High-resolution integrated stratigraphy of the OAE1a and enclosing strata from core drillings in the Bedoulian stratotype (Roquefort-La Bédoule, SE France)

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ABSTRACT

In 2009 two wells were drilled with 100% core recovery at Roquefort-La Bédoule (Bouches-du-Rhône, SE France), the historical Bedoulian stratotype. Here we present holostratigraphic results based on a detailed study of the cored sediments. Our work confirms that the La Bédoule area offers one of the best records for the period spanning the late Bedoulian, the anoxic event OAE1a and the Bedoulian/Gargasian (lower-upper Aptian substages) transition. New data provide a refined succession of micropaleontological events already well correlated with ammonites from previous fieldwork and, thus, improve the cross-calibration of bioevents with high-resolution isotope stratigraphy. Methods of the quantitative micropaleontology applied on benthic foraminifera such as tritaxias help testing their probable orbitally triggered cyclicity, which might be used to precise estimates of duration of events such as OAE1a, the Dufrenoya furcata ammonite Zone, the Globigerinelloides ferreolensis planktonic foraminiferal zone and the C7 isotopic stage.

The lithologic, biotic and possibly isotopic changes seen at the level of and around bed 170 (top of “Niveau Blanc” sensu auctorum) are strong arguments to use this key-level as the boundary between the two Aptian substages (or stages in an alternative classification) and to support the proposal of La Bédoule as a potential locality for the GSSP of the Gargasian Substage (or of historical Aptian sensu stricto, in the alternative classification).

1. Introduction

With a duration of about 12 myr (Scott, 2014), the Aptian is one of the three Cretaceous “superstages”, together with the Albian (15 myr) and the Campanian (11 myr), whereas most of the other Cretaceous stages are 6 myr in average length. This longevity may explain earlier somewhat confusing two- or three-fold divisions of the Aptian including two to three substages based on distinct stratotypes. Table 1 summarizes two recent proposals (Reboulet et al., 2011, 2014; Moullade et al., 2011) for the subdivision of the latest Barremian to earliest Albian chronostratigraphic interval. Awaiting an official position of the International Commission of Stratigraphy (ICS), and in view not to confuse the reader, in this work we will provisionally keep the terms Bedoulian and Gargasian for naming the Lower and Upper Aptian, respectively. However, our position (Moullade et al., 2011) is to subdivide the interval between the Barremian and the Albian into two distinct stages: 1) the Bedoulian, upgraded from its rank of substage, and 2) the Aptian sensu initio, i.e., sensu d’Orbigny (1840), covering the Gargasian (a junior synonym of the original Aptian).
Until recently the stratigraphy of the Bedoulian stratotypic area in south-Provence was based on a more or less continuous composite set of sections located in the territories of Cassis and Roquefort-La Bédoule (Bouches-du-Rhône, SE France) (Figs. 1–2). During the 19th Century and the first half of the 20th these localities were especially well-known for their rich ammonite faunas. Fabre-Taxy et al. (1965) published the first study of the Bedoulian historical stratotype that integrated ammonite and microfossil biostratigraphy. This trend has been continued during the last decade (Moullade et al., 1998a,b, 2005; Ropolo et al., 1998, 2006, 2008) and has been combined with chemostratigraphy (Renard & Rafélis, 1998; Renard et al., 2005; Kuhnt et al., 1998, 2011).

However, several upper Bedoulian levels (including beds of anoxic event OAE1a), as well as its transition to the Gargasian, remained poorly accessible for field observation. This prompted two of us (WK & MM) to undertake a project to continuously core in the stratotypic area of Roquefort-La Bédoule.

Table 1

Two recent proposals (Reboulet et al., 2011, 2014; Moullade et al., 2011) for the subdivision of the uppermost Barremian to lowermost Albian chronostratigraphic interval compared to Lyon 1963 Colloquium (Anonymous, 1965).

<table>
<thead>
<tr>
<th>Lower Cretaceous Colloquium (Lyon, 1963)</th>
<th>Reboulet et al., 2011 ammonite zonation</th>
<th>Moullade et al., 2011</th>
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<tr>
<td>Substages</td>
<td>Zones</td>
<td>Subzones</td>
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<tr>
<td>CLANSAYEAN</td>
<td>Hypacanthoplites jacobi</td>
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<td></td>
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<td></td>
<td>Parahoplites melchioris</td>
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<tr>
<td>GARGASIAN</td>
<td>Upper Aptian</td>
<td>Epicheloniceras buxtorfi</td>
</tr>
<tr>
<td></td>
<td>Epicheloniceras gracile</td>
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<tr>
<td></td>
<td>Epicheloniceras debile</td>
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<tr>
<td></td>
<td>Dufrenoyia dufrenoi</td>
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<td>Dufrenoyia furcata</td>
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<td></td>
<td>Deshayesites deshayesi</td>
<td>Deshayesites grandis</td>
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<td></td>
<td>Deshayesites forbesi</td>
<td>Roboloceras hambrovi</td>
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<tr>
<td></td>
<td>Deshayesites oglanensis</td>
<td>Deshayesites luppovi</td>
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<td>BEDOULIAN</td>
<td>Lower Aptian</td>
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<tr>
<td></td>
<td>Epicheloniceras martini</td>
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<td>Stages</td>
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(Reboulet et al., 2011; Moullade et al., 2011)

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<tr>
<th>Substages</th>
<th>Zones</th>
<th>Subzones</th>
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<tr>
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<td></td>
<td>Acanthohoplites notani</td>
<td>Diadochoceras nodosocostatum</td>
</tr>
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<td></td>
<td>Parahoplites melchioris</td>
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<td>Epicheloniceras buxtorfi</td>
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<td>Epicheloniceras gracile</td>
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<td>Epicheloniceras debile</td>
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<td>Dufrenoyia dufrenoi</td>
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<td>Dufrenoyia furcata</td>
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<td>Deshayesites deshayesi</td>
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<td>Roboloceras hambrovi</td>
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<td>Deshayesites oglanensis</td>
<td>Deshayesites luppovi</td>
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<tr>
<td>LOWER APTIAN</td>
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[Fig. 1. Geographic location of the studied sections and drill holes in the Cassis-La Bédoule area.]
which was carried out in 2009. Three holes (LB1, LB2, and LB3; Fig. 1) were drilled (Flögel et al., 2010), with the main goal to obtain a continuous succession covering the upper Bedoulian (LB1–LB2) and the Bedoulian–Gargasian transition (LB3).

First biostratigraphic results based on occurrences of the main foraminiferal markers from hole LB1 were published in a recent paper (Lorenzen et al., 2013). The aim of the present work is to expand this preliminary study by providing a higher-resolution
stratigraphic framework of the upper two-thirds of hole LB1 and the entire hole LB3. This report is based on a larger set of additional data including benthic and planktonic foraminifera, isotope geochemistry and to some extent ostracods and calcareous nanofossils. Integration with ammonite zones was performed by correlating the drilling results with lithological and faunal data collected in the nearby outcrops (Moullade et al., 1998a; Ropolo et al., 2006, 2008; Kuhnt et al., 2011).

We used foraminifera, bulk-rock carbon isotope measurements and natural gamma ray logging as main tools to establish a high-resolution stratigraphic framework for the LB1 and LB3 boreholes. This study represents a stratigraphically significant advance compared to previously published results (Moullade et al., 1998a, b, and subsequent studies), which were based on a composite succession of discrete outcrops implying possible observational gaps. A continuous succession and optimal core recovery gave us the opportunity (i) of high-resolution sampling and (ii) to fill these gaps.

This study is also intended to show how such a synthesis of complementary field and core-hole data in the Bedoulian stratotype area should strengthen the position of Cassis-La Bédoule as an Aptian reference section and a potential candidate for a GSSP of the boundary between two stratigraphic entities, understood either as sub-stages or as stages, whichever classification will be ratified by ICS.

2. Geographical setting

The geographical position of the boreholes is shown in Fig. 1. Holes LB1 and LB2 are located within a dozen metres of each other, 600 m SW of the settlement of Les Fourniers. Both holes covered 67 m of the same sedimentary succession of mostly Bedoulian age. For this study only LB1 has been sampled. Results from LB2 have not been taken into consideration in this paper because its stratigraphic interval duplicates that of LB1. LB3 is located 1.25 km ENE of LB1/LB2, just to the south of the residential development of Les Tocchis. Here a 55 m-thick succession including the uppermost Bedoulian and the lower part of the Gargasian was recovered. LB1 and LB3 overlap by fifteen metres on either side of the Bedoulian/Gargasian boundary.

3. Lithological nomenclature

Moullade et al. (1998a, 2004) described in detail the lithostratigraphy of the Bedoulian and Lower Gargasian beds from the Cassis-La Bédoule stratotype area on the basis of a composite set of discrete sections. Based on the respective lithologic composition, the authors divided the La Bédoule Formation into three Members: 1) the Calcareous Member, subdivided in three Units (1, 2, 3), including the uppermost Barremian and the lower Bedoulian; 2) the Marly Calcareous Member, made of alternating marls and limestones, divided in two Units (4, 5) and dated late Bedoulian; and 3) the Marly Member (Unit 6), dated early Gargasian. The Bedoulian/Gargasian boundary is defined at the top of key bed 170 (lowest occurrence of the ammonite Dufrenoyia furcata and the planktonic foraminifer Praehedbergella luterbacheri). Lithostratigraphic features, as well as some key beds or levels and ammonite zonal markers are summarized in Fig. 2. These data will be used for interpreting the drilled succession.

4. Material and methods

4.1. Microfossils (foraminifera and ostracods)

Hundred and five samples (48 from LB1 and 57 from LB3) were taken at spacings of one metre for LB1 and half a metre for LB3 and studied for foraminifera. Both the sediment sample and its washed residue were dried and weighed. Samples were treated by Rewoquat W 3690 (cationic tenside; see details in Moullade et al., 2005) before sieving through a 45 micron screen. The washed residue of each sample was divided into two equal aliquots using a microsplitter. (1) The first half was used for biostratigraphic analyses, with identification and counting of all specimens from every benthic and planktonic species. These data were used for constructing the distribution tables of LB1 and LB3 (Figs. 3–4), for which we applied the same frequency-classes as those defined for the Cassis-La Bédoule area by Moullade et al. (2005). (2) The second half was dry-sieved through a 140 micron screen and a microsplitter was used to get samples sizes of about 200 benthic foraminifera among which every individual species or groups of closely related species were counted. This technique allowed us to acquire various quantitative parameters in a comparable way (per gram of dried sample) for all samples, such as the total number of benthics, number of agglutinated or calcareous forms, of tritaxias, lenticulinas, gavelinellas, falsogaudyinellnas, etc.

The state of microfossil preservation from the core samples is variable, ranging from poor to moderate in the Bedoulian and moderate to good in the Gargasian. Ostracods are slightly better preserved than foraminifera. Specimens collected from the cores appeared less well-preserved than those from outcrop samples, possibly more resistant to corrosion by the Rewoquat.

4.2. Calcareous nanofossils

Two simple smear slides from each sample were prepared following the standard procedure of Bow and Young (1998). From each slide more than ~200 fields of view have been scanned for species of stratigraphic importance by using a polarizing light microscope (Zeiss Axio-Imager) with a magnification of 1250×. In order to integrate the results into existing stratigraphic frameworks species reported by Siessingh and Prins (1977), Roth (1978), Perch-Nielsen (1985), Bown et al. (1998) and Bergen (1998) were used to apply the NC zonation according to Roth (1978).

4.3. Natural gamma ray logging

The wire-line logging was performed with an Antares Aladdin logging system, equipped with a GR5 sensor probe. The probe was lowered into the drill hole after the drilling was completed. The walls of the hole were not covered with a metal casing. Measurements (5 cm spacing) are reported as API (American Petroleum Institute) radioactivity units.

4.4. Stable isotopes

For stable isotope measurements, core LB1 and LB3 were sampled at 20 cm interval. Stable isotopes were measured with a Finnigan MAT 251 mass spectrometer connected to a Carbo-Kiel (automated CO2 preparation) device at the Leibniz-Laboratory for Radiometric Dating and Isotope Research in Kiel, Germany. The results were calibrated by using the NBS 19 standard and are reported on the PeeDee Belemnite (PDB) scale. The mass spectrometer has an analytical uncertainty of ±0.04‰ for δ13C and ±0.07‰ δ18O for carbonate samples.

4.5. Carbon isotope stratigraphy

Based on data from the Cismon (Italy) and Roter Sattel (Switzerland) sections, Menegatti et al. (1998) developed a nomenclature for segments of the Aptian carbon isotope curve (Fig. 5). According to major changes in the carbon isotope record, segments were defined and labelled from C1 to C8. We used these definitions to correlate our carbon isotope curves. In the LB1
Fig. 3. Distribution of Foraminifera and selected Ostracoda in hole LB1 at La Bédoule plotted against ammonite (Reboulet et al., 2011), calcareous nannofossil (Roth, 1978), isotope stages (Menegatti et al., 1998; this study), and the main marker levels (Moullade et al., 1998a; Ropolo et al., 2006, 2008; this study).

<table>
<thead>
<tr>
<th>Depth in hole (m.)</th>
<th>LB1 Deshayesi</th>
<th>Grandis buriwi</th>
<th>Furcata cabri</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone</td>
<td>Ammodiscus cretaceus</td>
<td>Glomospirella guatilina</td>
<td>Ammodiscus cf. laevinodus</td>
</tr>
<tr>
<td></td>
<td>Triloculina sp.</td>
<td>Textulariina sp.</td>
<td>Triloculina sp.</td>
</tr>
<tr>
<td></td>
<td>Assemblage A</td>
<td>Assemblage B</td>
<td>Assemblage C</td>
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Fig. 4. Distribution of ammonites and selected Outoceri in hole LB 3 at la Bedouliére plotted against ammonite (Bedouliére et al., 2011), echinoid, nanofossil zones (Moullade et al., 1998a; Ropolo et al., 2006, 2008, this study).
Fig. 5. Comparison of bulk carbon isotope curves from La Bédoule area (Kuhnt et al., 2011; Lorenzen et al., 2013) with those of Rotter Sattel, Switzerland (Menegatti et al., 1998), Cismon, Italy (Li et al., 2008) and Cuchia (Spain, Najarro et al., 2011) [Scale bars = 5 m].
section, the anoxic event OAE 1a was identified on the basis of the structure of the δ13C excursion. Its beginning is defined by a negative shift at a depth of 36 m, which represents the boundary between segments C2 and C3, and the ends with a plateau after segment C6, at a depth of 17.50 m. The upper part of segment C7 and the lower part of segment C8 were identified in LB3, the C7/C8 boundary being identified on the basis of the beginning of a negative shift at a depth of 30 m.

5. Results

5.1. Lithostratigraphic key-levels

Previous studies of outcrops at the Cassis-La Bédoule railroad section as well as the La Bédoule area (Fabre-Taxy et al., 1965; Moullade et al., 1998a, 2005) revealed several striking lithologic features within the upper Bedoulian and lower Gargasian sequence (Fig. 2).

Even though based on lithologic, gamma ray logging, micropaleontologic and isotopic data, it has not been easy to identify the outcropping key-levels in the drilled sections. In contact with the atmosphere, small differences in chemical composition of the rocks are artificially accentuated by surface diagenesis, erosion and differential weathering. Yet gamma-ray logging as well as visual and colorimetric observation of the cores have shown that changes in sediment composition are actually much more gradual, making beds boundaries less distinct and, thus, less discernible than in the field. In the case of these Bedoulian and Gargasian rocks, the clay/carbonate ratios vary only in a fairly narrow range; so well-marked alternations of indurated “calcareous” beds and softer “marly” levels seen in the field (as in the Marly Member) were often difficult to correlate with the more diffuse features observed in the drilled sequence of LB3. Another source of uncertainty arose from the fact that the labelled stratotypic bedding nomenclature (Moullade et al., 1998a) comes from the Cassis section, where the succession is slightly thicker than at La Bédoule. Such an even slight condensation from west to east leads to thickness variations, different organization or even disappearance of some beds. However, by combining various approaches, we were able to identify in the cores three more conspicuous lithostratigraphic elements known from the field (Fig. 2):

- ‘Camping marls’. This 9.5 m-thick predominantly marly sequence was described (Moullade et al., 1998a; Kuhnt et al., 2011) from a section in the La Bédoule area, so called the “Camping section” (Figs. 1 and 6), located 300 m north of the LB1/LB2 drilling site. This conspicuous feature is well highlighted by gamma-ray logging and consists of LB1-15 to -20 cores, which include the top part of the isotopic stage C4 and the whole C5–C6 stages, i.e., about the upper half of OAE1a.

- Key bed ‘C19’. As labelled in the lithostratigraphic nomenclature of the stratotype in Moullade et al. (1998a), this benchmark is easily identifiable in the field in both Cassis and La Bédoule sections. This is the uppermost ~1 m-thick bed of a ~15 m-thick predominantly calcareous sequence attributed to the ammonite Deshayesites grandis Subzone (Ropolo et al., 1998, 2008). This sequence actually consists of an alternation of thin marlstones and thicker limestones. Bed 170 has been identified in both holes; in LB1 it forms the upper two-thirds of core 4 (Fig. 7b), and in LB3 it includes the lower half of core 29 plus the top of core 30 (Fig. 7c).

- The ‘triplet’, in the section called ‘Les Camerlots-Les Tocchis’, logged in 1963 by one of us (MM) and published in Moullade et al. (1998a) (Fig. 1), the “triplet” consists of three more conspicuous 0.4 to 0.5 m-thick marly calcareous beds within an otherwise lower Gargasian monotonous rhythmic succession of thinner 0.1 to 0.25 m-thick beds (Fig. 8b). In the sixties this triplet formed a sort of cuesta, i.e., a characteristic well individualized structural landform that could be easily followed in the landscape in the area between Les Fourniers and Les Tocchis, just north of the location chosen for drilling LB3. This area was not urbanized in 1963 and offered a continuous record of the Bedoulian/Gargasian transition, whereas today it is completely covered by residential developments.

This triplet can still be seen at Cassis, as three more prominent successive beds cropping out in the first metres of the stope face of La Marcouline quarry (Figs. 1 and 8a).

Carbonate content and gamma-ray data of hole LB3 (Fig. 9) show a sequence of three better shaped successive peaks from ~22 to ~24.60 m, which probably correspond to the triplet seen in the field. But the lithological succession in LB3 cores between ~20 and ~25 m (Fig. 8c) is not very diagnostic on this point. The three calcareous beds observed at this level (in cores 15 to 17) do not clearly differ in thickness from calcareous beds of the enclosing intervals. However, correlations based on the microfaunal distribution help to remove the uncertainty because, in Les Tocchis, La Marcouline and LB3, this triplet is located in the Globigerinelloides ferreolensis ferreolensis zone, just above the extinction of Schackoina gr. cabri.

5.2. Foraminifera

The tables (Figs. 3–4) built from the semi-quantitative distribution of each foraminiferal species show not only the overall composition of the microfauna, but also bring out the main markers and the most significant bioevents, which allowed strengthening and refinement of the current zonation.

5.2.1. Foraminiferal content and main markers (Figs. 3–4 & 10)

We identified 55 species or groups of polymorphically undifferentiated species (i.e., nodosarias, vaginulinas, etc.) among the benthic and planktonic foraminiferal content of LB1 and LB3 boreholes. Among these, 5 benthic and 5 planktonic taxa can be used as stratigraphic markers.

- Benthic agglutinated foraminifera: composed of rather long-ranging forms, this group does not include any significant stratigraphic marker in itself for the study interval. However, these forms commonly represent an important proportion of the benthic foraminiferal microfauna. The most common taxa are Tritaxia pyramidata Reuss, Falsogaudryinella moesiana (Neagu) and F. tealbyensis (Bartenstein). The semi-quantitative first approach by only using frequency classes shows some cyclicity in the distribution of T. pyramidata. We also note a trend of reversed frequencies of abundance between F. tealbyensis and F. moesiana. This confirms the results of Moullade and Tronchetti (2010), based on outcrop sample

- Benthic hyaline calcareous foraminifera: these are dominated by smooth lenticulinas of the gibba-nuda group and gavelinellals of the flandrini group, which also show a certain cyclicity in their distribution, more or less synchronous with that of tritaxias. In addition five species, even if generally rare, are of stratigraphic importance:
  - Lenticulina cf. heiermanni Bettenstaedt — even though a little too sporadic — and Globorotalites gr. bartensteini-intercedens Bettenstaedt become extinct at or very near the Bedoulian/Gargasian boundary.
- *Lenticulina cf. nodosa* (Reuss) and *Astacolus crepidularis tricarinella* (Reuss) both become extinct 4.5 m above this boundary.
- *Oolina apiculata* Reuss has its first appearance 5 m above the same boundary.
- Planktonic foraminifera: among a fairly constant and homogeneous stock over the duration of the studied period, which consists largely of small praehedbergellas and small few-chambered *Globigerinelloides (Blowiella)* emerge five taxa whose more accurately identified LO (lowest occurrence) allowed us to refine the zonation defined for the Aptian (Bedoulian and Gargasian) stratotypes in our previous works (Moullade et al., 1998b, 2005, 2008):

  - *Schackoina (Leupoldina) gr. cabri* Sigal; in hole LB1, the LO of this group coincides with the boundary between isotopic stages C3 and C4 sensu Menegatti et al. (1998). This confirms the result of Kuhnt et al. (2011) from the Camping outcrop section at La Bédoule. In addition to the main bioevent based on its first appearance, the evolution in the distribution of this group also allowed us to define three other bioevents: 1) the base (= uppermost Bedoulian) and 2) the top (= level of simultaneous disappearance of *L. cf. nodosa/A. crepidularis tricarinella* of its acme; and 3) its disappearance at the base of the *G. ferreolensis* ferreolensis zone.
  - *Praehedbergella luterbacheri* (Longoria); in both LB1 and LB3 holes, the LO of this 7-chambered low trochospiral...
species is seen right at the top of key bed 170 (according to the bed numbering for the stratotype in Moullade et al., 1998a), i.e., exactly at the Bedoulian/Gargasian boundary. This species is relatively rare and very small (usually < 100 μm) at its appearance, which falls within the ammonite Dufrenoyia furcata Zone. Then P. luterbacheri becomes more common and increases in size during the Cheloniceras martini Zone. Data from the two wells update previous studies on foraminifera of the Aptian stratotypes (Moullade et al., 2005, 2008). These studies suggested a slightly later appearance of this taxon, at the level of the event defined by the simultaneous last occurrence of the benthic species Lenticulina cf. nodosa and Astacolus crepidularis tricarinella. This slight discrepancy might be explained by the scarcity and small size of P. luterbacheri at the beginning of its range.

- Globigerinelloides ferreolensis ferreolensis (Moullade); this 8-chambered planispiral subspecies of the G. ferreolensis group evolved from the subspecies heptacameratus at the extinction level of Schackoina (Leupoldina) gracilis. The flat area in which LB3 was implanted, dated by the occurrence of G. barri, is located at the foot of disused quarries, the top of which provided few specimens of the following marker, the 10-chambered planispiral species Globigerinelloides algerianus (Cushman & ten Dam).

5.2.2. Bioevents

The studied strata include four major events which involve the almost simultaneous first occurrence and/or last occurrence of several taxa:

(1) Level of first occurrence of Schackoina (Leupoldina) gracilis cabri

Fig. 7. Bedoulian—Gargasian transition including key bed 170 at: A) Cassis-La Bédoule Comte Quarry section; B) La Bédoule Les Tocchis section (both adapted from Moullade et al., 1998a); C) hole LB1 and d) hole LB3 (this work).
The first but very rare specimens of this planktonic group are found in sample LB1-22-109 cm, at the boundary between the C3 and C4 isotopic stages. In this sample, also the first indisputable specimen of *Lenticulina cf. nodosa* is found; however, two metres below, a somewhat dubious specimen of this benthic form is already present in sample LB1-24-14 cm. *L. cf. nodosa* has actually been reported as appearing slightly earlier than *S. gr. cabri* in upper Bedoulian outcrops, such as Croagnes (Moullade et al., 2012) or Cassis-La Bédoule (Moullade et al., 1998b). These apparent slight discrepancies might result from the smaller size of core samples, thereby reducing the probability of finding rare species.
Fig. 9. Hole LB3: bulk carbon isotope, bulk oxygen isotope, carbonate content and natural gamma ray curves (measurements performed at the Institute of Geosciences of the University of Kiel, Germany). The possible Aparein shift is starred.
(2) Microfaunal turnover at the Bedoulian/Gargasian boundary.

This important bioevent is marked by the simultaneous extinction of *Globorotalites* gr. *bartensteini-intercedens* and *Lenticulina* cf. *heiermanni*, occurring with the simultaneous first appearance of *Prahedbergella luterbacheri* and *P. gr. aptiensis-solidus*. It should also be noted that the base of the acme of *Schackoina* (*Leuholdina*) gr. *cabri* is only 3 m below this quadruple datum. Incidentally, at this level *Spirillina minima* Schacko and *Patellina subcretacea* Cushman & Alexander temporarily disappear, their absence then spanning the entire lower Gargasian *Dufrenoyia furcata* Zone. We will return later to a discussion on the palaeoecological significance of these two calcareous benthic foraminifera.

(3) Microfaunal turnover at the *Dufrenoyia furcata/Cheloniceras martini* zonal boundary.
This event is located at the uppermost part of the Prae-hedbergella laterbacheri foraminiferal zone. It corresponds to the simultaneous extinction of Lenticulina cf. nodosa and Astartocapsa crepidularis tricarinella, together with the end of the acme of Schackoina (Leupoldina) gr. cabri. In addition, the ostracod marker Protocythere bedoulensis Moullade becomes extinct at this same foraminiferal level. These contemporaneous events are almost directly followed by the first occurrence of Oolina apiculata and Ramulina sp. gr. aculeata Wright.

(4) A last bioevent, which involves only two taxa, is located at the boundary between the Globigerinelloides ferreolensis heptacameratus and G. ferreolensis ferreolensis foraminiferal zones. It is characterized by the first occurrence of G. ferreolensis ferreolensis, 0.50 m below the disappearance of Schackoina (Leupoldina) gr. cabri. We will see later that the ostracod marker Parataxodontina inornata (Kaye) first occurs just below this double foraminiferal datum.

5.2.3. Zonation (Fig. 10)
On the basis of the markers distribution, the interval covered by LB1 and LB3 boreholes is divided into 6 foraminiferal biozones:

- Globigerinelloides (Blowiella) blowi zone; the first 14 m of the studied succession can be attributed to the upper part of this zone. In SE France its lower limit corresponds to the lower/upper Bedoulian boundary (Moullade et al., 1998c). The top of this zone is placed at –32 m, between samples LB1-23-65 cm and LB1-22-109 cm.
- Schackoina (Leupoldina) cabri zone; this zone equals the upper half of the upper Bedoulian, including isotopic stages C4, C5, C6 and the lower two-thirds of C7. The rather homogeneous distribution of both planktonic and benthic foraminifera during this interval does not permit a further subdivision of this 30 m thick zone.
- Praehedbergella laterbacheri zone; this first zonal subdivision of the Gargasian covers 6 m of sediment in LB3, from sample LB3-29-58 cm to LB3-25-65, 5 cm; its lower 3 m-thick part overlaps with the top of LB1. The extension of this zone corresponds to the lower half of the Dufrenoyia furcata ammonite Zone, i.e., approximately to the Dufrenoyia furcata Subzone in Reboulet et al. (2011, 2014).
- Globigerinelloides ferreolensis heptacameratus zone; initially created as a horizon (Moullade et al., 2008), this level, defined by the first appearance of the subspecies index, is here upgraded to zone. In LB3 this zone spans 8 m, from samples LB3-25-24 cm to LB3-19-80 cm.
- Globigerinelloides ferreolensis ferreolensis zone; this zone spans nearly 8 m, from samples LB3-18-77, 5 cm to LB3-14-83 cm.
- Globigerinelloides barri zone; the LB3 hole intersected slightly over 18 m of sediment attributed to this zone, from samples LB3-7-150 cm to LB3 1-10 cm.

5.2.4. Palaeoecological remarks
The composition of the foraminiferal microfauna (benthic especially) across the Bedoulian–Gargasian transition in holes LB1 and LB3 provides a number of indices that confirm the general trend of a gradual increase of paleo-water depth and pelagic biota through time. This confirms the hypotheses of Moullade et al. (1998b) and Moullade and Tronchetti (2010).

Of particular interest is the final disappearance in sample-LB1 25–52 cm, within the C3 isotopic stage, of taxa such as Conorboides spp. and small trocholinas of the infragranelata group (Fig. 3). These small neritic forms, which are present only in the lower part of LB1, are the ultimate survivors of a microfaunal inner platform assemblage, known as more abundant and more diverse (taxonomically and by the size of specimens, which may include larger orbitolinids) in the upper Barremian and lowermost Bedoulian of Cassis-La Bédoule (Moullade et al., 1998b). These shallow-water forms are also commonly found in strata that directly overlie the uppermost part of the Urgonian facies, of Bedoulian age, in the Apt basin (Moullade et al., 2012). In the lower part of LB1, Conorboides and Trocholina gr. infragranelata (Noth) are associated with abundant Patellina subcretacea, another member of the neritic assemblage mentioned above. P. subcretacea is thought to be bathymetrically more tolerant than the two others, as it occurs over a longer period of time, even though in lesser abundance, higher up in the section. As pointed out above, P. subcretacea and Spirillina minima temporarily disappear within the lower Gargasian Dufrenoyia furcata ammonite Zone. This leads us to consider this latter interval as that of the maximum paleodepth in the South Provençal Basin, because these shallower water indicators reappear higher in the Chelonierias martini Zone (Fig. 4).

An additional evidence points in the same direction. Compared to the upper Bedoulian, in the lowermost Gargasian strata the number of planktonic species as well as that of individuals of each species reach their maximum values.

5.2.5. Quantitative data (benthic foraminifera)
From outcrop samples of the Bedoulian and Gargasian stratotypic areas, Moullade and Tronchetti (2010) published abundance curves based on counts of the main species or groups of benthic foraminifera. Despite locally insufficient sample spacing, this study revealed some cyclicity in the stratigraphic distribution of the studied taxa.

As for LB1 and LB3 samples, the simple first approach of using frequency classes established during the biostratigraphic study (Figs. 3–4) reveals also a certain periodicity in the distribution of the best represented species or species groups. Moreover, there are two much more poorly microfossiliferous intervals inserted within the microfossil-rich succession:

- A 3 m-thick first sequence, from samples LB1-26-108 cm to LB1-27-158 cm, is virtually devoid of foraminiferal and ostracod microfauna. This practically barren interval corresponds to the end of the isotopic stage C2, follows a more diversified microfossiliferous interval and occurs just before the onset of OAE1a, during which the microfaunal density returns to normal values.
- A second similar interval begins at the level of sample LB1-13-65 cm, just at the boundary between isotopic stages C6 and C7, i.e., just above the top of OAE1a. This mostly barren interval spans 8 m of sediment, which corresponds to the basal portion of C7.

To obtain more accurate statistical data on this periodicity, we conducted normalized counts on a known fraction of the second half of the residue of each weighed sample (see Section 4.1.). This protocol was used to calculate the number of specimens of each taxon per gram of sample (Appendices 1–2). The >140 µm mesh for screening this fraction has emerged as the best compromise for minimizing biases of representation on a size basis. In the end, it appeared that both methods (raw frequency classes and normalized counts) produced broadly comparable results, but the latter allowed better comparisons between samples.

Tritaxia pyramidata, the group of lenticulinas (L. gr. gibbo-nuda, L. cf. nodosa, L. cf. heiermanni), the gavelinellas (G. gr. flandrinii) and falsogaudryinellas (F. moesiana and more incidentally F. tealbyensis)
are the most abundant taxa of these benthic foraminiferal assemblages. Among these forms, *T. pyramidata* showed the most pronounced cyclicity, commonly with sharp "on-off" fluctuations (Figs. 11e12). Abundance variations of lenticulinas are much less contrasted but mostly in phase with those of tritaxias. The frequency fluctuations of gavelinellas, locally strongly contrasted, are also quite consistent with those of tritaxias but may show occasionally a slight offset (Fig. 11).

These quantitative foraminiferal data provided an additional correlation tool for the overlapping portion of the two holes (Figs. 11e12). For example the position of key bed 170 (see §4.1), which was presumably identified on the basis of gamma-ray logging and lithology logs, then confirmed by biostratigraphy, is also strongly supported by the occurrence of a sharp abundance peak of tritaxias. Bed 170, which marks the Bedoulian/Gargasian boundary, is also distinguished over the whole Bedoulian underlying sequence by providing the same record value (80 benthic foraminiferal specimens per gram of dried sediment) in both holes, i.e., nearly twice that of the most productive Bedoulian levels.

### 5.3. Ostracods

This group is mainly represented in both Bedoulian and Gargasian strata by smooth long-ranging forms, among which the genus *Cytherella*, and especially *C. ovata* (Roemer) and secondarily *C. parallela* (Reuss), is the most common. The ornamented forms occur rather sporadically. Of these, three species confirm their value as biostratigraphic markers:

- *Protocythere bedoulensis*; the first occurrence of this species is recorded in the upper Bedoulian, within isotopic stage C4, and its disappearance occurs at the level of the simultaneous benthic foraminiferal HO (*Lenticulina cf. nodosa/Astacolus crepidularis tricornella*) (see §4.1.2.) (Figs. 3e4). This triple mixed datum, which involves the last occurrence of two benthic foraminifera and that of an ostracod, was already recognized in previous work on stratotypes (Moullade et al., 2005). It is confirmed here and calibrated in a more reliable context than from outcrop material. Within the first three metres of its range, i.e., the upper part of the isotopic stage C4 and the base of C5, *P. bedoulensis* is accompanied by *Hechticythere derooi* (Oertli), which does not occur higher up in LB1 cores. The somewhat erratic distribution of *H. derooi* in outcrops of the Aptian stratotypic area prevented us to retain this taxon as a marker.

- *Cytherelloidea bedouliana* (Babinot); in LB1 and LB3, this rare species only occurs in the very uppermost metres of the Bedoulian (Figs. 3e4). This confirms previous observations made at Cassis-La Bédoule (Fabre-Taxy et al., 1965) and La Tuilière (near Apt) (Babinot et al., 2007).

- *Parataxodonta inornata*; in LB3 this easily recognizable species is rare and shows a rather sporadic distribution. It has its lowest occurrence in the upper part of the *Globigerinelloides ferreolensis heptacameratus* foraminiferal zone, 1.5 m below that of *G. ferreolensis ferreolensis* (Fig. 4). However, in other places *P. inornata* has also been documented slightly lower, i.e., from the uppermost part of the *Praehedbergella luterbacheri* zone (Moullade et al., 2005: Cassis-La Marcouline; Moullade et al., 2009a, b: Gargas), but not below.

### 5.4. Calcareous nannofossils

Preservation of calcareous nannofossils is considered to be moderate to poor; specimens are often highly fragmented and show signs of overgrowth in carbonate-rich intervals indicating a slight early diagenetic overprint. The abundance of identifiable calcareous nannofossils is generally low. Most smear slides are almost barren or only few identifiable specimens have been observed. This state of preservation and the low abundance of calcareous nannofossils result in a very low diversity. Thus, the assemblages do not allow for ecological interpretations and hamper the development of a detailed, robust nannofossil-based...
biostratigraphic scheme. Therefore, we did not provide a detailed record of the nannofossil species from this study; we simply focused on the identification of biostratigraphic markers.

Calcareous nannofossil assemblages are dominated by rather dissolution-resistant forms, e.g., Watznaueria barnesiae (Black), various Rhagodiscus and Cretarhabdus species. In addition, typical common components of mid-Cretaceous nannofossil assemblages of the Tethyan region like Biscutum constans (Görka) and nannoconids were frequently found. However, most of these taxa are not of biostratigraphic importance for the studied interval.

Biostratigraphically, all samples studied from LB1 suggest an NC6 age as indicated by the sporadic occurrence of Hayesites irregularis (Thierstein). From sample LB1-20, 13–15 cm (depth in core 28 m) upwards marker species indicating NC6B occur consistently; these include Rhagodiscus angustus (Stradner), Eiffelithus hancockii Burnett and Cretarhabdus loriei (Gartner). NC7 marker species like Eprolithus floridus (Stradner) or Braarudosphaera africana Stradner have not been observed in samples from LB1.

The basal part of LB3 belongs unequivocally into NC6B, whereas the LO of E. floridus (base of NC7) has been identified in sample LB3-
32, 14–17 cm (depth 46.50 m). Because *E. floralis* is generally rare and usually poorly preserved, never more than two specimens have been identified per sample. The base of NC7B as approximated by the HO of *Micrantholithus hoschulzii* (Reinhardt) by Bergen (1998) was observed in sample LB3–30, 64–68 cm (depth 43.99 m); however, this taxon is very rare in all studied samples questioning its application as a marker species. An abundance increase of *Nannoconus truitti* in section 26 and above may indicate the widely-distributed "*Nannoconus truitti* (Brönnimann) acme" which starts within NC7B (Bown et al., 1998; Herrle & Mutterlose, 2003).

The nannofossil results strongly contrast with the findings based on planktonic foraminifera and gamma-ray wiggle matching between boreholes as well as regional correlation with outcrops. Specifically, the NC6/7 boundary has not been observed in LB1, where it is expected to be due other stratigraphic techniques. In LB3 the LO of *E. floralis* is slightly lower, specifically when compared to biostratigraphic results from outcrops close to the drill sites (Bergen, 1998).

As a consequence of the scarcity and the suboptimal preservation, calcareous nannofossil zonal boundaries drawn in Figs. 3–4, 9 and 13, are not strictly derived from this study. To define these boundaries we usually considered the results previously obtained from field studies (Bergen, 1998) to be more reliable. These data have been previously integrated into a stratigraphic framework which also included data from foraminifera, ostracods, ammonites and carbon isotopes. Further, we refrain from a detailed discussion of the nannofossil results.

### 5.5. Carbon isotope stratigraphy

The first bulk-rock carbonate δ¹³C and δ¹⁸O curves from Bedoulian field samples of Cassis were published by Kuhnt et al. (1998) and Moullade et al. (1998d). Even though sparse due to discontinuous outcrops, sampling of the middle part of the section permitted for the first time delineation of the main δ¹³C shift and identification of OAE1a signature in the South-Provençal Basin. However, this insufficient sampling density hampered the reliable identification of detailed isotopic stages as defined by Menegatti et al. (1998). Kuhnt and Moullade (2007) then extended the Bedoulian curve into the lower part of the Gargasian in La Marcouline quarry section, also at Cassis (Fig. 1).

In order to better document the middle part of the Bedoulian, Kuhnt et al. (2011) published a high resolution record based on a much denser sampling (5 cm increments) carried out in the La Béduole Camping section (Fig. 1). Their curve defined the isotopic stages C4 to C6 in great detail, allowing subdivision of stage C4 into four sub-stages (C4a, b, c, d) for the first time. Another important result of this work was to isotopically calibrate the *Schackoina cabri* lowest occurrence with the C3/C4 boundary. Isotopic δ¹³C and δ¹⁸O measurements have also been performed (in 20 cm increments) on LB1 (Fig. 13) and LB3 (Fig. 9) cores. LB1 records isotopic stages C2 to C7 in great detail (Lorenzen et al., 2013), providing a δ¹³C reference curve for the Bedoulian based on a continuous and dense sampling. Curves from La Béduole area are compared with those of Rotter Sattel, Switzerland (Menegatti et al., 2011).
et al., 1998), Cismon, Italy (revision by Li et al., 2008) of data from Menegatti et al., 1998; Erba et al., 1999) and Cuchia (Spain, Najarro et al., 2011) (Fig. 5).

LB3 records almost all of stage C7 (the missing part being only its extreme base, not reached by the drilling) and a large part of stage C8. The well identifiable boundary between C7 and C8 is located at ~30 m, 4 m below the first occurrence of the planktonic foraminiferal subspecies Globigerinelloides ferreolensis ferreolensis. By correlation between the distribution of foraminifera in LB3 (this work) and in La Marouline section (Moullade et al., 2005), the latter also calibrated by ammonites (Ropolo et al., 2008), it is possible for the first time to locate the C7/C8 boundary within the Cheloniceras martini ammonite Zone, more specifically at the level of the Epicheloniceras gracile Subzone.

We have also tried to look for the possible isotopic signature of the “Aparein” Aptian organic-rich level in the Bedoulian stratotypic area. This level was first known from the Cantabrian region of Spain (Garcia-Mondejar et al., 2009) and thought to be a subevent of OAE1 or of local occurrence (Million et al., 2009) on the basis of a thin negative δ13C shift. Since then, this event has been assumed to occur within stage C7 in several other sections of various regions of Spain, such as the Betic Cordillera (Núñez-Useche et al., 2014).

In fact the δ13C curve obtained at Cassis by Kuhnt et al. (1998) shows a clear negative shift of 1.28‰ at its upper end, exactly at the level of bed 174. This bed is located ~2.5 m above the top of the key bed 170, in the first few metres of the ammonite Dufrenoyia furcata Zone. This stratigraphic assignment is consistent with the Spanish context, which also involves the D. furcata Zone (Núñez-Useche et al., 2014).

However, the isotopic δ13C signature within the first few metres of LB1 hole (Fig. 13) is much less clear than in the Cassis section. Just above bed 170, the LB1 curve shows a pattern of several narrow successive oscillations, the most ample of which (at ~2 m) is a negative shift of only 0.8‰ at the level of bed 173, 1.8 m above the top of bed 170.

The same zigzag pattern is seen in LB3 (Fig. 9), but with a maximum negative shift of only 0.58‰, at ~41 m, i.e., also 1.8 m above bed 170.

Therefore, if present in the stratotype area, which seems likely at the Cassis field section, the “Aparein-like” isotopic shift appears to be much less conspicuous at La Bédoule, where the succession is slightly more condensed than at Cassis. Based on the distribution of foraminifera, this isotopic feature can be correlated with the extinction of the benthic foraminifera Lenticulina cf. heiermanni. Although very tenuous in the Bedoulian stratotype, this isotopic event might permit subdivision of the long stage C7 into approximately two equal parts, as already suggested by Núñez-Useche et al. (2014).

6. Discussion

6.1. Bioevents

Once more we would like to draw the reader’s attention to certain errors and approximations, resulting in apparent dia-chronisms that deal with several of the main Aptian planktonic foraminiferal datums.

Globigerinelloides ferreolensis first appearance. This bioevent is often mistakenly used in the literature as a marker of the boundary between the two subdivisions of the Aptian, i.e., the Bedoulian/Gargasian boundary. All our previous work shows that the first appearance of this species is located higher than this limit. The misplacement often results from erroneous attributions to G. ferreolensis of its ancestor, the 7-chambered low trochospiral species Praehedbergella luterbacheri. An evolutionary transition occurs between the two taxa in the lowermost Gargasian. More weakly trochospiral specimens become increasingly sub-symmetric going up in the succession; some intermediate specimens gradually make the transition towards more conspicuously planispiral forms (Banner & Desai, 1988). These latter only have to be placed within the G. ferreolensis group (see also Moullade et al., 2005, Pl. 4, figs. 7–9). Errors of diagnosis of these weakly asymmetrical transients may be aggravated because of poor preservation and/or insufficiently cleaned specimens. Therefore there is room left for a Praehedbergella luterbacheri zone between the boundary and the actual G. ferreolensis FAD, as shown in the present work.

- Schackoina (Leupoldina) gr. cabri first appearance. It begins to be more widely recognized that the first occurrence of the morphotypes (pustulans, cabri s. s.) of this planktonic foraminiferal group, which are easily identifiable by their elongate bulb-shaped chambers, is contemporaneous with the OAE1a. Our results (Kuhnt et al., 2011; Lorenzen et al., 2013; this study) show that this bioevent occurs more precisely at the C3/C4 isotopic boundary. However, the scarcity and the small size of these forms in the lower part of their range may explain many discrepancies in the calibration of this bioevent as seen in the literature.

- Larger Globigerinelloides lineage. The accurate delimitation of the successive zones based on the distribution of larger multi-chambered species of Globigerinelloides (ferreolensis heptacameratus, ferreolensis ferreolensis, barri, algerianus) implies that all specialists speak the same taxonomic language. The original criterion of species differentiation within this planispirally coiled planktonic foraminiferal lineage is — and should always be — based only on the number of chambers in the last whorl (see review in Moullade et al., 2005, 2008).

6.2. Microfaunal cyclicity

Patterns of the abundance curves of tritaxias

In their preliminary study of the distribution of Aptian stratotypic benthic foraminiferal microfauna, Moullade and Tronchetti (2010) hypothesized a cyclic forcing of orbital type to explain the synchronous fluctuations in abundance of these organisms. Their hypothesis was in line with other studies involving, among others, the Cenomanian (Leary et al., 1989; Paul, 1992) or the Upper Albian (Coccioni & Galeotti, 1993; Tyszka, 2009). However, in order to validate their interpretation, the authors stressed the need to resume such work on the basis of a denser sampling of the Aptian stratotypic succession. With about 100% core recovery, holes LB1 and LB3 therefore constituted a material of choice for performing this kind of investigation. It seemed to be an interesting possibility, after calibration, to use these micropaleontological quantitative data as a kind of “biological” geochronometer.

For this purpose, counts of specimens of Tritaxia pyramidata appeared to be the best tool. This long-ranging benthic agglutinated species is fairly large (mean size of ±250 μm), easy to identify with its tricarinate perimeter, and emerged as the most responsive taxon by its abundance variations. On the basis of the variations of abundance curves of tritaxias, a marked contrast appears between the upper Bedoulian and the lower Gargasian (Fig. 12):

- Bedoulian

Two successive intervals can be defined, according to the pattern of their constitutive cycles (Fig. 12):
- From ~45 m to ~14 m in LB1, the fluctuations of distribution of tritaxias are clear, regular and mostly on/off. The main peaks allow a subdivision of this first interval into four regular first-order cycles with a wavelength of about 7 m. This long period of stability corresponds to a set of strata including the entire OAE1a and the lowermost portion of the ammonite Deshayesites grandis Subzone.

- Conversely the overlying sequence (from ~14 m to ~4 m in LB1, ~51 m to ~43 m in LB3) shows a more uneven distribution, somewhat arhythmic, with tighter and more pronounced secondary oscillations. It is unclear whether this interval, which corresponds to the upper part of the D. grandis Subzone and ends with bed 170, consists of one or two cycles. In the case of a two-fold subdivision, the pattern of a lower 6 m thick cycle (5a) recalls that of the underlying cycles 1 to 4, whereas an upper 4 m thick cycle (5b) differs by more prominent and progressively increasing second order peaks of tritaxias.

- **Gargasian**
  - Above bed 170, from ~43 m to ~37 m in hole LB3, the sequence consists of a well-defined 6 m-thick unique cycle (n° 6), which shows a pattern reminiscent of that of the Bedoulian cycles 1—4. This cycle 6 spans the lower part of the Dufrenovia furcata Zone. Only the 3 m-thick lower portion of cycle 6 is present at the top of hole LB1.
  - The pattern of the remaining part of LB3 (from ~37 m to the top of the hole) significantly differs from those of the underlying strata and its subdivision into first and second order cycles is less clear. In a first approach, this interval can be tentatively divided into two parts:
    - from ~37 m to ~27 m, occurs a 10 m-thick cycle (n° 7) well-bound by two marked peaks of abundance (>350 specimens) of tritaxias; this cycle is in turn clearly divided into five regular ± 2 m thick subcycles.
    - the last interval, from ~27 m to the top of hole LB3, shows less regular oscillations (in wavelength and values) than those seen in cycle 7. Thus the subdivision of this thicker interval is hard to establish logically (how many main cycles?) and is made still more complicated by the fact that the sequence is interrupted by the top of the hole.

- **Attempt of interpretation**
  To be able to interpret the variations shown by the abundance curves of tritaxias in terms of orbital forcing we have to use time estimates published in the literature. Considering the strong dissimilarity between the Bedoulian and the Gargasian patterns, these estimates have to be specific.

- **Bedoulian** 1 to 4 cycles (including OAE1a)
  It is possible to calibrate most of the upper Bedoulian main cycles by using recently published estimates of the duration of OAE1a, which are of 1.1 myr by Malinverno et al. (2010), 1.5 myr by Ogg and Hinnov (2012) and 1.36 myr by Scott (2014). In hole LB1, OAE1a is 20 m-thick, i.e., 55—75 kyr per metre of sediment, depending on the duration retained for the anoxic event. On this basis, the ~7 m thick tritaxias cycles observed in the interval enclosing the anoxic event will range from 385 to 525 kyr, i.e., within the range of long 405 kyr eccentricity cycles.
  Assuming that the sediment accumulation rate remained constant during cycles 1 to 4 and that the ~7 m-thick tritaxias cycles are actually orbitally triggered, we can calculate a duration of
  \[ \text{405x20/7 = 1.157 myr for OAE1a, close to that proposed by Malinverno et al. (2010).} \]
  The uniform 1 m routine sampling in LB1 has not been dense enough at this level for a clear recording of smaller scale cycles, corresponding to the other orbital parameters (precession, obliquity or even short eccentricity mode).

- **Uppermost Bedoulian n° 5 cycle**
  The question arises to know whether this section comprises one or two long eccentricity cycles. The latter hypothesis implies a minimum (80 kyr/m) of sediment accumulation rate at the level of 5b.

- **Gargasian**
  The Gargasian patterns are much less easy to decipher than the Bedoulian ones. Based on a spectral analysis of Gargasian sedimentary rhythms in La Marcouline section at Cassis, located 2 km southwest of drill site LB3, Kuhnt and Moullade (2007) showed significant frequency peaks with a wavelength of about 1 m that they attributed to the precession (circa 20 kyr), and much longer cycles with wavelength of 20 m, related to the long 405 kyr eccentricity cycles. It should seem relevant to transpose these results to the Gargasian of La Bédoule, assuming a comparable sediment accumulation rates in these two very close locations. Thus, applying the Kuhnt and Moullade (2007) calculations, a Gargasian sediment accumulation rate of 20 kyr/m in Cassis and La Bédoule appears to be about 3.5 times higher than during the late Bedoulian OAE1a (55—75 kyr/m, see above), or even 4 times higher than in the latest Bedoulian, in the hypothesis of a two-fold subdivision of cycle 5.

On the basis of the position of the ‘Triplet’ kyr-level in the La Marcouline quarry (Kuhnt & Moullade, 2007, figs. 2 & 8) and in LB3 (Fig. 12), we can attribute the 20 m thick interval beginning 2 m below the Triplet in LB3 (say hypothetically cycle n° 8) to a 405 kyr long eccentricity cycle. Below the Triplet there is the better delineated but only 10 m thick cycle 7. Assuming that it also corresponds to a long 405 kyr long eccentricity cycle would imply a lower sediment accumulation rate of 40 kyr/m at this level (instead of 20 kyr/m in cycle 8), and that the second order oscillations seen within this cycle 7 might correspond to the obliquity. The ~6.5 m thick cycle 6, the pattern of which is very similar to that of the 405 kyr well-calibrated Bedoulian cycles 1 to 4, is likely to have the same duration.

These calculations lead to a model of low sediment accumulation rate during the late Bedoulian, towards a maximum of sedimentary condensation at the level of the uppermost Bedoulian cycle 5b, followed by progressively increasing rates during the early Gargasian.

A recent paper of Ghirardi et al. (2014) may provide additional ways to verify our attempts of interpreting the Gargasian curve.

- Based on an orbital calibration of the Serre Chaïteau section in the Vucovician basin, these authors proposed a duration for lower Gargasian biozones (Globigerinoides ferreolensis: 1.22 myr, Dufrenovia furcata: 0.6 myr) and the isotopic stage C7 (2.03 myr). If we apply these values to the thicknesses measured for these units in holes LB3/LB1, we obtain a sediment accumulation rate of 36.3 kyr/m for the section based on D. furcata duration; this is rather consistent with our calculation derived from the hypothesis of cycles 6 and 7 being long eccentricity cycles.

Kuhnt and Moullade (2007) showed also that the G. ferreolensis zone at Cassis spans 33 precessional cycles and its duration is thus estimated to be approximately 0.76 myr (1.22 myr at Serre Chaïteau according to Ghirardi et al., 2014, instead). It is important to note that all these authors used a broad concept of the G. ferreolensis zone which includes the G. ferreolensis heptacameratus, G. ferreolensis ferreolensis and G. barii zones as defined in the present article, i.e., 36 m of sediment in La Marcouline section at Cassis. In hole LB3, the G. ferreolensis group first occurs at a depth of ~36 m and spans at least the remaining part of the hole. However, the equivalent of the past G. ferreolensis zone (used by Kuhnt & Moullade, 2007; Ghirardi et al., 2014) cannot be precisely identified in LB3, since the zonal upper boundary (lowest occurrence of G. algerianus) was not reached by the drilling but should have been very close. Considering our calculated durations of cycles 7 and 8
(0.8 myr together), added to an estimate of ~0.12 myr for the lower part of cycle 9 (assuming that the complete cycle is a long eccentricity cycle as n° 8), the duration of the G. ferreolensis ‘long’ zone in La Bédoule should be of at least 0.92 myr. This value is intermediate between those proposed by Kuhn and Mouladé (2007), i.e., 0.76 and Ghirardi et al. (2014), i.e., 1.22.

Using the same method of calculation for the isotopic stage C7 (lower limit at ~18 m in LB1, upper limit at ~30 m in LB3, i.e., a total thickness of ~27 m):

\[ C7 = \frac{14}{7} \text{cycle 4 + 1 cycle 5a + 1 cycle 5b + 1 cycle 6 + 2/3 cycle 7} \times 0.4 \text{ myr} = 4.238 \text{ cycles} \times 0.4 \text{ myr} = 1.695 \text{ myr} \]

led to a 1.7 myr maximum of duration, with a two-fold subdivision of cycle 5, i.e., less than the 2.03 myr proposed by Ghirardi et al. (2014).

In conclusion, using raw abundance curves of tritaxias can help identify 405 kyr long eccentricity cycles in the type-Bedoulian, which leads to assume a duration of 1.157 myr for OAE1a. However, more sophisticated ways of analysis (for instance spectral) are needed for a possible use of this tool towards a better detailed cyclostratigraphy, particularly in the Gargasian. Our approach led also to suspect a marked contrast in sediment accumulation rates from the upper Bedoulian to the lower Gargasian at Cassis-La Bédoule, with a maximum of condensation in the topmost Bedoulian.

6.3. Geological importance of the Bedoulian stratotype

Over the last decades the development of concepts in defining stratigraphic boundaries led to an underestimation of the role of historical stratotypes in favour of a concept of benchmarks (GSSP) focused on defining each stage by its base. This perspective has promoted a search for new reference sections, that supposedly overcome the deficiencies and inconsistencies arising from incomplete stratotypic type sections.

As for the Aptian, two drill cores in the northern Tethys have been recently highlighted as references sections. At Cismon (NE Italy, where “Apticore” was drilled; Erba et al., 1999), Li et al. (2008) wrote “The 100% core recovery and existing high-resolution data render APTICORE the highest quality reference section for OAE1a”. More recently the Poggio le Guaine core (near Piobbico, Umbria-Marche Basin, N. Apennines, Italy), “can be considered as a reference section for the Aptian-Albian interval at low latitudes” according to Coccioni et al. (2012).

However, it should be noted that OAE1a, a well-recorded event by drilling at La Bédoule, is there represented by 20 m of sediment, but is only 5.2 m thick at Cismon and 1.95 m at Poggio le Guaine. Therefore, the Bedoulian stratotype offers more favourable conditions for high-resolution studies than the Italian localities; the condensation of these sections may even result in the loss of signal because of gaps in the record.

The Vocontian Basin, likewise, cannot constitute a reference area for the interval that spans OAE1a and the Bedoulian/Gargasian transition. From the works of Herrle and Mutterlose (2003), Herrle et al. (2004, 2010), and Heimhofer et al. (2006) it appears effectively that the Vocontian mid-Aptian succession is very condensed or even incomplete. The black shales (“niveau Goguel”) (=OAE1a), which overlie disconformably the Barremo-Bedoulian limestones and span isotopic stages C4 (pro parte) to C6, are only 3 m thick in the section of Serre-Chaîtieu, which was considered as a reference by the authors. In contrast the OAE1a interval is 20 m thick at Cassis-La Bédoule, where a more detailed isotopic curve was documented.

Aptian sections in several areas of Spain (Cantabric, Subbetic, Prebetic, eastern Iberian chain) have been studied in detail these last years using ammonite biostratigraphy and carbon isotope stratigraphy (García-Mondéjar et al., 2009; Milán et al., 2009; Najarro et al., 2011; Moreno-Bedmar et al., 2012; Gaona-Narvaez et al., 2012; Quijano et al., 2012; Aguado et al., 2014a,b). Some of these sections might be considered as references if a certain number of problems are solved, such as rare micropaleontological data, strong differences of ammonite identification between specialists (Moreno-Bedmar et al., 2014), and poorly or too discontinuously fossiliferous sections unfavourable for high resolution stratigraphic studies.

Following the pioneering review of Mutterlose and Böckel (1998) and study of Bischoff and Mutterlose (1998), within the last decade a bundle of holostratigraphic work (Lehmann et al., 2012; Heldt et al., 2012; Weiβ, 2012; Bottini & Mutterlose, 2012) has been published for the Aptian of the Boreal Realm (mainly N. Germany, Saxony Basin). These studies confirm that the dark “Fischschiefer” shales correspond to most of OAE1a. However, correlations with the Tethyan domain still remain imperfect, because in the Boreal Realm the biostratigraphic elements that are available in SE France for accurate dating (ammonites, planktonic foraminifera, even calcareous nannofossils) are rare and not always as significant because communications between the two areas were only progressively established during the Aptian.

Thus, the regional geological context is in favour of SE France Aptian stratotypes as references. There, drill hole data such as those provided by Lorenzen et al. (2013) and in this paper add to previously published field work in Cassis-La Bédoule and Apt areas, which constitutes a considerable amount of information on the Bedoulian and Gargasian high-resolution holostratigraphy. The corpus of available data allows, better than anywhere else, a high-resolution calibration of global events registered during this period.

7. Conclusion

Results obtained by our high-resolution stratigraphic study of the two drill holes at La Bédoule supplement previous field work carried out over the last two decades. Here we present for the first time a detailed and continuous upper Bedoulian to lower Gargasian lithostratigraphic record put in parallel with an updated microfaunal zonation. The latter is based on a succession of foraminiferal events, calibrated with ammonites that are recognized in both stratotypic areas of Apt and Cassis-La Bédoule. Some species of ornamented ostracods can also be used as additional markers.

This biostratigraphic framework can also be put in conjunction with a detailed isotopic chemosтратigraphy, which shows that the La Bédoule cores offer one of the best worldwide records of the OAE1a global event and provide a reference curve for the succession of isotopic stages C2 to C8. It is also possible that the Cassis-La Bédoule area recorded, though less obviously, the very short negative isotopic shift of the ‘Aparin level’ so far only detected clearly in the Aptian of Spain. By correlating data from drill cores and stratotypic field sections, it is now possible to precisely locate this brief event in the Cassis-La Bédoule area at the base of the Dufrenoya furcata (ammonites) and Praehedbergella luterbacheri (planktonic foraminifera) zones. This shift allows subdivision of the long isotopic stage C7 in two subequal parts, which potentially represent an additional chemosтратigraphic proxy for the definition of the Bedoulian/Gargasian boundary.

In the stratotype, this boundary is fixed at the top of bed 170 and corresponds to the quasi-simultaneous occurrence of the following events:

- Chemostratigraphy = ‘Aparin’ level,
- Calcareous nannofossils = NC6/NC7 zonal boundary,
- Planktonic foraminifera = first appearance of 7-chambered trochospiral forms (Praehedbergella luterbacheri),
The database available, enriched by our results from LB1/LB3 drill cores, encourages us to initiate a proposal that the Cassis-La Bédoule area is a potential candidate for a GSSP of the base of the Gagarinian substage or, in the alternative current classification, to reiterate our proposal (Moullade et al., 2011) of this locality for a GSSP of the Aptian [senso d’Orbigny, 1840] stage.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cretes.2015.03.004.