onto the GSSP of PLB/TOA. At Almonacid de la Cuba, the PLB/TOA falls in the upper part of the magnetozone N2 (Comas-Rengifo et al., 2010; Figs. 12, 13). This assignment is not in agreement with data from the basal Toarcian intervals studied by Galbrun et al. (1994) and Horner and Heller (1983), who reported the PLB/TOA within a reversed magnetochron. This discrepancy is probably due to the presence of highly condensed intervals, or hiatuses in sections both from W France (Galbrun et al., 1994) and from the Southern Alps (Horner and Heller, 1983). The following magnetozone N3 at Almonacid de la Cuba seems to last longer than the previous normal magnetochrons (Fig. 12), although a possible increase in the sedimentation rate in this interval cannot be excluded.

The magnetostratigraphy in the Karoo volcanic rocks sampled along the Lebombo volcanic rifted margin (Riley et al., 2004, and references therein), dated to the PLB/TOA, shows a reversed/normal polarity succession characterized by three normal magnetozones. The intermediate magnetozone corresponds to a very thick interval (~4 km) within the Sabie River Basalt Formation. Duncan et al. (1997)

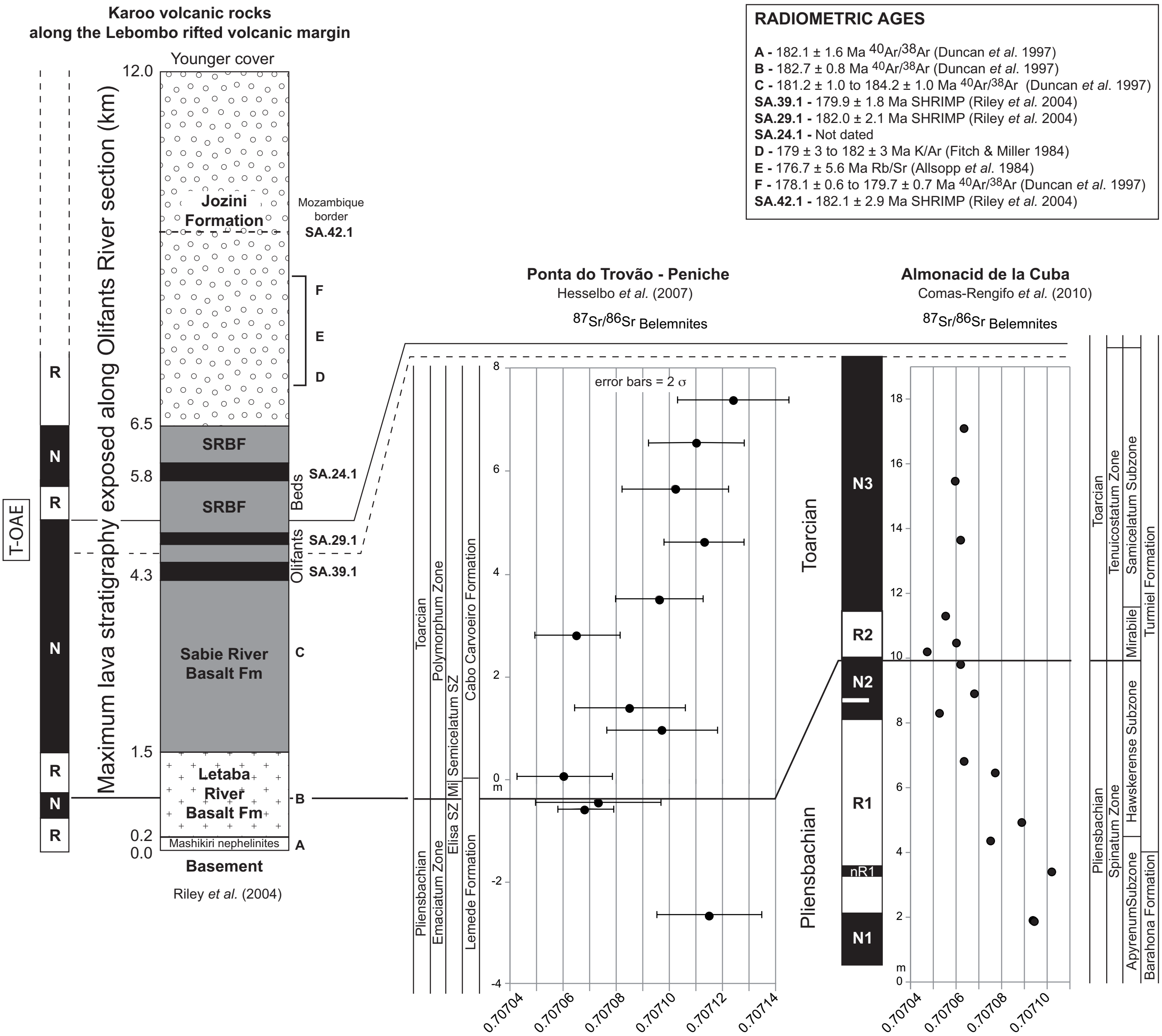


Figure 13. Proposed correlations between Peniche ages and strontium isotope curve with magnetostratigraphy of the Almonacid de la Cuba section and the Karoo volcanic rocks in South Africa. Mi = Mirabile Subzone.

interpreted the Sabie River Basalt Formation as having been erupted during a period of <0.5 million years, since the sequence lies within this single normal magnetozone.

We tentatively correlate the upper part of the N2 magnetozone of the Almonacid de la Cuba section, where the PLB/TOA lies (base of Mirabile Subzone that is well correlated to Peniche), to the Karoo volcanic rocks dated as 182.7 ± 0.8 Ma $^{40}Ar/^{38}Ar$ (Duncan et al., 1997), also corresponding to the upper part of a magnetic normal chron (Fig. 13). If this correlation holds true, this age would be within error but slightly younger than the 183.6 +1.7/-1.1 Ma measured by Pálfy and Smith (2000) or 183.0 ± 1.5 Ma estimated by Ogg (2004).

The N3 normal magnetozone of the Almonacid de la Cuba section, which is dated to the Tenuicostatum ammonite Zone, Semicelatum Subzone (well correlated to the Semicelatum Subzone of Peniche), might correspond to the thick normal magnetozone in the Sabie River Basalt Formation, if the respective thicknesses were not due to a higher sedimentation rate within the N3 (at Almonacid de la Cuba) or to an increased rate of basalt production (within the Sabie River Basalt Formation).

Protection of the site

Besides the major importance of the Toarcian GSSP, the Peniche Peninsula shows the most significant section for the Lower Jurassic of Portugal (Duarte, 2004), recording ~20 million years of Portuguese geological history. Several papers emphasize the considerable value of this outcrop in terms of geological heritage (Duarte, 2004, 2005; Brilha et al., 2005; Rilo et al., 2010). In fact, Peniche brings together three features that support its importance as a site of high heritage interest: several geological objects and structures show high scientific value with international relevance; the sedimentary geology has a huge potential for educational activities both for academic and industrial purposes. In spite of its high potential for the geological heritage of the Jurassic, the Peniche peninsula is not yet included in any national geological protection system. However, based on a special report presented to local authorities (Duarte, 2007b), the City Hall of Peniche declared, in April 2007, the locality of Ponta do Trovão as a “Site of City Hall Interest”.

Summary

The Global Boundary Stratotype Section and Point for the base of the Toarcian Stage has been established at the Peniche section (Ponta do Trovão, Lusitanian Basin, Portugal) because it satisfies most of the requirements recommended by the International Commission on Stratigraphy (http://www.stratigraphy.org/).

1. The Pliensbachian/Toarcian boundary (PLB/TOA) at Peniche is included in a continuous section that comprises over 450 m of carbonate-rich sediments.
2. Structural complexity, synsedimentary and tectonic disturbances, metamorphism and strong diagenetic alteration are minimal constraints in this area.
3. At the PLB/TOA, as recorded in a hemipelagic marlstone/limestone alternation unit, no significant vertical facies changes, stratigraphical gaps and hiatuses have been recorded. An increase in clay content is observed above the boundary.
4. The palaeontological record of the Elisa and Mirabile subzones shows abundant and diverse well-preserved macro- and microfossil assemblages. The PLB/TOA is characterized thanks to both primary (ammonites) and auxiliary biostratigraphical markers (calcareous nannofossils, brachiopods and ostracods). The ammonite assemblages of the PLB/TOA mainly contain taxa characteristic of the Mediterranean (*Paltarpites*, *Lioceratoides*) and the Northwest European provinces (*Dactylioceras* and *Tiltoniceras*) that allow global correlations. The boundary is identified at Peniche (as well as in other sections) by the mass occurrence of Dactylioceratids and, in particular, by the FO of *D.* (*Eodactylites*) *pseudocommune* and *D.* (*E.*) *simplex*. The ammonite zones and subzones defined at Peniche are assemblage (Oppel) zones based on the co-occurrence of several species of ammonites. Calcareous nannofossils first and last occurrences constitute a valuable secondary proxy for recognition and correlation of the base of the Toarcian. A succession of events is recorded across the PLB/TOA, namely the FOs of *B. intermedium L. velatus*, *B. intermedium*, *D. ignotus* and *C. superbus* are recorded in Peniche as well as other Tethyan settings.
5. High-resolution stable carbon and oxygen isotopes, and ^{87}Sr/^{86}Sr ratios show distinctive changes just above the PLB/TOA at Peniche, constituting powerful tools for global correlation.
6. No data are currently available for radioisotopic dating or magnetostratigraphy. The requirement of suitability for magnetostratigraphy is available at the Almonacid de la Cuba section (Iberian Range, Spain), which correlates well with Peniche. The N2–R2 magnetozone boundary is recorded just above the PLB/TOA at Almonacid. The precise correlation between the two sections allows indirect correlation of Peniche to the magnetic record of the Karoo Group.
7. Sequence stratigraphy is available for the Pliensbachian and Toarcian series of the Lusitanian Basin. Cyclostratigraphy analysis is available for the Lower Toarcian of Ponta do Trovão.
8. The Peniche area is not yet included in any national geological protection system; nevertheless, the Peniche City Hall has recognized the high geological heritage value of the Jurassic of the Peniche Peninsula and has declared, in 2007, the site of Ponta do Trovão as a «Site of City Hall Interest». A permanent fixed marker (i.e., a golden spike) is going to be placed by the Peniche City Hall.

With this Toarcian GSSP, all international stages of the Lower Jurassic have been officially defined.

The requirements for a GSSP(ICS)	**Ponta do Trovão Peniche section (Portugal)**
Geological requirements	**Adequacy of geological requirements**
Exposure over an adequate thickness	Yes
Continuous sedimentation. No gaps or condensation close to the boundary	Little condensation 20 cm above the boundary
Sedimentary rate	Thickness: 9m for the Emaciatum Zone and 11m for the Polymorphum Zone. Sedimentary rate at the PLB/TOA: 3.26–3.81 m/Myr
Absence of synsedimentary and tectonic disturbances	Yes
Absence of metamorphism and strong diagenetic alteration	Yes
Biostratigraphical requirements	
Abundance and diversity of well-preserved fossils	Abundant and well preserved ammonites and brachiopods
Absence of vertical facies changes at or near the boundary	No (slight facies variation 20 cm above the boundary)
Favourable facies for long-range biostratigraphical correlations	Yes
Micropalaeontological data	Calcareous nannofossils (well preserved and abundant), ostracods, palynomorphs, and foraminifera
Other methods	
Radioisotopic dating	No results
Magnetostratigraphy	No results at Peniche; good results in the Almonacid de la Cuba section (Spain) well-correlated to Peniche. Indirect correlation of Peniche to the Karoo magnetic record.
Chemostratigraphy	Hesselbo et al. (2007); Suan et al. (2008a)
Sequence stratigraphy	Duarte et al. (2004b); Duarte (2007a); Pittet et al. (2014)
Cyclostratigraphy	Suan et al. (2008b); Huang and Hesselbo (2014)
Other requirements	
GSSP indicated by a permanent fixed marker	Yes
Physical and logistical accessibility	Yes, very easy accessibility
Free access for research	Yes
Protection of the site	Designated as a “Site of City Hall Interest” since 2007

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