The base of the Toarcian (Early Jurassic) in the Almonacid de la Cuba section (Spain). Ammonite biostratigraphy, magnetostratigraphy and isotope stratigraphy

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The Almonacid de la Cuba section, located in the Iberian Range, in central–eastern Spain (Fig.1), shows a good representative record for the Pliensbachian–Toarcian boundary (Early Jurassic). 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. The presence of Boreal and Mediterranean taxa allows correlation between both bioprovinces. Magnetostratigraphy shows the most complete record of reversals of the Earth magnetic field for the base of Toarcian. The onset of the positive δ¹³C excursion which has been found in the Toarcian of several sections in Europe has been recorded. Average paleotemperatures for the latest Pliensbachian Spinatum Zone was about 12.5°C. Seawater temperature rise during the lowermost Toarcian, reaching average temperatures of 16.7°C at the Tenuicostatum Zone. The ⁸⁷Sr/⁸⁶Sr curve fits with the LOWESS calibration curve.

Introduction

The Almonacid de la Cuba section, located in the Iberian Range of central–eastern Spain (Fig.1), shows a good representative record for the Pliensbachian–Toarcian boundary under outstanding outcrop conditions. The succession has been previously described by Sequeiros et al. (1978), Comas-Engilfo (1982), Comas-Engilfo and Goy (1997), Comas-Engilfo et al. (1999, 2010) and proposed as a complementary section of the Toarcian global stratotype (Goy et al., 2006).

The current official candidate for designation as the Global Stratotype Section and Point (GSSP) for the base of the Toarcian Stage is the Peniche section, located in western Portugal (Elmi et al., 1996; Elmi, 2004, 2006; Hesselbo et al., 2007). However, no magnetostratigraphic scale has been constructed in the potential stratotype. Stable isotope curves in the Peniche section have been acquired from bulk carbonates (Duarte, 1998; Hesselbo et al., 2007), from brachiopods (Suan et al., 2008), and δ¹³C and ⁸⁷Sr/⁸⁶Sr from belemnite carbonates (Hesselbo et al., 2007). However, δ¹⁸O curves have been obtained from brachiopods and the resolution of the record of paleotemperature variations based on δ¹⁸O proxies across the Pliensbachian–Toarcian is low (Suan et al., 2008).

Here we present the biostratigraphy, lithostratigraphy, sedimentology, sequence stratigraphy, magnetostratigraphy and isotope stratigraphy of the Almonacid de la Cuba section which contains a continuous record of the Pliensbachian–Toarcian boundary. Results are compared with other European and American sections and discussed.

Material and methods

The Almonacid de la Cuba section has been studied bed by bed, collected ammonites were classified and belemnites prepared for isotopic studies. The natural gamma ray of the sediments was measured with a portable scintillation counter.

The magnetostratigraphic sampling was carried out using a gasoline-powered drilling machine. A magnetic compass and an inclinometer were used for sample orientation. A total of 57 oriented cores were collected for the magnetostratigraphic study. To perform field test, an additional site (18 samples) with a different structural tilt was studied (ACI site, Fig.1b). The structure sampled is not a single cylindrical fold, therefore the only-inclination fold-test was performed. Magnetic analyses of specimens were carried out in the Paleomagnetic Laboratories of the ETH in Zürich and Madrid. The natural remanent magnetisation (NRM) of the samples was measured.
using a three-axis 2G-Enterprise cryogenic and a JR5 spinner
magnetometers. Stepwise acquisition of isothermal remanent
magnetization (IRM) followed by isothermal remagnetisation in three
orthogonal directions and subsequent progressive thermal
demagnetisation was carried out in order to identify the magnetic
mineralogy of the samples. The field applied along the three
orthogonal axes was: 2 T, 0.4 T and 0.12 T.

To obtain the primary seawater stable and strontium isotope signal,
a total of 40 belemnite rostra were collected and analysed. The rostra
were studied on polished samples and thick sections under the
petrographic and cathodoluminescence microscope. The potentially
unaltered non-luminescent portions of the rostra were sampled using
a microscope-mounted dental drill. Stable isotopes analyses were
performed in the Michigan University (USA) labs. In all samples,
isotope ratios are reported in per mil with respect to the standard
Peedee belemnite (PDB). A total of 15 diagenetically screened
belemnite calcite were analyzed for strontium isotope in the Laboratory
of Geochronology and Isotopic Geochemistry of the Universidad
Complutense of Madrid.

**Lithostratigraphy, sedimentology and sequence stratigraphy**

Two lithostratigraphical units can be recognized in the Almonacid
de la Cuba section: the upper part of the Barahona Fm, which is
composed of bioclastic wackestone–packstone limestone with
interbedded marls, and the lower part of the Turmiel Fm which is
constituted by an alternation of lime mudstones and marls, except on
its lowermost part, where the limestones are bioclastic lime
wackestones. The Pliensbachian–Toarcian boundary is located within
the deposits of the Turmiel Fm (Fig.2). The Barahona Fm was
deposited in an internal shallow, well-oxygenated carbonate platform
on which oysters (*Gryphaea*) predominated, but remains of nektic
organisms, such as ammonites and belemnites, are rare (Gómez and
Goy, 2005). Deposition of the Turmiel Fm at Almonacid de la Cuba
took place in a low-energy, normal salinity, open-marine external
platform environment. The hemipelagic facies of the Turmiel Fm in
the Almonacid de la Cuba section were deposited in the downthrown
block of a syndepositional fault, where expanded sections with no
significant discontinuities and containing ammonites and belemnites,
were deposited (Goy et al., 1997; Gómez and Goy, 2005).

The Upper Pliensbachian deposits are organized in shallowing-
upward sequences characterized by thickening-upward carbonates,
which are frequently topped by soft- to firm-grounds and occasionally
by hard-grounds with ferruginous crusts. The Pliensbachian–Toarcian
boundary is located within one of these shallowing-upward sequences,
where no indications of significant stratigraphic gaps were found.
The set of shallowing-upward sequences containing the
Pliensbachian–Toarcian boundary, which corresponds to the LJ3–1
cycle for Central and Northern Spain (Gómez and Goy, 2005), is
interrupted by an ephemeral transgressive interval that occurred in
the lower Tenuicostatum Zone. However, the shallowing-upward
sequences continue up to the top of level 64, where a new transgressive
episode corresponding to cycle LJ3–2 starts. The “Toarcian
transgression” developed in a few pulses, reaching the transgressive
peak at the Middle Toarcian Bifrons Zone, as it was observed in many
other areas of Spain (Gómez and Goy, 2000, 2005).

**Ammonite record and biostratigraphy**

The ammonite assemblages of both the Spinatum and the
Tenuicostatum zones are well represented in the Almonacid de la Cuba
section. The studied time interval is characterized by the occurrence of *Pleuroceras, Canavarria, Dactylioceras (Eodactylites)*
and *D. (Orthodactylites).* The latest subgenus also occurs in younger
beds. A similar succession was recognized in the Peniche section of
Portugal (Mouterde, 1955; Elmi, 2004, 2006), and in northwestern
Algeria (Elmi et al., 2006).

**Spinatum Zone (Upper Pliensbachian).** The ammonite
assemblages of the Upper Pliensbachian Spinatum Zone (at least
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10.16 m thick) are characterized by the presence of Pleuroceras and Canavaria. Other genera are Emaciaticeras, Fontanelliceras, Lioceratoides and Neolioceratoides. The Spinatum Zone has been subdivided into a lower Apyrenum Subzone and an upper Hawkserense Subzone (Dean et al., 1961; Dommergues et al., 1997; Page, 2003; Meister et al., 2006).

The 4.98 m thick Apyrenum Subzone is characterized by the occurrence of Amaltheidae, particularly of the genus Pleuroceras (P. solare, P. spinatum, P. apyrenum and P. yeovilense). Hildoceratidae (Harpoceratinae) of the genera Lioceratoides (L. cf. serotinus) and Neolioceratoides (N. cf. hoffmanni) also occur.

In the Hawkserense Subzone, the Amaltheidae are recorded together with the last occurrences of Hildoceratidae (Harpoceratinae). Between beds CU16 and CU34, the Pleuroceras are replaced by Hildoceratidae (Hildoceratinae) of the genus Emaciaticeras, Canavaria and locally, Fontanelliceras. This subzone, which is 5.18 m thick, is characterized by Pleuroceras (P. spinatum, P. cf. yeovilense, P. hawkerense). The Pleuroceras occur together with Lioceratoides (L. cf. serotinus) and Neolioceratoides (N. cf. hoffmanni), as well as Canavaria [C. (C.) zancleana, C. (C.) cf. gregalis, C. (T.) elisa, and C. (T.) cf. nodosa]. In the lower part of its stratigraphic range, the genus Pleuroceras occurs together with Emaciaticeras (E. lottii, E. cf. imitator, E. emaciatum) whereas in the upper part, it occurs with Fontanelliceras (F. fontanellense) and Neolioceratoides (N. hoffmanni). In summary, the assemblages of the lower part of this subzone are dominated by the amaltheids (i.e. Pleuroceras), whereas in some levels of the upper part the Arieticeratinae became the only constituent of the ammonite assemblage. No Arieticeratinae were found, the Harpoceratinae are less than the 10% of the total, and the Harpoceratinae are always present but in a low proportion.

Tenuicostatum Zone (Lower Toarcian). The Lower Toarcian Tenuicostatum Zone has been marked by the first appearance datum of the genus Dactylioceras, used here for recognition of the base of the Toarcian. The assemblage is characterized by species of the subgenera Dactylioceras (Eodactylites) and Dactylioceras (Orthodactylites) which characterize the Mirabile and the Semicelatum subzones, respectively. The stratigraphic range of the Tenuicostatum Zone in the Iberian Range coincides with the Polymorphum Zone in the Betic Cordillera, and with the Semicelatum Zone in Portugal (Mouterde, 1967; Comas-Rengifo and Goy, 1978; Goy et al., 1988; Elmi et al., 1989, 1994, 1997).

The 1.57 m thick Mirabile Subzone is characterized by species of the subgenus Dactylioceras (Eodactylites) such as D. (E.) simplex and D. (E)
Magnetic polarity column for the Pliensbachian–Toarcian boundary at the Almonacid de la Cuba section has been constructed on the basis of the polarities of the ChRM (Fig. 2). Three normal and two reversed polarity magnetozones have been identified. Named N1–3 and R1–2. Within R1 magnetozone, a smaller magneto-subzone has been identified and labeled nR1. Polarity identified by only one sample is marked by a discontinuous bar.

At the bottom of the column, the N1 magnetozone is observed within the Pliensbachian Apyrenum Subzone. R1 is a long magnetozone extending up to the upper Hawskerense Subzone. The small magnetosubzone nR1 is located near the top of the Barahona Fm. The end of the Hawskerense Subzone is characterized by a normal polarity (N2 magnetozone). R2 nearly coincides with the boundaries of the Mirabile Subzone and the lower boundary of the Toarcian. N3 is a long magnetozone which characterizes the Tenuicostatum Zone, starting in the upper part of the Mirabile Subzone and extending up to the top of the section (Semicelatum Subzone).

**Isotope stratigraphy and palaeotemperatures**

The presence of belemnites in virtually all the studied beds allowed obtaining excellent $^{87} \text{Sr}/^{86} \text{Sr}$ and $^{13} \text{C}_{\text{b}}$ curves based on diagenetically screened belemnite calcite (Fig. 2).

**Stable isotope record.** The $^{13} \text{C}_{\text{b}}$ record shows values ranging from −0.52 to 3.59 ‰ PDB. These values tend to be quite uniform at within the uppermost Pliensbachian, averaging 1 ‰ PDB, but they tend to increase at the Lower Toarcian, where average values of 1.88 ‰ PDB were reached. The increase in the $^{13} \text{C}_{\text{b}}$ values marks the onset of a positive excursion which has been recorded in most European sections, whether in bulk rock or belemnite carbonates, in marine organic matter, and in wood (e.g. Jenkyns and Clayton, 1997; Schouten et al., 2000; McArthur et al., 2000; Hesselbo et al., 2007; Gómez et al., 2008).

In the $^{18} \text{O}_{\text{b}}$ curve, which shows values ranging from 0.73 ‰ to −1.71 ‰ PDB, also significant changes at the Pliensbachian–Toarcian transition are observed. At the Spinatum Zone, the $^{18} \text{O}_{\text{b}}$ values were slightly negative (−0.29 ‰ PDB in average), but around the transition between both stages, an excursion towards more negative values, averaging −1.3 ‰ PDB, is recorded. This negative $^{18} \text{O}_{\text{b}}$ shift has also been reported in many European sections such as the Whitby and the Yorkshire areas in the UK (Sælen et al., 1996; Jenkyns, 2003), in the French Paris Basin (Dera et al., 2009), in the Peniche section in Portugal (Suan et al., 2008), in Bulgaria (Metodieva and Koleva-Rekalova, 2008), in Northern Spain, in the Basque-Cantabrian Basin (Rosa et al., 2004), Asturias (Gómez et al., 2008), and in Central Spain (Gómez et al., 2008).

**Seawater palaeotemperatures.** The obtained $^{18} \text{O}_{\text{b}}$ values have been used as a proxy for calculation of the seawater palaeotemperatures at the Pliensbachian–Toarcian transition, using the Anderson and Arthur (1983) equation.

The temperature variations during the Late Pliensbachian–Early Toarcian are shown in Fig. 2. At the uppermost Pliensbachian Spinatum Zone, the palaeotemperatures were relatively low, from 9.2°C recorded around the Apyrenum–Hawskerense zonal boundary, up to 17°C calculated for one sample located near the Pliensbachian–
Toarcian boundary. Average paleotemperature of 12.5°C calculated for the Late Pliensbachian notably increased during the Early Toarcian, where average calculated temperatures were 16.7°C, including peak values above 19.5°C, reached at the Mirabile and the Semicelatum subzones.

\(^{87}\text{Sr}/^{86}\text{Sr} \text{ curve.} \) Plots of obtained \(^{87}\text{Sr}/^{86}\text{Sr} \) values against the stratigraphic column are displayed in Fig.2. The highest values (0.707104) are recorded at the uppermost Pliensbachian Apyrennum Zone. These values gradually fall towards values lower than 0.707050 around the Pliensbachian–Toarcian boundary, shifting towards higher values in the Lower Toarcian, where values of 0.707062 are reached in the belemnite calcite sampled in the Semicelatum Subzone.

Discussion and conclusions

The Almonacid de la Cuba section contains an excellent record of the Pliensbachian–Toarcian boundary, where no indications of major sedimentary breaks have been 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*.

The Spinatum Zone is characterized by the succession of *Pleuroceras* (*P. transiens* - *P. solare* - *P. cf. hawskerense*), which are also used as zonal marker in NW Europe (Howarth, 1958; Comas-Rengifo, 1982; Dommergues et al., 1997; Meister et al., 2006). However, the assemblages of the upper part of the Spinatum Zone at Almonacid de la Cuba can also be compared with the ammonite zonation proposed for Southern Europe, on which the use of the Emaciaticeras Zone, subdivided into the Solare and the Elisa subzones, is preferred (Braga et al., 1982, 1984; Braga, 1983; Macchioni, 2002; Meister et al., 2006). Beds containing *P. hawskerense* are correlated with the Hawskerense Subzone of the NW European province (Dommergues et al., 1997; Page, 2003; Meister et al., 2006). Levels with *Emaciaticeras* and *Canavaria* can be correlated with the Elisa Subzone of the Emaciaticeras Zone, described by Braga (1983) in the Betic Cordillera (Southern Spain), and also documented in the Mediterranean area by Macchioni and Cecca (2002), Macchioni and Meister (2003), Page (2003) and Meister et al. (2006).

Ammonite assemblages of the Tenuicostatum Zone mainly contain taxa characteristic of the NW European province such as *Plectogrammoceras pallium* and *Dactylioceras* (*Orthodactylites*) with predominance of *Dactylioceras* and smaller *Harpoceratinae*. However, taxa of the Mediterranean province, such as *Neolioceratoides*, *Dactylioceras* (*Eodactylites*) and *P. madagascariense* are only recognized in a few levels. In the Mirabile Subzone, *D. (Eodactylites)* co-occurs with *P. pallium*. The occurrence of taxa from both provinces in the Almonacid de la Cuba section is useful to improve the correlation between the NW European and the Mediterranean provinces.

Two paleobiogeographic features can be highlighted: (1) the occurrence of *D. (E.) simplex* allows correlation with the level 1SE of the Peniche section, as well as with some North American and South American sections (Elmi et al., 1974, 2006; Hillebrandt and Schmidt-Effing, 1981); (2) *P. pallium* is a good marker for correlation with the NW European and the Mediterranean provinces. In the Ricla section (Iberian Range, Spain), Peniche section (Lusitanian Basin, Portugal) and the Melllala section (Traras Mountains, Algeria), this species, or a similar form, occurs at the base of the Mirabile Subzone (Goy and Martínez, 1990; Elmi, 2004; Bécaud, 2006; Elmi et al., 2006). Also Macchioni (2002) found that *P. pallium* is common at the Mirabile Horizon in the Mediterranean area.

Referring magnetostratigraphy, N3 is a clear magnetozone observed at the Iznalloz section (Betic Cordillera, southern Spain) by Galbrun et al. (1990) and recently described at the Sierra Palomera and Arriño sections (Iberian Range, Central Spain) by Ossete et al. (2007). R2 magnetozone is also in agreement with the reversed polarity observed in the lower part of the Iznalloz section. R2 and R1 were also recorded in the Breggia section (Horner and Heller, 1983), but the N2 magnetozone was not detected in the Alpine section. Probably because the Lower Toarcian is only poorly represented in Breggia (the Tenuicostatum Zone is around 30 cm thick, Horner and Heller, 1983). According with data presented here, it seems that there is a gap at the Pliensbachian–Toarcian boundary in the Alpine section.

The Magnetic Polarity Time Scale (MPTS) proposed by Ogg (1995, 2004) was mostly based on the Breggia section, consequently, is consistent with the general pattern of our data, but the N2 magnetozone is absent, and the age control of lower Toarcian reversals is poor. The new MPTS proposed by Osete et al. (2007) for the Toarcian is in agreement with the new data presented here, but it does not extend below the Toarcian. The magnetostratigraphic study of the Neuquén section (Iglesia-Llanos and Riccardi, 2000) has not enough resolution to describe in detail the reversals of the earth magnetic field for this time period. Therefore the magnetostratigraphic data presented here are the most complete record of reversals of the earth magnetic field for the Pliensbachian–Toarcian boundary.

A good record of the onset of the positive \(^{87}\text{Sr}/^{86}\text{Sr} \) excursion reported in many European sections has been obtained in the Almonacid de la Cuba section. Most authors are in agreement about the interpretation of the Early Toarcian positive excursion as the response of water masses to excess and rapid burial of large amounts of organic carbon rich in \(^{13}\text{C} \), that led to enrichment in \(^{13}\text{C} \) of the sediments (Jenkyns and Clayton 1997; Schouten et al., 2000), or to removal from oceans of large amounts of isotopically light carbon as organic matter into black shales or methane hydrates, which leaves oceanic carbon isotopically heavy (McArthur et al., 2000). Data presented in this work show a good latest Pliensbachian–earliest Toarcian \(^{87}\text{Sr}/^{86}\text{Sr} \)-based paleotemperature curve (Fig. 2). Average paleotemperatures measured in the latest Pliensbachian Spinatum Biochron of about 12.5°C are in good agreement with average temperatures of 11.6°C calculated in Asturias (Northern Spain, Gómez et al., 2008) and of 12°C in the Basque-Cantabrian Basin (also in Northern Spain, Rosales et al., 2004). These temperatures can be considered low for a calculated Central Spain palaeolatitude of about 35°N during the Pliensbachian–Toarcian (Osete et al., in press). Similar values of oceanic paleotemperatures recorded in the UK and in Germany (Bailey et al., 2003) confirm that the latest Pliensbachian and the earliest Toarcian represent a relative cooling interval.

A marked increase of the seawater temperature started during the Toarcian. At the Tenuicostatum Zone average temperatures of 16.7°C in the Almonacid de la Cuba section, 15°C in the Asturias sections, in Northern Spain and 16°C in the La Almunia-Ricla section, located in the Iberian Range, near the studied section, were reached (Gómez et al., 2008). That represents a ΔT between 4 and 5°C around the Pliensbachian–Toarcian transition. This palaeotemperature rise is probably one of the main causes of the so-called upper Pliensbachian...
biotic crises, and clearly marks the onset of the outstanding Early Toarcian warming interval which accelerates around the Tenuicostatum - Serpentinum zonal boundary in many European sections and extensively develops during the Early and Middle Toarcian (McArthur et al., 2000; Jenkyns, 2003; Rosales et al., 2004; Gómez et al., 2008).

The $^{87}$Sr/$^{86}$Sr values obtained in the Almonacid de la Cuba section fully agree with the previously published data (McArthur et al., 2000, 2001; McArthur and Howarth, 2004; Hesselbo et al., 2007). Upper Pliensbachian $^{87}$Sr/$^{86}$Sr values generally decrease at the Hawskerense Zone, reaching a first minimum value below 0.707050 in the upper portion of this Zone and a slight increase in the uppermost portion of this Zone. Minimum values are recorded at the base of the Toarcian, as predicted by the LOWESS calibration curves, and $^{87}$Sr/$^{86}$Sr slowly recovers along the Tenuicostatum Zone. These results strongly support the reliability of the available $^{87}$Sr/$^{86}$Sr values and the good geochemical signal included in the belemnite calcite of this section.

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