# The base of the Zigzag Zone in the Ravin du Bès Section (Bas-Auran, Subalpine Basin, SE France) as the GSSP for the base of the Bathonian Stage

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## Abstract

The Global Boundary Stratotype Section and Point (GSSP) for the base of the Bathonian Stage is proposed at the base of limestone bed RB071 (bed 23 in Sturani 1967) in the Ravin du Bès Section (43º57'38''N, 6º18'55''E), Bas-Auran area, in the Chaudon-Norante commune, around 25 km at the South-Southeast of Digne-les-Bains, in the "Alpes de Haute Provence" French department. The Ravin du Bès Section, as formal candidate GSSP for the base of the Bathonian Stage, satisfies most of the requirements recommended by the International Commission on Stratigraphy (ICS): 1) The exposure extends over 13 m in thickness, comprising more than five metres of fossiliferous levels below and above the boundary. The Bathonian basal bed corresponds to the "Marno-calcaires à *Cancellophycus*", is located 7.8 m below the "Terres Noires" Formation and forms part of a transgressive-facies cycle. At the Bajocian-Bathonian transition, no vertical (bio-, ichno- or tapho-) facies changes, stratigraphic gaps or hiatuses have been recorded. There is no evidence of taphonomic condensation (i.e. mixture of fossils of different age or different chronostratigraphic units). Structural complexity, synsedimentary and tectonic disturbances, or important alterations by metamorphism are not relevant constraints in the Bas-Auran area. 2) There is a well-preserved, abundant and diverse fossil record across the boundary interval, with key markers (ammonites and nannofossils) for worldwide correlation of the uppermost Bajocian and Lower Bathonian. The boundary can be characterized by both primary and secondary (auxiliary) biostratigraphic markers. The section appears to be suitable for biostratigraphic study of microfossils, such as foraminifera, but as yet there are no published studies. The base of Bathonian Stage and Zigzag Zone in Bas-Auran corresponds to the first occurrence level of *Gonolkites convergens* Buckman and the renewal of parkinsonids. This level coincides with the first occurrence of *Morphoceras parvum* Wetzel. Calcareous nannofossils, as secondary global marker, are present in all beds, enabling documentation of the Bajocian-Bathonian transition. 3) Regional analyses of sequence stratigraphy and manganese chemostratigraphy are available. Spectral gamma-ray data corroborate interpretation of an Early Bathonian deepening half-cycle of second order. No data are currently available for strontium isotope ($^{87}Sr/^{86}Sr$ ratio), oxygen isotope ($\delta^{18}O$) or carbon isotope ($\delta^{13}C$) chemostratigraphy. Bajocian and Bathonian deposits have been remagnetized with a steady normal polarity. Volcanogenic deposits suitable for direct radio-isotope dating are not known in the section. 4) The criteria of accessibility, conservation and protection are assured by the "Réserve Naturelle Géologique de Haute Provence", protected under national law as recognised by UNESCO. The Cabo Mondego Section (Portugal), which provides complementary data on the ammonite succession in the Sub-Mediterranean Parvum Subzone and its chronocorrelation with the Northwest European Convergens Subzone, is suggested as the Bathonian auxiliary section and point (ASP) within this GSSP proposal.

Key-words: Bathonian Working Group, chronostratigraphy, biostratigraphy, geochronology.

## Introduction

The Bathonian Working Group (BtWG) was established in 1984, during the 1st International Symposium on Jurassic Stratigraphy in Erlangen, in order to improve the geologic data relative to the Bajocian/Bathonian boundary. The Bas-Auran section was first proposed as stratotype in a presentation to the Luxembourg II (1967) Colloquium by Torrens, but not published until 1974 (Morton 1974; Torrens 1974a, b, 1987, 2002). This section was formally proposed as a candidate for the basal boundary stratotype of the Bathonian Stage by Innocenti *et al.* (1990) during the 2nd International Symposium on Jurassic Stratigraphy in Lisbon (1987). Over the following 20 years, several meetings have been organized by the Bathonian Working Group in Digne, La Palud, Budapest, Lyon and Torino. In the Bas-Auran area, the sections of Ravin du Bès, Ravin d'Auran and Ravin des Robines have been remeasured and recollected for taphonomic, sedimentologic and palaeoichnological analyses during 2006 and 2007. Reports from the Bathonian Working Group have been published by Mangold (from 1985 to 1999) and Fernández-López (from 2003 to 2007) as mentioned in Fernández-Lopez (2008). Over all these many years, no other candidate section (except Cabo Mondego) was judged worthy of consideration.

The present dossier, proposing the GSSP for the Bathonian Stage at the base of the Zigzag Zone in the Ravin du Bès Section, has been developed by several specialists and members of the Bathonian Working Group. The proposal has been submitted for voting to all members of the Bathonian Working Group (S.R. Fernández-López, convenor). The members of the Bathonian Working Group are: Alméras Y. (France), Bardhan S. (India), Bodergat A.M. (France), Callomon J.H. (UK), Cresta S. (Italy), Dietl G. (Germany), Dietze V. (Germany), Enay R. (France), Fernández-López S.R. (Spain), Galácz A. (Hungary), Hall R.L. (Canada), Henriques M.H. (Portugal), Hillebrandt A. von (Germany), Lanza R. (Italy), Mangold C. (France), Matyja B. (Poland), Meléndez G. (Spain), Mitta, V. (Russia), Mönnig, E. (Germany), Morton N. (France), Page K. (UK), Pandey D.K. (India), Pavia G. (Italy), Poulsen N. (Denmark), Poulton T.P. (Canada), Riccardi A.C. (Argentina), Rogov M.A. (Russia), Sandoval J. (Spain), Schlögl J. (Slovak Republic), Schweigert G. (Germany), Seyed-Emami K. (Iran), Wierzbowski A. (Poland), Yin J.-R. (China). The results of the vote (December 2007) were as follows: Total BtWG members = 33, YES votes = 31 (93.94%), NO votes = 1 (3.03%), ABSTAIN = 1 (3.03%), NO RESPONSE = 0. This dossier summarizes relevant results published by specialists, and incorporates comments and responses of the BtWG ballot 2007, in order to achieve the formal ballot on the proposal of the GSSP for the Bathonian Stage within the International Subcommission on Jurassic Stratigraphy.

## **Definition of the base of the Bathonian Stage** (S.R. Fernández-López)

The Bathonian is the third of the four stages of the Middle Jurassic Series, above the Bajocian and below the Callovian. The name was introduced by d'Halloy (1843) and used as a stage by d'Orbigny (1850, pp. 607–608; 1852, pp. 491–492), derived from the "Bath Oolite", in the vicinity of the city of Bath (SW England). *Zigzagiceras zigzag* (d'Orbigny 1846, p. 390, pl. 129, figs. 9–10; Arkell 1958, p. 177, text-fig. 60, 1–3) and *Gonolkites convergens* Buckman (1925, pl. 546 A-B; Arkell 1956, pl. 18, fig. 8; pl. 19, figs. 1–2) are the index species, respectively, of the Bathonian basal zone and subzone. The Zigzag Zone was distinguished from the underlying Parkinsoni Zone by Oppel (1857, p. 579), and later assigned to the "Bath-Gruppe" (Oppel 1865, p. 309) in a discussion of the section at "Montagne de Crussol" in the Ardèche (France). The Convergens Subzone was mentioned by Maubeuge (1950, p. 4), based on the "Convergens horizon" that was used in letters by Arkell (1951–59, p.10; 1956, p. 62). The Bajocian/Bathonian boundary established between the Parkinsoni and Zigzag zones was recommended at the two congresses called "Colloque du Jurassique" held in Luxembourg (Rioult 1964; Torrens 1965, 1974a, b). The localities of Bath (England) and the "Montagne de Crussol" (France), however, were considered unsuitable for a typological definition of the Bathonian Stage, because they are condensed sections with discontinuous and lenticular beds (Torrens 1974a, b, 2002; Page 1996b). Following the publication of Sturani (1967), the base of bed 23 in the Bas-Auran section, in which *Gonolkites convergens* Buckman, *Parkinsonia pachypleura* Buckman and *Morphoceras parvum* Wetzel first appear, was designated as the type locality at which to define the base for the Convergens Subzone of the Zigzag Zone and the base of the Bathonian Stage by several authors (Morton 1974; Torrens 1974, 1987; Harland *et al.* 1982). Later, there was general agreement among Bathonian specialists that the Bathonian Stage should start with the Standard Zigzag Zone, whose base is defined by the Convergens Subzone (Horizon 1 of Mangold 1984) followed by the Macrescens Subzone (Sturani 1967). The Parvum Subzone was proposed by Mangold (1990) to denote the first Bathonian subzone of the Zigzag Zone in the Sub-Mediterranean Province, equivalent to the Convergens Subzone of the Northwest European Province and below the Macrescens Subzone. Analogously, due to palaeobiogeographical changes, the Dimorphitiformis Subzone was proposed by Sandoval (1983) as the basal Bathonian subzone of the Zigzag Zone in the Mediterranean Province. Therefore, placing the basal boundary of the Bathonian at the base of the Northwest European Convergens Subzone of the Zigzag Zone can be justified because this is well preserved and recorded also in the Bas-Auran area, as is the Sub-Mediterranean Parvum Subzone. The bases of the zones can be precisely correlated (Fernández-López *et al.* 2007, Pavia *et al.* 2008).

## The Ravin du Bès Section (Bas-Auran area)

The Bas-Auran sections are located in southeastern France, in the "Alpes de Haute Provence" French Department, in the Chaudon-Norante commune, approximately 25 km SSE of Digne-les-Bains (Fig. 1). Three sections have been selected in two ravines (Fig. 2). The first is the Ravin du Bès Section (RB), located near the l'Amata farm (coordinates: 43º57'38''N, 6º18'55''E, altitude 730 m). The second is the Ravin d'Auran Section (RA), located in front of the Bas-Auran farm (coordinates: 43º57'29''N, 6º19'00''E, altitude 790 m). The third, the Ravin des Robines Section (RR), is only 400 metres south of the RA section, along the Robines ravine (coordinates: 43º57'09''N, 6º18'50''E, altitude 830 m). All are located on the Castellane sheet of the "Carte géologique détaillée de la France" at the 1:80000 scale (Goguel 1966), on the Digne sheet of the "Carte géologique de la France" at the 1:50000 scale (Graciansky *et al.* 1982) and on the topographic sheet, scale 1:25000, Barrême, nº IGN 3615.

These sections, which are free of significant disconformities, range from the Bomfordi Subzone (Parkinsoni Zone, Upper Bajocian) to the Tenuiplicatus Subzone (Aurigerus Zone, Lower Bathonian) and are over 13 m thick. Structural complexity, synsedimentary and tectonic disturbance, or significant alterations by metamorphism, are not relevant constraints in the Bas-Auran area.

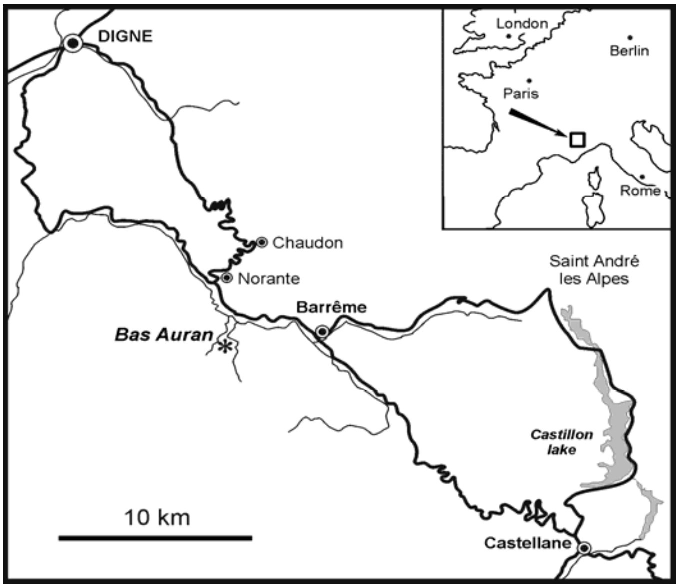


*Fig. 1.* Geographic location of the Bas-Auran area (France).

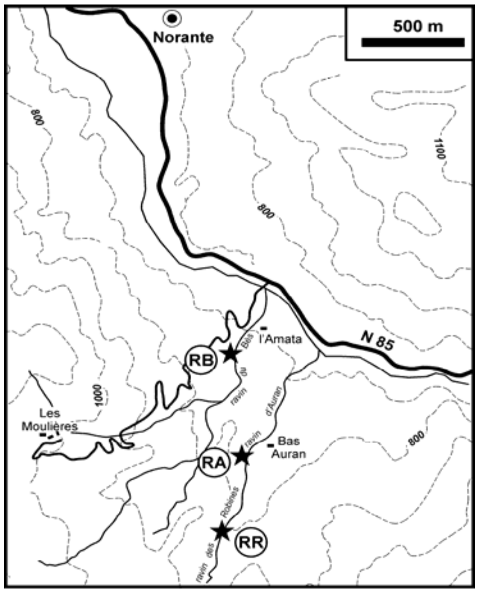


*Fig. 2.* Topographic sketch of the Bas-Auran area and location of the stratigraphic sections.

## History of research on the Bathonian succession of the "Alpes de Haute Provence" and in particular of the Bas-Auran area (G. Pavia)

The Digne-Barrême area was noted by various authors as one of the most important in the world for establishing the ammonite zonal succession of the Bathonian Stage (Garnier 1872; Haug 1891, p. 80; Guillaume 1938; Arkell 1956, p.149). The Bas-Auran locality was first mentioned by Haug (1891) and later visited by the French Geological Society (Zurcher 1895). Sturani published in 1967 a detailed study of the Bajocian-Bathonian succession with a litho- and biostratigraphical log based on all the outcrops in the Bas-Auran area. A partial revision of Sturani's work by Torrens (1987) was mainly on the Tenuiplicatus Subzone in the uppermost part of the marly-calcareous succession. Contributions on the lowermost Bathonian beds were later presented by Innocenti *et al.* (1990), inserting into Sturani's log new material derived from fieldwork over ten years. More recent sampling, mainly concentrated on poorly documented and critical intervals, enlarged the Bas-Auran database from the Zigzag Zone, and furnished new and complementary results on the taphonomy of the ammonoid fossil-assemblages (Fernández-López 2007), as well as on the taxonomy and phylogeny of Bathonian Bigotitinae and the origin of Zigzagiceratinae (Fernández-López *et al.* 2007). More recently Pavia *et al.* (2008), have: 1) Described the successive ammonoid assemblages of the uppermost Bajocian and lowermost Bathonian in the Bas-Auran area; 2) Refined the subzonal biostratigraphic subdivision of the marly-calcareous succession; 3) Detailed the ammonoid content of the very base of the Zigzag Zone; 4) Demonstrated the general continuity of the ammonoid succession; 5) Attested to the suitability of one of those sections to be selected as the GSSP of the Bathonian Stage.

## **Geological setting of the marly-calcareous succession from the Bajocian to Bathonian in the Digne area** (D. Olivero & G. Pavia)

The area studied is located in the French Subalpine Basin (FSB), corresponding to a gulf on the northwestern margin of the Tethyan Ocean (Fig. 3).

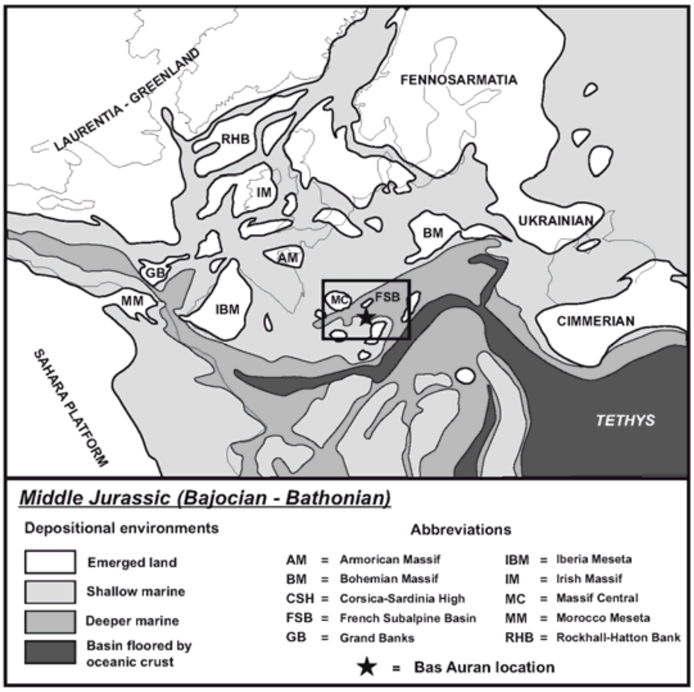


*Fig. 3.* The northwestern margin of the Tethyan Ocean, with location of the French Subalpine Basin (modified from Ziegler 1999).

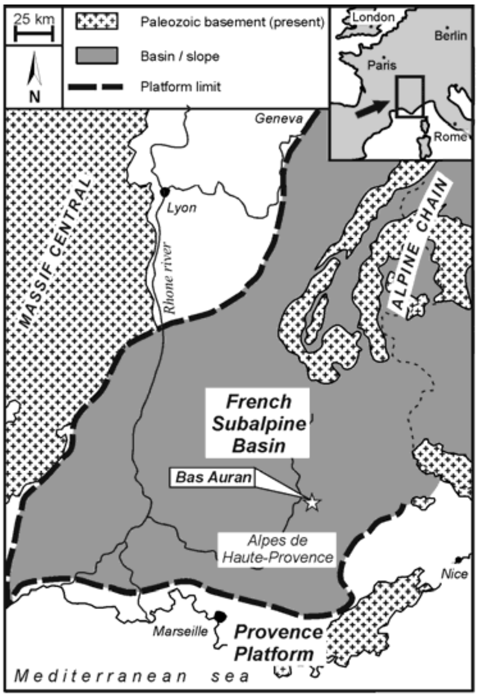


*Fig. 4.* The French Subalpine Basin, with the location of the Bas-Auran area (from Olivero 2003, modified).

The basin is bordered by the "Massif Central" to the West and by the Alpine Chain to the East (Fig. 4). During Middle Jurassic time, the basin margin was characterized by a network of tilted blocks similar to the present margin of the Atlantic Ocean (Lemoine 1984, 1985). The maximum depth of the central part of the basin probably was probably about 700–800 metres (Ferry 1990). The region was a transitional area between the epicontinental sea of the Paris Basin and the deep Piedmont oceanic domain. The thrust boundaries shown in the simplified tectonic map (Fig. 5) correspond to the limits of the various tilted blocks. The Bas-Auran area, located in the middle of one of such block, was thus on the continental slope of the French Subalpine Basin. The succession studied is a cyclic marl-limestone alternation. In most previous works and on the geological map of Digne (Graciansky *et al.* 1982, Olivero and Atrops 1996), it was described as the "Calcaires à *Cancellophycus*" Formation which, in this region, ranges from Aalenian to Bathonian and is covered by the "Terres Noires" Formation (Late Bathonian to Oxfordian). The "Calcaires à *Cancellophycus*" Formation should not be mistaken for the partially coeval "Calcaires à *Zoophycos* du Verdon" Formation, Lower Bathonian to Middle Callovian in age, proposed by Olivero and Atrops (1996) in the southernmost transitional area, between the Subalpine Basin and the Provence Platform.

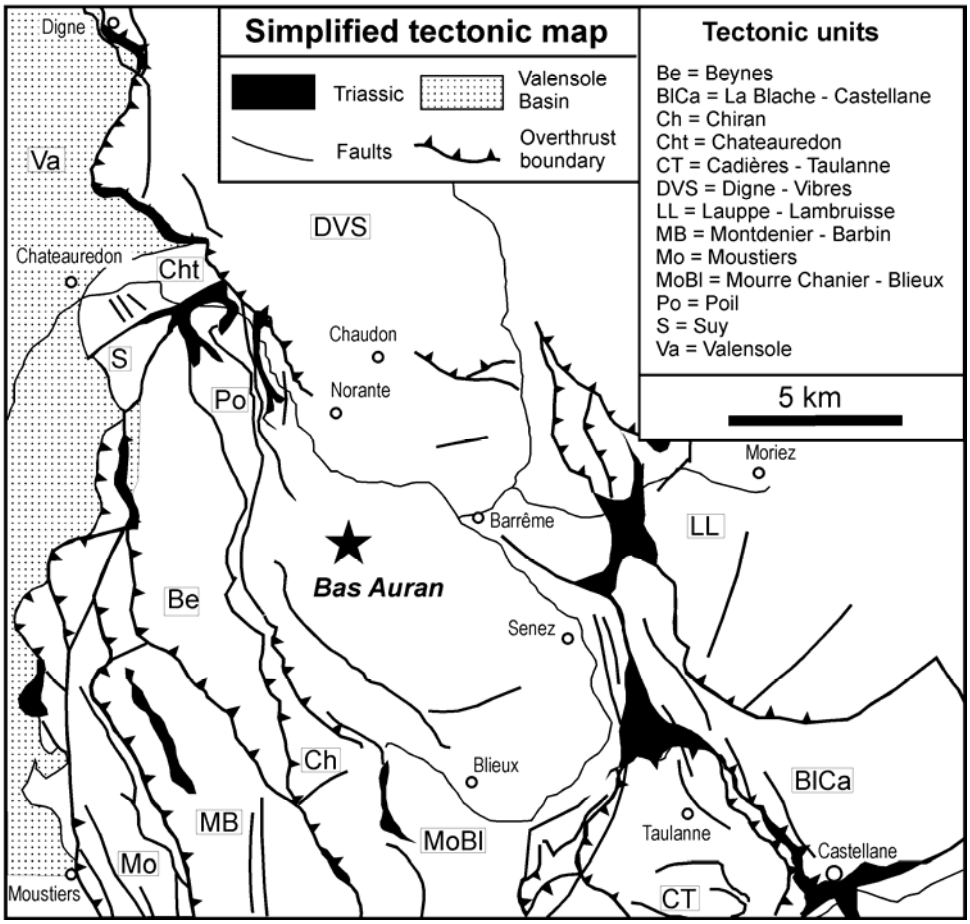


*Fig. 5.* Simplified tectonic map of the Bas-Auran region (Olivero 2003, modified from Graciansky *et al.* 1982).

## Palaeoichnology, taphonomy, sedimentology and sequence stratigraphy of the upper Bajocian to lower Bathonian of the Bas-Auran area (S.R. Fernández-López & D. Olivero)

In the Bas-Auran area, Lower Bathonian deposits comprise black or grey limestone beds alternating with marls usually known as "Marno-calcaires à *Cancellophycus*" (Graciansky *et al.* 1982; Olivero & Atrops 1996). Petrographically, and in terms of biofacies, these deposits are relatively uniform mudstones to wackestones, with common ammonoids, scarce sponges and very scarce nautiloids, brachiopods, bivalves, belemnites, echinoids, crinoids and gastropods. As to microfossils, the overall sedimentary facies shows a calcisphere-mudstone texture; the marls contain foraminifers (*Lenticulina*, *Dentalina*), ostracods and molluscs (cephalopods, bivalves, gastropods) along with detrital minerals, quartz, muscovite and biotite (Corbin *et al.* 2000).

Palaeoichnological studies have been carried out by Olivero (1994, 2003). Bioturbation textures are common and bioturbation structures are scarce, indicating dominant softgrounds. *Zoophycos*, *Chondrites* and *Planolites* occur in beds RB093 to RB001. Local concentrations of trace fossils of these ichnotaxa in bed RB039 suggest the development of a soft- to firmground at this stratigraphic level (Fig. 6). Bioturbation structures indicative of firmground (*Thalassinoides*, *Rhizocorallium*, *Zoophycos* and trace fossils related to large *Halimedides*) occur in a more calcareous layer just overlying the top of bed RB003. Biogenic borings indicative of hardground (*Zapfella*) are common, associated with very scarce encrusting serpulids, on the top of bed RB001, indicating the exceptional development of a stratigraphic discontinuity at the top of the "Marno-calcaires à *Cancellophycus*" in the Bas-Auran area. Sedimentation appears irregular and condensed from bed RB093 towards the top of the Bathonian Zigzag Zone, compared with previous intervals where a more constant and expanded sedimentation is suggested. At the Bajocian-Bathonian transition, however, no stratigraphic gaps or hiatuses have been recorded.

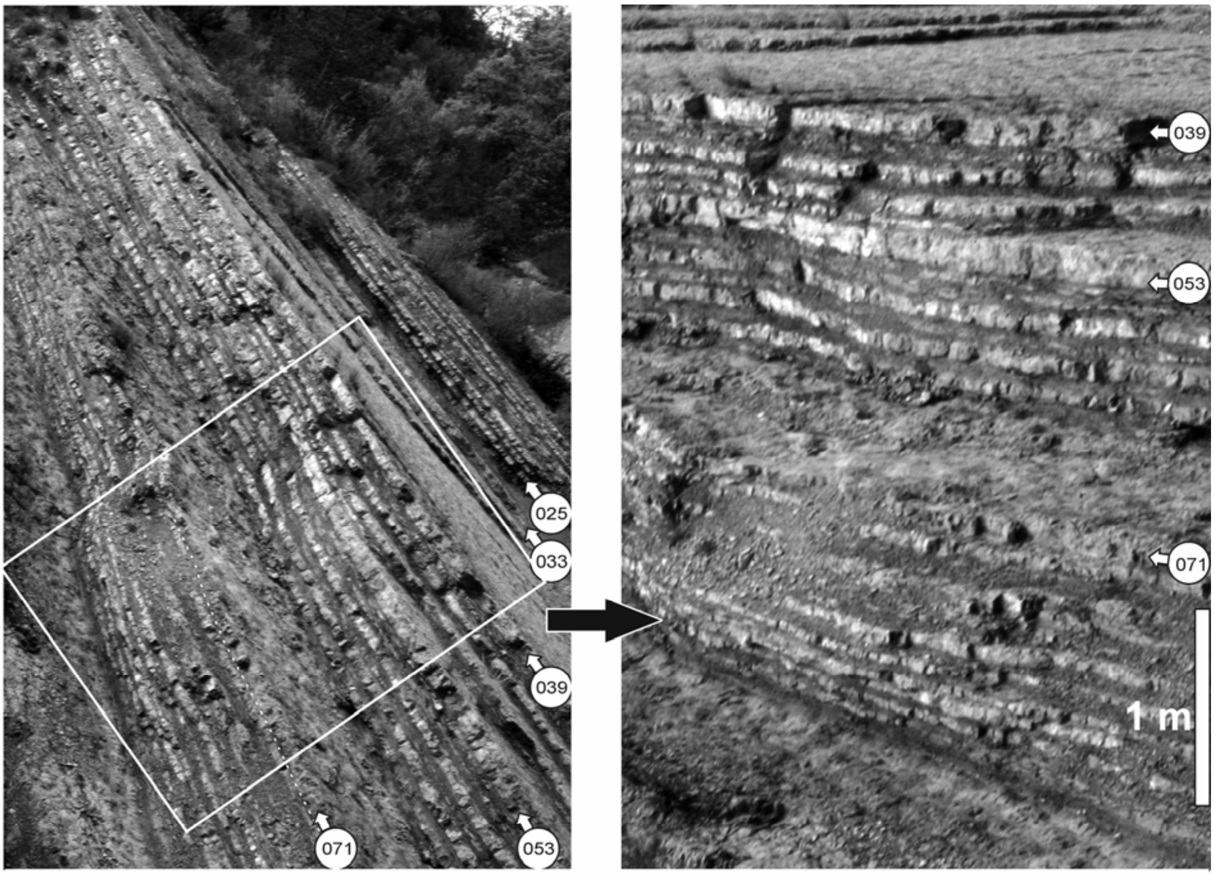


*Fig. 6*. Ravin du Bès Section and detail of beds around the Bajocian/Bathonian boundary. Limestone bed 071 indicates the base of the Bathonian. Scale bar 1 m.

From a taphonomic point of view (Fig. 7), the occurrence of resedimented and reelaborated ammonoids implies that some form of current flow or winnowing affected the burial of concretionary internal moulds. Ammonoids show the following taphonomic characters at the Bajocian-Bathonian transition: 1) high values of stratigraphic persistence of ammonoid shells, 2) dominance of homogeneous concretionary internal moulds of phragmocones, completely filled with sediment, and 3) dominance of unflattened sedimentary moulds bearing no signs of rounding, bioerosion or dense encrusting by organisms (such as serpulids, bryozoans or oysters). These taphonomic features are indicative of a low rate of sedimentation and a low rate of accumulation of sediment, associated with sedimentary starvation in deep environments (Fernández-López 2007).

The bed-scale limestone-marl alternation is primary in origin, although accentuated by diagenetic redistribution of carbonate. Lithological differentiation between marly and limestone intervals resulted from alternating episodes of carbonate input and starvation. Both lithologies may contain evidence of sedimentary and taphonomic reworking, associated with scours, which reflect low rates of sedimentation and stratigraphic condensation. There is no evidence, however, of taphonomic condensation (i.e. mixture of fossils of different age or different chronostratigraphic units) in the ammonoid fossil-assemblages, except in level 002. Sedimentological data and sequence-stratigraphy interpretations of the Jurassic deposits in the French Subalpine Basin have been published by Graciansky *et al.* (1993, 1998a, b), Olivero & Atrops 1996, Olivero *et al.* (1997), Hardenbol *et al.* (1998) and Jacquin *et al.* (1998).

Palaeoichnological, taphonomic and sedimentological results confirm, therefore, the development of a deepening phase associated with sedimentary starvation, within 3rd and 2nd order cycles, in the Bas-Auran area, during the Early Bathonian. The maximum deepening of a 2nd-order transgressive/regressive facies cycle (T/R 7, Upper Aalenian–Upper Bathonian, in Graciansky *et al.* 1993, 1998) is at the end of the Early Bathonian, which corresponds to an extensional and deepening phase of the basin. The outcrop successions at Bas-Auran show no obvious signs of non-sequence or discontinuity across the Bajocian/Bathonian boundary interval.

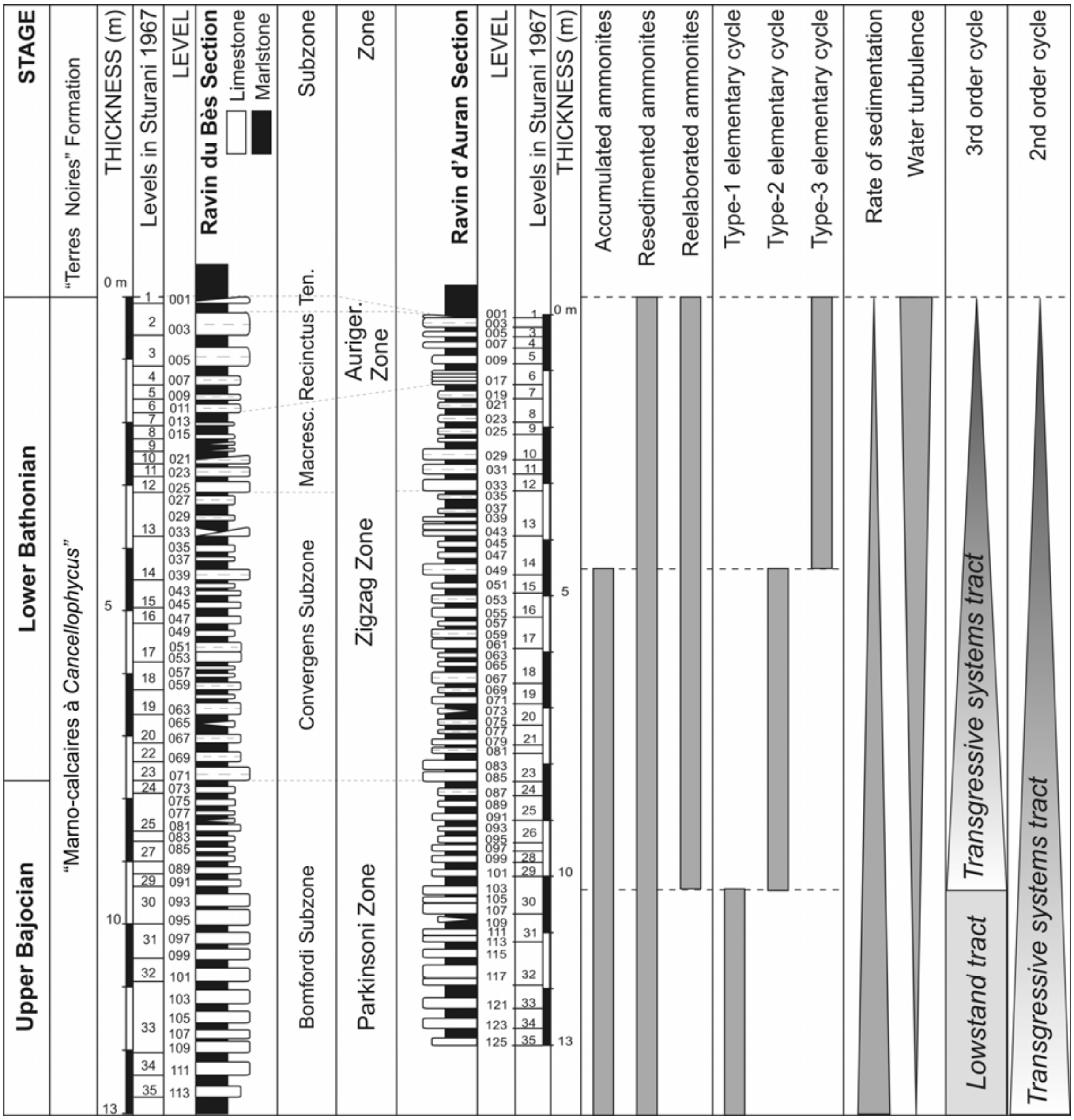


*Fig. 7.* Ammonoid biochronostratigraphic data at the Bajocian/Bathonian boundary in the Ravin du Bès and Ravin d'Auran sections, indicating ammonoid preservation states, types of elementary cycles, and system tracts of 3rd and 2nd order cycles (Fernández-López 2007 modified).

## Palaeontological records

The Bomfordi and Convergens subzones in the Bas-Auran area contain an ammonoid succession that displays a maximum value of biostratigraphic and biochronostratigraphic completeness. Additional macrofossil groups occur in the sections (e. g. sponges, bivalves, brachiopods and belemnites), although they are scarce and have not yet been studied in detail.

### ***Ammonites*** *(S.R. Fernández-López, C. Mangold & G. Pavia)*

Biochronostratigraphic data on ammonoids of the Bas-Auran sections have been published by Sturani (1967), Pavia (1973, 1983a, b, 1984, 1994, 2000, 2007), Torrens (1987), Innocenti *et al.* (1990), Olivero *et al.* (1997) and Joly (2000). New and complementary results from the

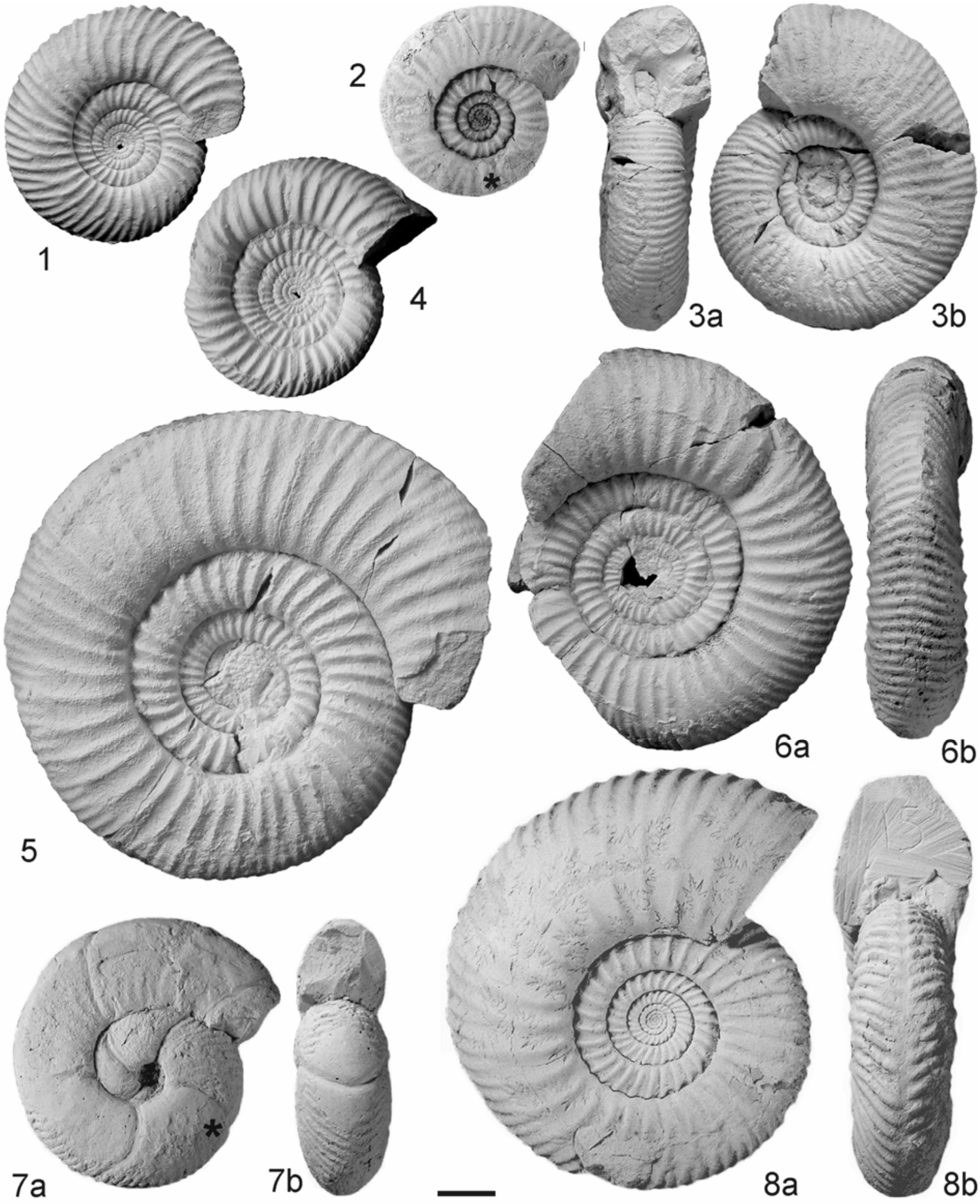


*Fig. 8.* Lower Bathonian ammonites from Bas-Auran area. Specimens have been whitened with magnesium oxide prior to photography. Black asterisk marks the last septum of the phragmocone. Scale bar 1 cm.
1. *Bigotites mondegoensis* Fernández-López *et al.* [M], specimen PU111312, level BA14, Convergens Sbz.
2. *Protozigzagiceras* cf. *torrensi* (Sturani) [m], specimen PU111573, level RA033 (=BA12), Macrescens Sbz.
3ab. *Protozigzagiceras* aff. *torrensi* (Sturani) [M], specimen PU31694, level BA13, Convergens Sbz.
4. *Bigotites sturanii* Fernández-López *et al.* [M], specimen PU111253, level BA19, Convergens Sbz.
5. *Bigotites diniensis* Sturani [m], specimen PU111243, level BA20, Convergens Sbz.
6ab. *Bigotites sturanii* Fernández-López *et al.* [M], specimen PU111233, level BA20, Convergens Sbz.
7ab. *Morphoceras parvum* Wetzel [M], specimen PU111564, level BA17, Convergens Sbz.
8ab. *Gonolkites convergens* Buckman [M], specimen PU111067, level BA15, Convergens Sbz.

biochronostratigraphic analyses of ammonoid fossil-assemblages at the Bajocian/Bathonian boundary in Bas-Auran are in press (Fig. 8, Fernández-López *et al.* 2007, Pavia *et al.* 2008). In the French Subalpine Basin, the successive ammonoid fossil-assemblages are composed of Mediterranean and Northwest European representatives, associated with some Sub-Mediterranean ones. Upper Bajocian and Lower Bathonian Phylloceratina and Lytoceratina, which represent Mediterranean taxa, are relatively common (up to 25% at subzonal scale, Fig. 9). Northwest European taxa, such as Parkinsoniinae, may surpass 25% at subzonal scale. Lower Bathonian Bigotitinae, endemic and characteristic of the Sub-Mediterranean Province, reach 13%. This complex palaeobiogeographical pattern of the Upper Bajocian and Lower Bathonian ammonoid fossil-assemblages enables recognition of diverse subzonal schemes and accurate chronocorrelation between the three main provinces of the West Tethyan Subrealm.

Among the possible guide fossils for the Bajocian/Bathonian boundary, Parkinsoniidae have a better record than Morphoceratidae. The lowest occurrences of *Gonolkites* [M] and *Morphoceras* [M] may be evidence of palaeobiological events, respectively, of origination of *Gonolkites* (from a species of *Parkinsonia*) and immigration of *Morphoceras*. The base of the Bathonian and of the Zigzag Zone corresponds to the first occurrence level of *Gonolkites convergens* and the renewal of parkinsonids at the base of limestone bed RB071 (bed 23 in Sturani 1967) in the Ravin du Bès Section. Additionally, the base of the Bathonian in Bas-Auran sections also coincides with the lowest occurrence of *Morphoceras parvum*. Thus, the bases of the Northwest European primary standard Convergens Subzone and the Sub-Mediterranean secondary standard Parvum Subzone are in fact precisely coeval in the Bas-Auran area.

The basal ammonite assemblage includes the following ammonite species (Fig. 10):
*Oxycerites limosus* (Buckman) [M],
*Cadomites deslongchampsi* (d'Orbigny) [M+m],
*Cadomites crassispinosus* Kopik [M+m],
*Cadomites stegeus* (Buckman) [M+m],
*Cadomites psilacanthus* (Wermbter) [M+m],
*Cadomites* gr. *rectelobatus* (Hauer) [M],
*Parkinsonia subplanulata* Wetzel [m+M],
*Gonolkites subgaleatus* (Buckman) [M],
*Gonolkites convergens* Buckman [M],
*Morphoceras parvum* Wetzel [M].

The potential ammonite content of the basal Bathonian fossil-assemblage could be enlarged by the following taxa, known from below and above but not actually in the basal bed:
*Cadomites sturanii* Galácz [M+m],
*Polyplectites rozyckii* (Kopik) [m],
*Parkinsonia* cf. *subplanulata* Wetzel [m+M],
*Parkinsonia crassa* Nicolesco [m+M],
*Parkinsonia schloenbachi* Schlippe [m+M],
*Planisphinctes planilobus* Buckman [m],
*Phaulozigzag phaulomorphus* Buckman [m].

Similarly, the following species of Phylloceratina and Lytoceratina could also be part of a basal Bathonian fossil-assemblage (Fig. 9):
*Phylloceras kudernatschi* (Hauer),
*Adabofoloceras subobtusum* (Kudernatsch),
*Adabofoloceras wendti* (Sturani),
*Phyllopachyceras ebrayi* (Ferry),
*Calliphylloceras achtalense* (Redlich),
*Calliphylloceras* gr. *disputabile* (Zittel),
*Nannolytoceras tripartitum* (Raspail),
*Lytoceras* gr. *eudesianum* (d'Orbigny).

New palaeontological data about the youngest members of Bigotitinae and the oldest members of Zigzagiceratinae are of biochronostratigraphic importance for the subdivision and correlation of the basal Bathonian Zigzag Zone. Three successive biohorizons have been identified and chronocorrelated between the Bas-Auran (French Subalpine Basin) and Cabo Mondego (Lusitanian Basin) successions (Fernández-López *et al.* 2007, Pavia *et al.* 2008):

1) The Diniensis Biohorizon is characterized by the occurrence of *Bigotites diniensis* and corresponds to the lowest part of the Bathonian Zigzag Zone in the Sub-Mediterranean Province (e.g., Cabo Mondego and Bas-Auran). It encompasses the stratigraphic intervals RA085–RA062 (Fig. 10, levels 23–18 of Sturani 1967) in Ravin d'Auran Section and RB071–RB054 (Fig. 7, levels 23–18 of Sturani 1967) in Ravin du Bès Section.

2) The Mondegoensis Biohorizon is defined by the lowest occurrence of *Bigotites mondegoensis*. It comprises the stratigraphic intervals RA061–RA044 (Fig. 10, levels 17–14 of Sturani 1967) in Ravin d'Auran Section and RB053–RB034 (Fig. 7, levels 17–14 of Sturani 1967) in Ravin du Bès Section.

3) The Protozigzagiceras Biohorizon is defined by the lowest occurrence of Zigzagiceratinae, in particular *Protozigzagiceras* [M+m] and *Franchia* [M+m]. It encompasses the stratigraphic intervals RA043–RA034 (Fig. 7, level 13 of Sturani 1967) in Ravin d'Auran Section and RB033–RB026 (level 13 of Sturani 1967) in Ravin du Bès Section.

According to Pavia *et al.* (2008), the quality of the record of the ammonoid biostratigraphic succession in the Bas-Auran area can be tested with various palaeontological criteria: the preservation state of fossil-specimens, taphonic populations and fossil-assemblages; abundance, concentration, packing and stratigraphic persistence of fossil-specimens; completeness, constancy and persistence of stratigraphic ranges; completeness and taxonomic diversity of successive fossil-assemblages; biostratigraphic turnover; proportion of virtual and actual palaeontological gaps in successive stratigraphic intervals; proportion of first and last occurrences of taxa; proportion of lowest and highest occurrences of taxa; successive or coincident clustering of last and first occurrences. Values of these twenty-one palaeontological attributes indicate a relatively homogeneous and good record quality, gradual biostratigraphic change and high degree of taxonomic similarity between the Bomfordi and Convergens subzones. These criteria, applied to the ammonoid genera which are known from the Bas-Auran area, also indicate relatively high values of palaeontological and stratigraphic completeness at the base of levels RB070–RB071 (= level 23 in Sturani 1967; i.e., the Bajocian/Bathonian boundary). The ammonoid biostratigraphic succession of Bas-Auran shows no evidence of biochronostratigraphic mixing, taphonomic condensation, signs of non-sequence or biostratigraphic discontinuities across the Bajocian/Bathonian boundary interval. Moreover, with forty-six successive ammonoid fossil-assemblages of the Convergens Subzone, through up to 5 metres of thickness belonging to three biohorizons, the Ravin du Bès Section displays maximum values of biostratigraphic and biochronostratigraphic completeness.

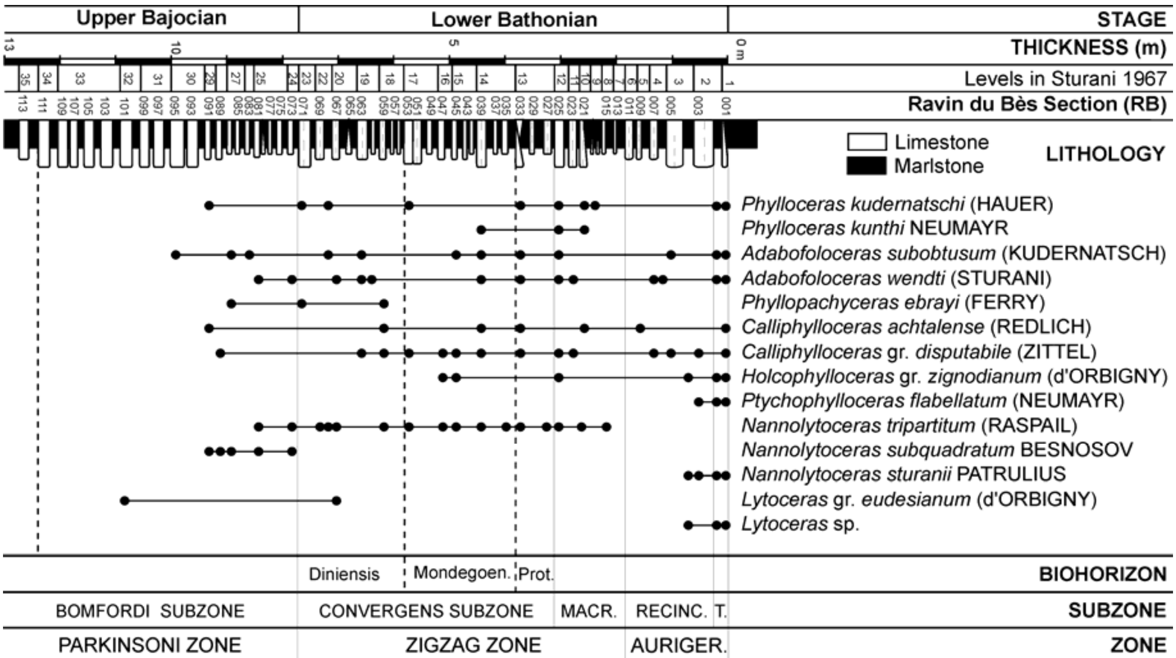


*Fig. 9.* Phylloceratina and Lytoceratina biochronostratigraphic data at the Bajocian/Bathonian boundary in the Ravin du Bès Section (from Pavia *et al.* 2008).

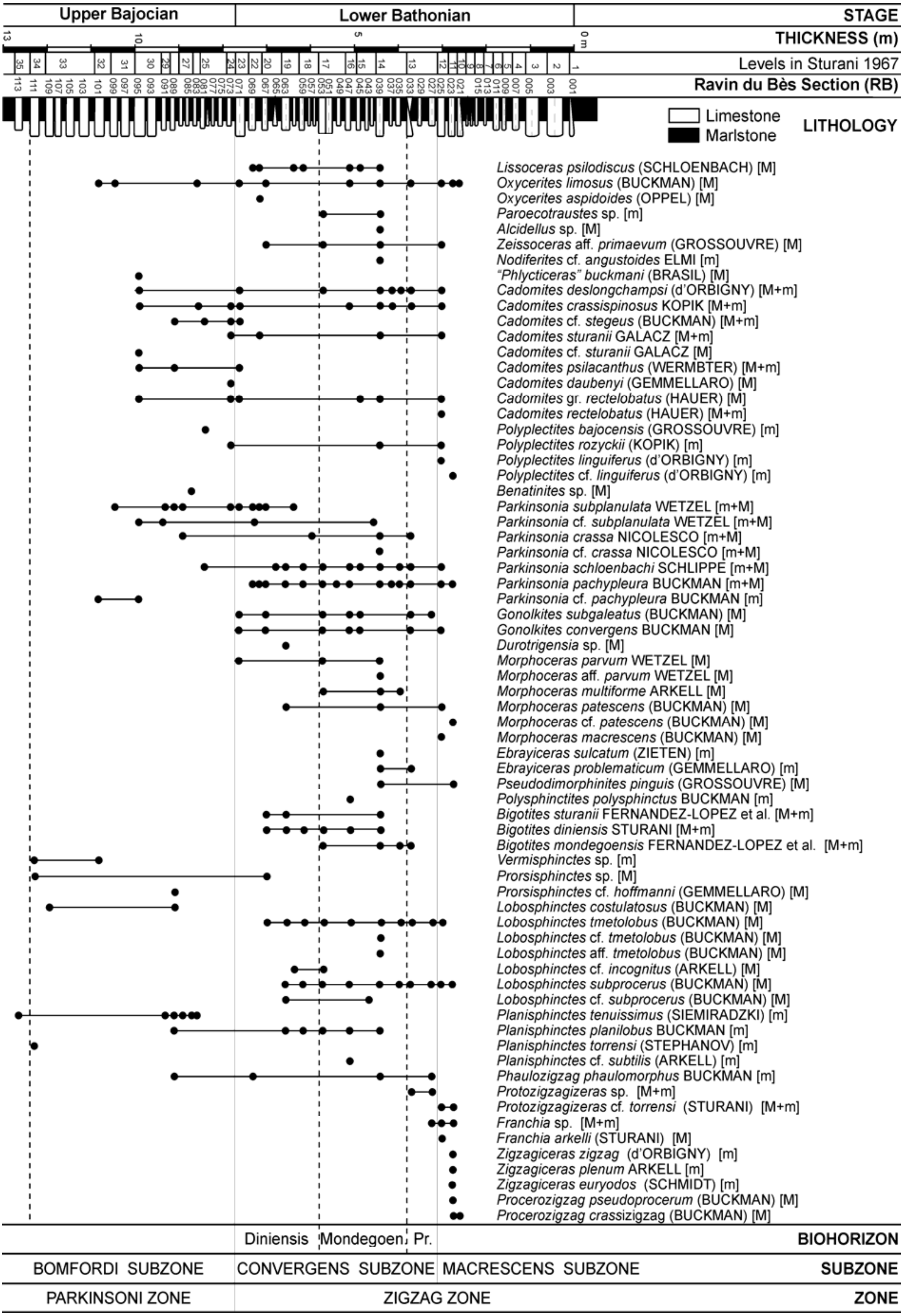


*Fig. 10.* Ammonitina biochronostratigraphic data at the Bajocian/Bathonian boundary in the Ravin du Bès Section (from Pavia *et al.* 2008).

## *Microfossils*

The Bajocian/Bathonian boundary may be characterized by secondary (auxiliary) biostratigraphic markers, such as nannofossils. According to the results of Erba (1990a, b; Cobianchi *et al.* 1992; Mattioli & Erba 1999), calcareous nannofossils are present in all beds and facilitate the characterization of the Bajocian-Bathonian transition. The Ravin du Bès Section appears to be suitable for the biostratigraphical study of microfossils, such as foraminifers or ostracods, but there are at present no published studies. According to preliminary results (Bodergat in Mangold 1999), ostracods are present in all marly samplings, but are badly preserved between bed RB71 and bed RB33. The marine taxa are different from those known in the Paris Basin and England. The Subalpine taxa, specially the genera *Pontocyprella*, *Isobythocypris* and *Cordobairdia*, indicate deeper environments (more than 200 m). Palynomorphs are poorly preserved and are not yet stratigraphically useful across the boundary (Poulsen 1997, Mangold 1999).

## ***Calcareous nannofossils*** *(E. Erba & D. Tiraboschi)*

Nannofossil biostratigraphic investigation was performed on 59 samples (approximately every 20 cm) collected from the Ravin du Bès section in the Bas-Auran area; sample figures correspond to the bed numbers of the lithostratigraphic column of Fig. 7. This study is a revision of the previous work by Erba (1990a, b), extended to limestone layers and additional marlstone beds. Simple smear slides were prepared for both limestone and marlstone, using standard techniques and without centrifuging cleaning /concentration in order to retain the original sediment composition. A few milligrams of powdered sediments were mounted on a glass slide with the Norland Optical Adhesive, and then analyzed using a light polarizing microscope, at 1250x magnification.

All studied samples contain calcareous nannofossils. A total of 37 taxa were identified and their distribution is given in Fig. 11. The nannofossil total abundance fluctuates from extremely rare to common; the preservation is poor to moderate, with evidence of dissolution and overgrowth. Limestone levels generally contain depauperated and poorly preserved nannofloras, with stronger overgrowth and dissolution.

The nannofloras are characteristic of the Upper Bajocian–Lower Bathonian interval. Assemblages are dominated by *Watznaueria britannica* and *Watznaueria communis*, with common *Schizosphaerella punctulata*, *Watznaueria* aff. *W. manivitiae*, *Watznaueria manivitiae*, *Cyclagelosphaera margerelii*, *Cyclagelosphaera deflandrei*, *Lotharingius crucicentralis*, *Lotharingius velatus*, *Lotharingius sigillatus* and *Ethmorhabdus gallicus*.

Based on absence of *Carinolithus superbus* and of *Watznaueria barnesiae*, the lowermost portion of the investigated interval (samples 110 through 68b) corresponds to the Tethyan *W. communis* Subzone (NJT 10b) indicating a Late Bajocian age (Mattioli & Erba 1999). This subzone corresponds to the upper part of the Boreal NJ 10 Zone and the lower part of the NJ 11 Zone of Bown & Cooper (1998). The first occurrence (FO) of *Pseudoconus enigma* in sample 89 identifies the NJ10/NJ11 zonal boundary (Figs. 12–13). This taxon is rare and occurs only in limestones, with the only exception of a single specimen in marlstone sample 20, and this is why Erba (1990b) did not report this species.

The last occurrence (LO) of *Hexalithus magharensis* was observed in sample 82 indicating a latest Bajocian age (Mattioli & Erba 1999). Similarly, Erba (1990b) recorded this event in the Parkinsoni Zone (latest Bajocian) of the Digne area, whereas in Portugal and Morocco de Kaenel *et al.* (1996) found an older age for the LO of *H. magharensis*, calibrated between the end of the Early Bajocian and the beginning of the Late Bajocian.

The FO of *Stephanolithion speciosum octum* was observed in sample 76; the taxon is extremely rare and scarce in the studied section. This event has been correlated to the base of the Parkinsoni Zone in NW Europe and Portugal (de Kaenel *et al.* 1996), but within the Zigzag Zone in SE France (Erba 1990b). Bown *et al.* (1988) and Bown & Cooper (1998) report the FO of *S. speciosum octum* at the base of the Boreal NJ 11 Zone.

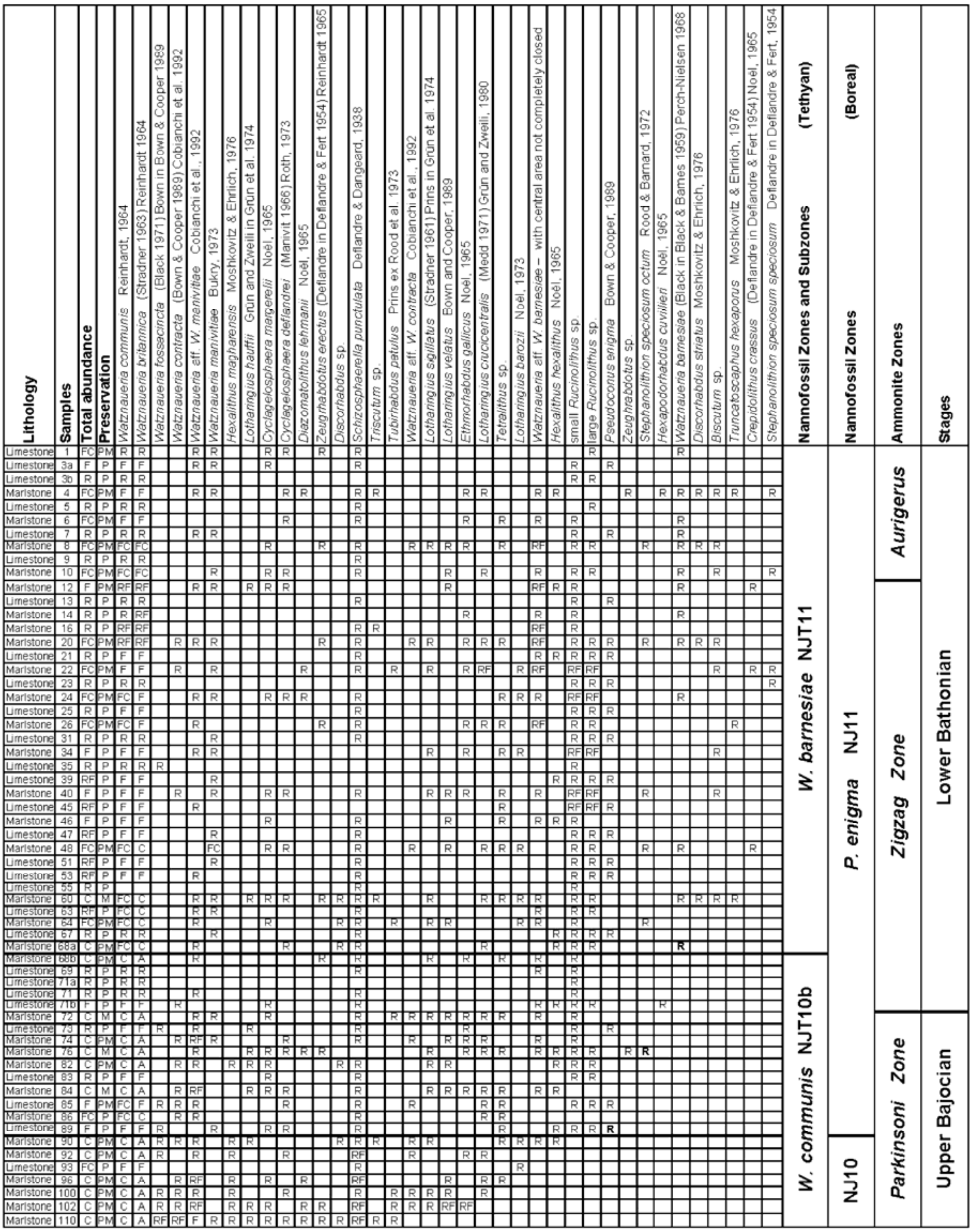


*Fig. 11.* Calcareous nannofossil range chart of the Ravin du Bès Section. The semiquantitative distribution of nannofloras was coded as follows: Total abundance. C= 10–15 specimens in each field of view; FC= few/common: 5–9 specimens in each field of view; F= few: about 5 specimens in each field of view; RF=rare/few: 2–5 specimens in each field of view; R= rare: 1 specimen in each field of view. Preservation. M= moderate: little evidence of dissolution and/or overgrowth is present; primary morphological characteristics are sometimes altered; MP= moderate/poor: evidence of dissolution and/or overgrowth is present; primary morphological characteristics are sometimes modified, fragmentation has occurred; P= poor: most specimens exhibit dissolution or overgrowth; primary morphological characteristics are sometimes destroyed; fragmentation has occurred. Species abundance. A= abundant: > 10 specimens in each field of view; C= common: 1 specimen in 1–9 fields of view; FC= few/common: 1 specimen every 10 fields of view; F= few: 1 specimen in 11–29 fields of view; RF= rare/few: 1 specimen every 30 fields of view; R= rare: 1 specimen in 31–100 fields of view.

The FO of *W. barnesiae* (NJT11) was observed in sample 68a of earliest Bathonian age (Zigzag Zone). This event defines the base of the Tethyan NJT11 Zone (Mattioli & Erba 1999), comparable to most of the Boreal NJ11 Zone and NJ12a Subzone (Bown *et al.* 1988, Bown & Cooper 1998).

The uppermost portion of the studied interval corresponds to the Tethyan NJT 11 Zone (Mattioli & Erba 1999), since *Cyclagelosphaera wiedmannii* was not observed.

From sample 89 upwards, rosetta-shaped specimens likely to be the genus *Rucinolithus* were consistently observed. They show highest abundance in the interval between sample 45 through 22 (Fig. 11), both in limestone and marlstone beds. Two morphotypes were distinguished, namely small (< 8 microns) and large (> 8 microns) *Rucinolithus* spp., based on their diameter. More detailed investigations are in progress to characterize the taxonomy of these morphotypes (Tiraboschi & Erba in prep.).

Our results are consistent with previous biostratigraphic data from the Upper Bajocian–Lower Bathonian interval in SE France (Erba 1990b), Portugal, NW Europe (de Kaenel & Bergen 1993, de Kaenel *et al.* 1996), Lombardian Basin (Chiari *et al.* 2007) and Boreal Realm (Bown & Cooper 1998). For the first time *P. enigma* has been documented from mid to low latitudes allowing a direct calibration between Tethyan and Boreal nannofossil events and biozones (Figs. 12–13).

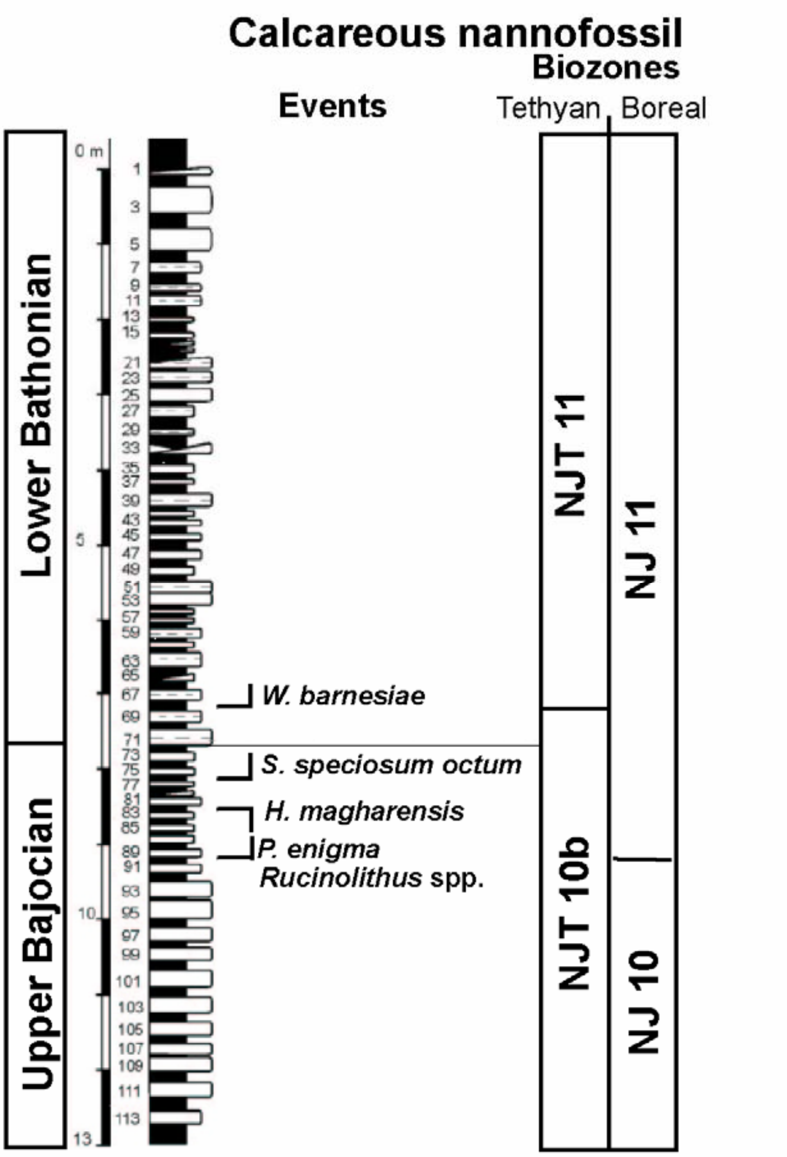


*Fig. 12.* Nannofossil events detected in the Ravin du Bès Section. Tethyan biozones after Mattioli & Erba (1999) and Boreal biozones after Bown & Cooper (1998).

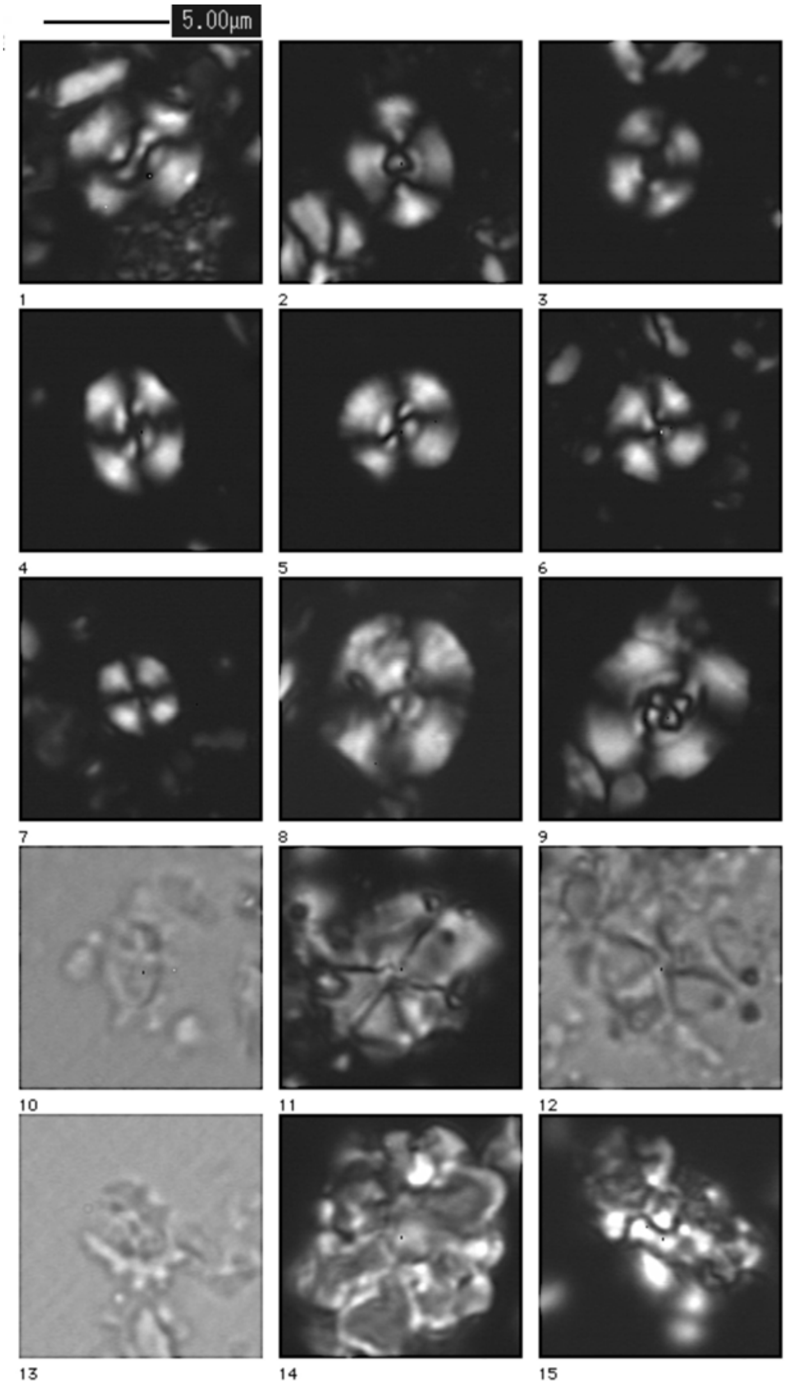


*Fig. 13.* Upper Bajocian and Lower Bathonian calcareous nannofossils from the Bas-Auran area. All specimens at 1250x magnification.
1. *Watznaueria communis*, crossed nicols, sample 110.
2. *Watznaueria britannica*, crossed nicols, sample 102.
3. *Watznaueria fossacincta*, crossed nicols, sample 110.
4. *Watznaueria* aff. *W. barnesiae*, crossed nicols, sample 60.
5. *Watznaueria barnesiae*, crossed nicols, sample 68a.
6. *Watznaueria barnesiae*, crossed nicols, sample 10.
7. *Cyclagelosphaera margerelii*, crossed nicols, sample 40.
8. *Watznaueria manivitiae*, crossed nicols, sample 67.
9. *Watznaueria* aff. *W. contracta*, crossed nicols, sample 48.
10. *Stephanolithion speciosum octum*, transmitted light, sample 76.
11. *Hexalithus magharensis*, crossed nicols, sample 110.
12. *Hexalithus magharensis*, transmitted light, sample 110.
13. *Stephanolithion speciosum speciosum*, transmitted light, sample 76.
14. *Rucinolithus* sp., crossed nicols, sample 6.
15. *Pseudoconus enigma*, crossed nicols, sample 53.

## **Correlation** (S.R. Fernández-López)

Ammonites are the most relevant taxonomic group for global biochronostratigraphic correlation of the Bajocian/Bathonian boundary. Nevertheless, various other taxonomic groups of macroinvertebrates and microfossils are also of biochronostratigraphic relevance.

### ***Ammonites***

Late Bajocian and Early Bathonian ammonites are found worldwide in the three major, oceanic or marine, palaeogeographical units: Tethyan, Pacific and Boreal domains or realms (Fig. 14; Cariou *et al.* 1985; Hillebrandt *et al.* 1992a, b; Taylor *et al.* 1992; Westermann 1993a, 2000; Page 1996a; Enay & Cariou 1999). The most difficult problem in biochronocorrelation of the boundary is not the low biostratigraphic turnover of the ammonoid succession across the boundary in Bas Auran area or the low faunal turnover at the Bajocian/Bathonian transition, but the strong provincialism with three separate realms.

Figure 15 shows standard zonations for the three ammonite biogeographical provinces represented in western Europe. Ammonites of the Zigzag Zone have a wide distribution through the Northwest European, Sub-Mediterranean and Mediterranean provinces of the West Tethyan Subrealm. In the Bas-Auran area, Northwest European and Sub-Mediterranean taxa are relatively common, the primary standard Convergens Subzone and the secondary standard Parvum Subzone can be recognized.

The Northwest European Province, in which parkinsonids are common, comprises the following epeiric areas: England (Torrens 1980; Callomon 1995, 2003; Callomon & Cope 1995; Page 1996b, 2001; Dietze and Chandler 1998; Chandler *et al.* 1999), Normandy, Boulonnais, Lorraine, Alsace, northern Jura (Mangold & Rioult 1997, Rioult *et al.* 1997, Thierry 2003), northern Germany (Westermann 1958; Metz 1990, 1992), northern and central Poland (Kopik 2006, Zaton 2006).

The Sub-Mediterranean Province, in which Bathonian *Morphoceras* [M] - *Ebrayiceras* [m] occur associated with parkinsoniids and scarce phylloceratids and lytoceratids, includes the following epeiric areas: Lusitanian Basin (Fernández-López *et al.* 2006a, b), Iberian Basin (Fernández-López 2000, 2001), Aquitaine, Causses, Centre-west France, Nièvre (Delance *et al.* 1979, Courville *et al.* 1999, Enay *et al.* 2001), Mâconnais, Ardèche, southern Jura (Elmi 1967; Mangold 1971a, b, c, 1997a, b; Rulleau 2006), western Alps and Subalpine Basin (Sturani 1967, Pavia & Sturani 1968, Pavia 1973, 1984, Torrens 1987, Innocenti *et al.* 1990, Zany *et al.* 1990, Joly 2000), southern Germany (Dietl 1978, 1981, 1982, 1983, 1986, 1988; Dietl *et al.* 1978, 1983; Dietl & Hugger 1979; Dietl & Kapitzke 1983; Callomon *et al.* 1987; Schairer 1987, 1994; Dietze & Chandler 1996; Köstler & Schairer 1996; Dietze *et al.* 1997, 2002, 2004; Schweigert & Dietze 1998; Dietze 2000; Dietze & Schweigert 2000; Schweigert *et al.* 2002, 2003, 2007; Ohmert *et al.* 2004; Dietze & Dietl 2006), South Poland (Luczynski *et al.* 2000; Matyja & Wierzbowski 2000, 2001; Zaton & Marynowski 2006), Pieniny Klippen Belt (Wierzbowski *et al.* 1999; Schlögl & Rakús 2004; Schlögl *et al.* 2005, 2006), South Transdanubian Mecksek (Galácz 1995a, Geczy & Galácz 1998), Romania (Galácz 1994, Patrulius 1996), Balkans (Stephanov 1972), northwestern-central Iran (Seyed-Emami *et al.* 1985, 1989, 1991, 1998a, b) and north-eastern Iran (Majidifard 2003).

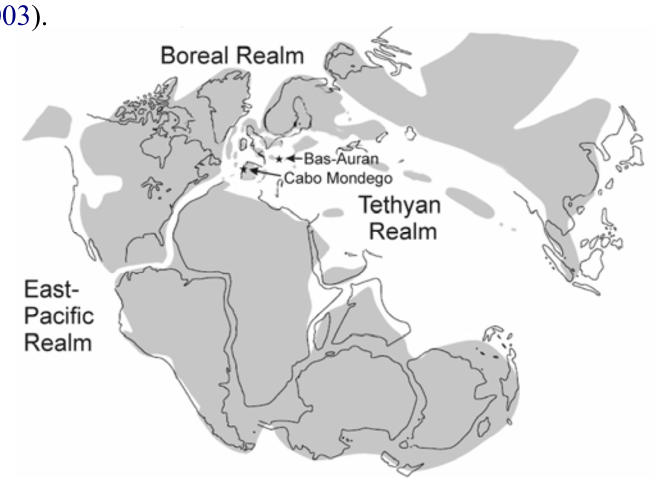


*Fig. 14.* Principal palaeobiogeographical units during Bajocian/ Bathonian transition, with location of Bas-Auran and Cabo Mondego areas (modified from Moyne & Neige 2007).

| | NW European Province | | Sub-Mediterranean Province | | Mediterranean Province | |
|---|---|---|---|---|---|---|
| | England, Normandy, Boulonnais, Lorraine, Alsace, northern Germany, northern and central Poland. | | Portugal, Iberian Basin, Aquitaine, Causses, Centre-west France, Nièvre, southern Jura, Mâconnais, Ardèche, southern Germany peri-Carp. Poland, Balkans, northern and central Iran. | | Betic Basin, Sicily, Appennines, Switzerland, Austria, Hungary p.p (Villany and Mecsek), Hellenids, Serbia. | |
| Lower Bathonian | Tenuiplicatus | | Aurigerus | Tenuiplicatus | Aurigerus | Postpollubrum |
| | Zigzag | Yeovilensis | | Recinctus | | Yeovilensis |
| | | Macrescens | Zigzag | Macrescens | Zigzag | Macrescens |
| | | Convergens | | Parvum | | Dimorphitiformis |
| Upper Bajocian | Parkinsoni | Bomfordi | Parkinsoni | Bomfordi | Parkinsoni | Dimorphus |
| | | Truellei | | Densicosta | | Daubenyi |
| | | Acris | | Acris | | |

*Fig. 15.* Ammonite zones and subzones of the Uppermost Bajocian and Lower Bathonian in several palaeobiogeographical provinces: Northwest European (Westermann & Callomon 1988, Callomon & Cope 1995, Callomon 2003), Sub-Mediterranean (Mangold 1990, Rioult *et al.* 1997, Mangold & Rioult 1997) and Mediterranean (Galacz 1980, 1993; Sandoval 1983, 1990; Sandoval *et al.* 2001; O'Dogherty *et al.* 2006) provinces.

The Mediterranean Province, in which Late Bajocian and Early Bathonian morphoceratids occur associated with common phylloceratids and lytoceratids, comprises the following shelfal or oceanic areas: Betic Basin (Mangold 1981; Sandoval 1983, 1986, 1990; Sandoval *et al.* 2001), Majorca (Sandoval 1994), Sicily (Wendt 1963, 1971; Galácz 1985, 1999a, b; Pavia & Cresta 2002; Pavia *et al.* 2002; Martire & Pavia 2004; Pavia 2007), Alps (Sturani 1971, Krystyn 1972, Joly 2000, Martire 1989, Mangold & Gygi 1997), North Transdanubian Bakony (Galácz 1980, 1993, 1995b).

In the north-eastern Tethyan border (Donetz, Crimea, Caucasus, Great Balkhan, Turkmenistan, Tadzhikistan, Uzbekistan, Kazakhstan) latest Bajocian to Early Bathonian parkinsonids and morphoceratids have been described, below Middle Bathonian specimens of *Bullatimorphites*, *Procerites* and *Siemiradzkia* (Rostovtsev 1985; Tseretely 1989; Beznosov & Mitta 1998, 2000).

In Tibet and South-East Asia, Bathonian *Siemiradzkia*, *Procerites* and *Wagnericeras* have been identified (Cariou & Enay 1999, Yin *et al*. 2000, Yin 2005). Upper Bajocian *Leptosphinctes* and *Cadomites* have been recognized in Japan, below Upper Bathonian *Pseudoneuqueniceras* (Sato 1992).

Lower Bathonian morphoceratids, parkinsoniids and phylloceratids have been recognized in several basins of the southern Tethyan border: Morocco, Algeria and Tunisia (Elmi 1971, Elmi & Alméras 1984, Enay *et al.* 1987b, Ouahhabi 1994, Soussi *et al.* 2000). *Oraniceras*, *Micromphalites* and *Oxycerites* occur in Lower Bathonian, whereas *Ermoceras*, *Leptosphinctes* and *Oppelia* characterize Upper Bajocian deposits.

In the Ethiopian Province, including Libya, Egypt, Israel, southern Turkey, southern Iran and Saudi Arabia (Parnes 1981, 1984, 1988; Enay *et al.* 1986, 1987a; Enay & Mangold 1994, 1996), the Lower Bathonian comprises the Tuwaiqensis (*Tulites*) and Clydocromphalus (*Micromphalites*) zones of the Arabian Province, including *Procerites* and *Zigzagiceras* in basal levels. Upper Bajocian deposits with *Ermoceras*, *Thambites*, *Leptosphinctes* and *Spiroceras* represent the Runcinatum (*Ermoceras*), Mogharense (*Ermoceras*) and Planus (*Thambites*) zones.

In the Indo-Malgach Province, Late Bajocian and Middle Bathonian ammonites, but not Early Bathonian, have been described from Kenya, Madagascar and India (Singh *et al*. 1982, 1983; Jaitly & Singh 1983, 1984; Pandey & Agrawal 1984; Pandey & Westermann 1988; Galácz 1990; Pandey & Callomon 1995; Prasad *et al*. 2007; Roy *et al*. 2007).

| | Ammonite NW European standard zonation | | Argentina | Northern Chile | Eastern Oregon | British Columbia |
|---|---|---|---|---|---|---|
| Lower Bathonian | Tenuiplicatus | | Cadomites - Tulitidae Assemblage | ?Zigzagiceras | *Cobbanites Parareinekeia* | *Iniskinites? costidensus* |
| | Zigzag | Yeovilensis | | | | |
| | | Macrescens | *Lobosphinctes* | | | |
| | | Convergens | | | | |
| Upper Bajocian | Parkinsoni | Bomfordi | | *"Cobbanites"* | *Parachondroceras + Sohlites* | |
| | | Truellei | | | | |
| | | Acris | | | | |

*Fig. 16.* Uppermost Bajocian and Lower Bathonian ammonite horizons in several palaeobiogeographical areas of the East-Pacific Realm (modified from Imlay 1981, 1984; Callomon 1984; Hall 1988;Westermann & Riccardi 1991; Hillebrand *et al.* 1992a, b; Gröschke & Hillebrandt 1994; Hillebrandt 2001).

In south-western Pacific areas, Sula, Irian Jaya and New Guinea, latest Bajocian to Early Bathonian *Pretulites* and Early to Middle Bathonian *Satoceras*, as well as Bathonian specimens of *Asphinctites*, *Rugiferites* and *Bullatimorphites* have been described (Westermann & Getty 1970, Westermann & Callomon 1988, Sukamto & Westermann 1992, Westermann 1995, Callomon & Rose 2000).

Separate Late Bajocian and Early Bathonian ammonoid faunas have been distinguished, associated with characteristic Eurycephalitinae, in the southern East-Pacific Subrealm of the Tethyan Realm: New Zealand (Westermann & Hudson 1991; Westermann 1993b; Westermann *et al.* 2000, 2002), Argentina, Chile and Peru (Westermann & Riccardi 1980; Westermann *et al.* 1980; Riccardi 1985, 1991; Riccardi *et al.* 1990a, b, 1991, 1992, 1994; Riccardi & Westermann 1991a, b, 1999; Hillebrandt *et al.* 1992a, b; Fernández-López *et al.* 1994; Gröschke & Hillebrandt 1994; Hillebrandt 1995, 2001; Gröschke 1996; Parent 1998). *Leptosphinctes*, *Lupherites, Strenoceras, Spiroceras* and *Megasphaeroceras* occur in the Upper Bajocian of the Andean Province. *Lobosphinctes intersertus* Buckman has been identified in Chacay Melehue (Argentina) below a Bathonian *Cadomites*-Tulitidae mixed assemblage. The first occurrence of several genera such as *Oxycerites*, *Zeissoceras*, *Prohecticoceras and Rugiferites*, below the oldest representatives of Bathonian *Bullatimorphites*, have been used to recognize Lower Bathonian deposits. New species of Bathonian ?*Zigzagiceras* and *Morphoceras* have been proposed (Fig. 16; Gröschke & Hillebrandt 1995; Riccardi & Westermann 1999).

In Mexico (Sandoval & Westermann 1986, Sandoval *et al.* 1990) Upper Bajocian begins with the upper Floresi Zone of Oaxaca, containing the Mediterranean *Subcollina lucretia* (Orbigny). The overlaying Zapotecum Zone includes *Parastrenoceras*, *Leptosphinctes* and *Oppelia*. The Upper Bathonian Retrocostatum Zone has been identified by *Prohecticoceras blanazense*, associated with *Epistrenoceras*, *Lilloettia* and *Neuqueniceras*.

In the Western Interior of the United States of America (Shoshonean Province, Imlay 1981), western Canada and southern Alaska (Athabascan Province; Imlay 1980, 1982, 1984; Hall & Westermann 1980; Hall & Stronach 1981; Callomon 1984; Hall 1984, 1988, 1989; Poulton *et al.* 1991, 1994) the Upper Bajocian Rotundum Zone includes *Leptosphinctes*, *Lupherites, Spiroceras* and *Megasphaeroceras*, below the *Epizigzagiceras-Parareineckeia* association. The *Parachondroceras-Sohlites* assemblages from Oregon may be Upper Bajocian or Lower Bathonian (Fig. 16; Imlay 1984).

The Boreal Realm (Eastern Greenland, Siberia, Northern Alaska and Northern Canada) became clearly differentiated in the Late Bajocian and several zonations for the Early Bathonian have been proposed. The Cardioceratidae, in particular *Cranocephalites* and *Arctocephalites*, constituted characteristic elements of the Boreal Realm at the Bajocian/Bathonian boundary (Callomon 1985). The Zone of *Arctocephalites arcticus* (Newton & Teall), above the Zone of *Cranocephalites pompeckji* (Madsen), may represent the basal Bathonian zone in the Boreal Realm (Callomon 1993, 1994, 2003; Rawson 1982; Zakharov *et al.* 1998). The Zone of *Arctocephalites spathi* from northern

| Stage | West Europe | | North Caucasus | | Volga basin | | Petchora basin | | East Greenland | |
|---|---|---|---|---|---|---|---|---|---|---|
| M.B. | Progracilis | | Hiatus | | ammonites not found | | Hiatus? | | Ishmae | *crassiplicatum* |
| Lower Bathonian | Zigzag | Tenuiplicatus | | | Ishmae | *ishmae* β | Ishmae | *ishmae* | | *ishmae* β |
| | | | | | | "belemn. level" | | | | *ishmae* α |
| | | Yeovilensis | | | | *harlandi* | | *harlandi* | | *harlandi* |
| | | Macrescens | Zigzag | Macrescens | Besnosovi | *freboldi* | Greenlan-dicus | *freboldi* | Greenlan-dicus | *freboldi* |
| | | | | | | *besnosovi* | | | | *greenlandicus* |
| | | Convergens | | Convergens | | *mojarowskii* | | | | *micrumbilicatus* |
| U. Bajoc | Parkinsoni | Bomfordi | Parkinsoni | | Michalskii | *masarowici* | Arcticus | | Arcticus | *delicatus* |
| | | Densicosta | | | | *michalskii* | | *arcticus* | | *arcticus* |

*Fig. 17*. Ammonite zones and subzones of the Uppermost Bajocian and Lower Bathonian in several palaeobiogeographical areas (after Mitta 2007).

Yukon probably is coeval with the Boreal Arcticus Zone of eastern Greenland (Poulton 1987). Boreal Arctocephalitinae are associated with parkinsoniids in the south-eastern part of the Russian platform, allowing the correlation between the regional Michalskii-Besnosovi zonal boundary and the Boreal Arcticus-Greenlandicus boundary or the Northwest European Parkinsoni-Zigzag boundary (Fig. 17; Mitta 2001, 2004, 2005, 2006, 2007; Mitta & Seltzer 2002; Mitta *et al*. 2004; Saltykov 2007; Zakharov 2007).

### *Other taxonomic groups*

Several authors have proposed diverse biozonations for the Upper Bajocian and Lower Bathonian based in different taxonomic groups of macroinvertebrates (Fig. 18): brachiopods (Manceñido & Dagys 1992, Vörös 2001, Alméras *et al*. 2007), belemnites (Challinor 1992, Challinor *et al*. 1992, Combémorel 1997), nautiloids (Branger 2004), bivalves (Damborenea *et al*. 1992, Hallam 1994, Damborenea 2002, Ruban 2006), echinoderms (Thierry *et al*. 1997, Moyne *et al*. 2005), corals (Beauvais 1992).

| Stage | **Ammonite NW European standard zonation** | | **Brachiopods** (Alméras *et al*. 2007) **North-western Tethyan border** | | **Southern Tethyan border** | | **Belemnites** Combémorel, 1997 |
|---|---|---|---|---|---|---|---|
| **Lower Bathonian** | Tenuiplicatus | | Cymatorhynchia reynesi (ex. Formosarhynchia dumortieri) | Rugitela cadomensis | Callirhynchia oranensis Cymatorhynchia reynesi | Rugitela cadomensis | Duvalia disputabilis *(partim)* |
| | Zigzag | Yeovilensis | | Tubithyris whatleyensis | | Sphaeroidothyris szajnochai | |
| | | Macrescens | | | | | |
| | | Convergens | | Caucasella voultensis | | Burmirhynchia athiensis | |
| **Upper Bajocian** | Parkinsoni | Bomfordi | | | | | Megateuthis elliptica *(partim)* |
| | | Truellei | | | | | |
| | | Acris | | | | | |

*Fig. 18*. Zonations for brachiopods and belemnites (from Alméras *et al*. 2007 and Combémorel 1997).

| | **Ammonite NW European standard zonation** | | **Ostracoda** Bodergat, 1997 | | **Foraminifera** Ruget & Nicollin, 1997 | | **Dinoflagellate cysts** Riding & Thomas, 1992 Fauconnier, 1997 |
|---|---|---|---|---|---|---|---|
| **Lower Bathonian** | Tenuiplicatus | | Levis - Bathonica (*partim*) | Quasicitrella (*partim*) | L. quenstedti, L. galeata, L. polymorpha and L. argonauta (*partim*) | T. bartensteini + M. bathonica | Ctenidodinium predae (*partim*) |
| | Zigzag | Yeovilensis | | Bessinensis -Malzi- Bessinensis | | | |
| | | Macrescens | | | | | |
| | | Convergens | | | | | |
| **Upper Bajocian** | Parkinsoni | Bomfordi | Regularis - Richteri (*partim*) | | | | Acanthaulax crispa (*partim*) |
| | | Truellei | | | | | |
| | | Acris | | | | | |

*Fig. 19.* Zonations for ostracods (from Bodergat, 1997), foraminifera (from Ruget & Nicollin, 1997) and dinflagellate cysts (from Riding & Thomas 1992, Fauconnier 1997).

The following taxonomic groups of microfossils are of biochronostratigraphic relevance also (Fig. 19): foraminifera (Bassoullet 1997, Ruget & Nicollin 1997, Gräfe 2005, Cai *et al.* 2006, Saltykov 2007, Wernli & Görög 2007), ostracods (Braun & Brooke 1992, Bodergat 1997), dinoflagellate cysts (Riding & Thomas 1992, Fauconnier 1997, Poulsen & Riding 2003), radiolarians and calcareous nannofossils (Pessagno & Mizutani, 1992, Baumgartner *et al.* 1995, Cordey *et al.* 2005, Chiari *et al.* 2007). Palaeobotanical and palynological data have been recently published by: Kimura *et al.* 1992, Sarjeant *et al.* 1992, Cleal & Rees 2003, Wang *et al.* 2005, Vaez-Javadi & Mirzaei-Ataabadi 2006, Jana & Hilton 2007.

## Isotope stratigraphy

From a geochemical point of view, in the French Subalpine Basin during the Jurassic Period, several authors have emphasized that the manganese content of pelagic carbonates is related to second-order sea-level changes and episodes of hydrothermal activity that affected the chemistry of global sea water. The main transgressive phases are marked by a manganese content increase, whereas regressive phases are characterized by decreasing trends (Corbin 1994, Corbin *et al.* 2000). In the Chaudon-Norante section, 4 km north of the Bas-Auran area, the Early Bathonian maximum transgressive is marked by sedimentary condensations, associated with high manganese content (from 300 to 1370 mg $kg^{-1}$). In contrast, the Middle and Late Bathonian regressive phase coincides with low manganese content periods. These stratigraphical patterns in divalent manganese can be of either local or regional significance, being concentrated, most probably as a very early diagenetic phase, only in oxygen-depleted waters that typically underlie zones of elevated organic productivity (Jenkyns *et al.* 2002). For strontium isotope ($^{87}Sr/^{86}Sr$ ratio), oxygen isotope ($\delta^{18}O$) or carbon isotope ($\delta^{13}C$) chemostratigraphy, no data are currently available.

Volcanogenic deposits suitable for direct radio-isotope dating are not known in the section. The age of the Bajocian/Bathonian boundary has been dated 167.7 ± 3.5 Ma by Gradstein & Ogg (2004) and Gradstein *et al.* (2005).

## **Magnetostratigraphy** (R. Lanza)

In the autumn 1994, the Bas-Auran section was extensively sampled across the Bajocian/ Bathonian boundary. Some 30 hand-samples were collected and eventually cored in the rock-magnetism laboratory of Torino University. All specimens were measured with a JR-5 spinner magnetometer and thermally demagnetized using a Schonstedt furnace (Degiorgis 1996).

The specimens are characterized by three remanent magnetization components:

– a viscous (VRM) component close to the present field and removed at temperature values about 120 °C

– a secondary component stable up to values of 300 to 450 °C.

– a high-temperature component, stable between 350–450 and 480–500 °C.

The secondary component has been interpreted as a Tertiary magnetic overprint: declination points to the NW (310° to 330°), inclination is positive (30° to 50°).

The high-temperature component has been isolated only in 11 out of the 32 analyzed specimens. Its definition is difficult and often poor, because its intensity is very low, usually 10–25 % of the initial NRM. This component may be regarded as the more stable fraction of the primary Jurassic remanence acquired when the rocks formed. The fact that the primary remanence can be isolated only in few specimens and its poor definition prevent any reliable magnetostratigraphic interpretation.

The results found by Degiorgis (1996) in the Bas-Auran section have been fully substantiated throughout the southern Subalpine Chains by Aubourg & Chabert-Pelline (1999).

## Gamma-ray spectrometry

Field gamma-ray spectrometry data have been obtained by G. Pavia, P. Lazarin and L. Leroy (April 2007) and are presented in Fig. 20. Spectral gamma-ray data from the Ravin du Bès Section show an increase in the total gamma-ray counts at the Aurigerus Zone. The values are relatively low and display insignificant variation at the Bajocian-Bathonian boundary, but they show a positive peak at the top of the Lower Bathonian. Total gamma-ray logs have been used in sequence stratigraphy on the basis that gamma-ray peaks commonly correspond to maximum flooding surfaces (cf. Parkinson 1996; Deconinck *et al.* 2003; Pawellek & Aigner 2003, 2004; Pellenard *et al.* 2003; Raddadi *et al.* 2005; Ruf *et al.* 2005; Schnyder *et al.* 2006). High gamma-ray counts, low sedimentation rates and high concentrations of ammonites may be associated with the development of condensed sections. These features, however, developed both in condensed deposits of deep carbonate environments during transgressions or episodes of relative sea-level rise and in expanded deposits of shallow carbonate epicontinental platforms during regressions or episodes of relative sea-level fall (Fernández-López *et al.* 2002). The stratigraphic trend in spectral gamma-ray data associated with sedimentary condensation on the Bas-Auran area, from the Bajocian Bomfordi Subzone towards Bathonian Tenuiplicatus Subzone, provides support for an Early Bathonian deepening half-cycle of second order, lacking evidence of stratigraphic gaps at the Bajocian-Bathonian transition.

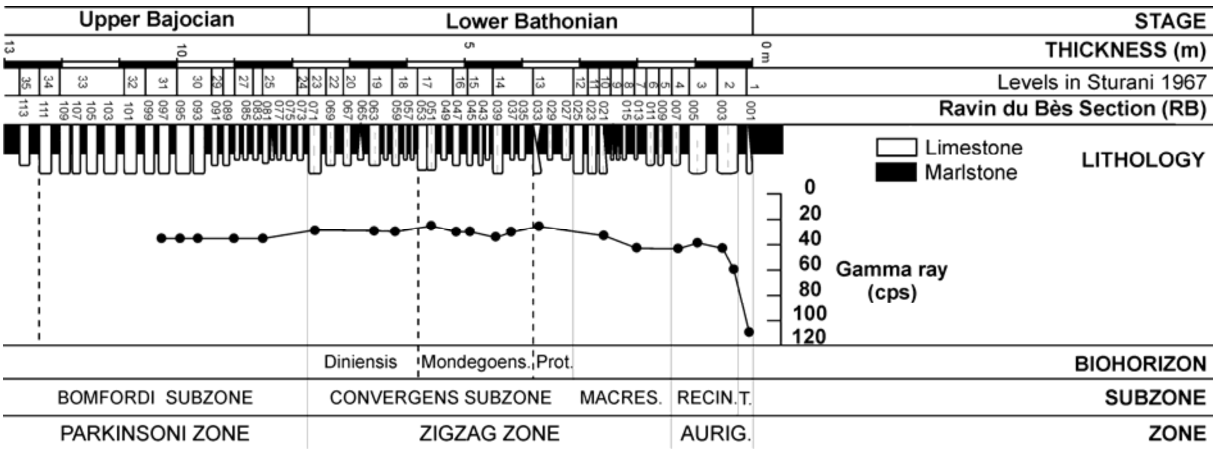


*Fig. 20.* Gamma-ray log of the Ravin du Bès Section, showing a positive peak at the top of the "Marno-calcaires à *Cancellophycus*" in the Lower Bathonian Tenuiplicatus Subzone (Aurigerus Zone).

Therefore, the current data do not support the existence of “a gap of the order of a whole biohorizon or even a subzone” (as suggested by Callomon and emailed to all members of Bathonian Working Group, 12/02/2007, but not determined or tested with palaeontological or biostratigraphic criteria). The base of the bed RB071 is a minor sedimentary and stratigraphic discontinuity (tested with sequence stratigraphy and sedimentological data, as well as with palaeoichnological and taphonomic analyses), lacking evidence of significant hiatus (such as a peak in the spectral gamma-ray data shown in Fig. 20), non-existing evidence of biostratigraphic gap (as argued with diverse criteria in the chapter of record quality by Pavia *et al.* 2008) or missing biochronostratigraphic unit (the first subzone at the base of the Zigzag Zone, with three successive biohorizons, shows the highest biochronostratigraphic completeness, so far only recognized in the Cabo Mondego and Bas Auran sections, Fernández-López *et al.* 2007).

## **Protection of the site** (M. Guiomar)

The sites of Bas-Auran and Le Bès are part of the protected territory of “La Réserve Naturelle Géologique de Haute Provence”. The Geological Reserve, which covers 55 communes in the “Alpes de Haute-Provence” and Var departments, has been entrusted with the main missions of protecting, enhancing and raising awareness of the environment and supporting economic development of this heritage. These different missions are based on scientific knowledge of geological sites and inventories. For this reason the Reserve wishes to encourage scientific studies of its territory. While some of this research is instigated and supported by the Reserve itself and conducted in collaboration with its partners, academic or other, there is also independent research, conducted with technical support from the Reserve, in particular for the authorization to collect fossils. Two types of regulations apply in protected territory: those relative to sites listed as natural reserves (Réserve Naturelle) by Ministerial decree and those relative to protected areas, by Prefectoral order (arrêtés préfectoraux). This explains why the sites of Bas-Auran and Le Bès do not have the same status. Bas-Auran is listed as a natural reserve (RN): no collecting or surface removal is possible, except by ministerial authorization. The section of Le Bès is part of the protected area where fossils may be collected and authorizations delivered for extraction or excavation (files managed by the Reserve), mainly in the context of research projects. Authorizations delivered by the Reserve in no way affect private property rights and all applications for excavation must be accompanied by a request to the owner of the land. According to the site’s scientific value, the Reserve may request that a geological site be added to or removed from listing to facilitate its management and/or protection; exceptionally, the Reserve may approach local communities for the acquisition of certain lands. For the section(s) to obtain GSSP status, it is necessary to undertake all the requisite measures to maintain free access to them as well as consider minimum developments (ease of access, safety) as well as enhancement (to be defined with scientists and managers), whenever possible.

## **The Bathonian ASP in Cabo Mondego Section (Portugal)** (S.R. Fernández-López, M.H. Henriques & C. Mangold)

An auxiliary section and point (ASP) for the base of the Bathonian Stage is located in Cabo Mondego, 40 km west of Coimbra, 7 km north of Figueira da Foz (40º11’19’’N, 8º54’30’’W, Section 02 in Fig. 21). It provides complementary data about the ammonite succession and biochronostratigraphic subdivision of the Sub-Mediterranean Parvum Subzone and the Northwest European Convergens Subzone.

These classical fossiliferous deposits have been studied by numerous specialists (Ruget-Perrot 1961; Elmi *et al.* 1971; Mangold 1971c, 1990; Rocha *et al.* 1981, 1987; Mangold & Rioult 1997; Fernández-López & Henriques 2002; Fernández-López *et al.* 2006a, b). The Bathonian deposits correspond to the Cabo Mondego Formation and comprise limestone-marl alternations, with ammonoids, bivalves (*Bositra*), rhynchonellid brachiopods, crinoids and belemnites. Bioturbation structures are common (*Zoophycos*, *Thalassinoides*, *Chondrites*). These fossiliferous deposits were developed in an open sea, in hemipelagic environment of distal and outer carbonate ramp, below wave base (Watkinson 1989, Soares *et al.* 1993, Azerêdo *et al.* 2003).

In the Lusitanian Basin, Upper Bajocian and Lower Bathonian Phylloceratina and Lytoceratina represent less than 1% of the total ammonoid assemblage, and parkinsonids are very scarce (less than 5.0%). Successive ammonoid fossil assemblages are composed of Submediterranean taxa, but they allow correlation with the zonal scales of the diverse basins of the Mediterranean and NW European provinces.

The base of the Bathonian and has been established by the lowest occurrence of representatives of the *Morphoceras* [M] - *Ebrayiceras* [m] group, at the base of the marly interval 123 of Section-02 (Fig. 22), which corresponds to the base of the marly interval FC1 of Section-90. The Lower Bathonian index ammonite *Morphoceras parvum* occurs in the marly interval 02CM139. The Lower Bathonian index ammonite *Gonolkites convergens* occurs in the marly interval 02CM181. From a biochronostratigraphic point of view, 10 metres of thickness with 62 successive ammonoid fossil-assemblages from 77 successive fossiliferous stratigraphic intervals have been recognized and sampled in the Parvum Subzone.

New taxa of Perisphinctidae, based on data from Cabo Mondego, are of primary relevance for the biochronostratigraphic subdivision and correlation of the Submediterranean Parvum Subzone. The lowest occurrences of *Bigotites mondegoensis* and *Protozigzagiceras* correspond to two successive biostratigraphic events allowing distinction of three successive biohorizons in the Parvum Subzone in Cabo Mondego (Lusitanian Basin) and Bas Auran (Alpine Basin): the Diniensis, Mondegoensis and Protozigzagiceras biohorizons (Fernández-López *et al.* 2007, Pavia *et al. 2008*). The Diniensis Biohorizon is represented by the stratigraphic intervals 02CM123–02CM145 in Section 02 and FC1–FC17 in Section 90 (Fig. 22). The Mondegoensis Biohorizon is represented by the stratigraphic intervals 02CM146–02CM182 (Section 02) and FC18–FC43 (Section 90), taking into account the occurrence of *B. mondegoensis* at the level 02CM146. The Protozigzagiceras Biohorizon is represented by the stratigraphic intervals 02CM183–02CM198 (Section 02) and FC44–FD11 (Section 90), taking into account the occurrence of *Protozigzagiceras* at the level 04CM183.

New provisions for the conservation and protection of this Portuguese outcrop have now been implemented under national laws, after the classification of the Cabo Mondego area as a Natural Monument of the Portuguese Republic in 2007 (Henriques & Ramalho 2005, Page *et al.* 2006).

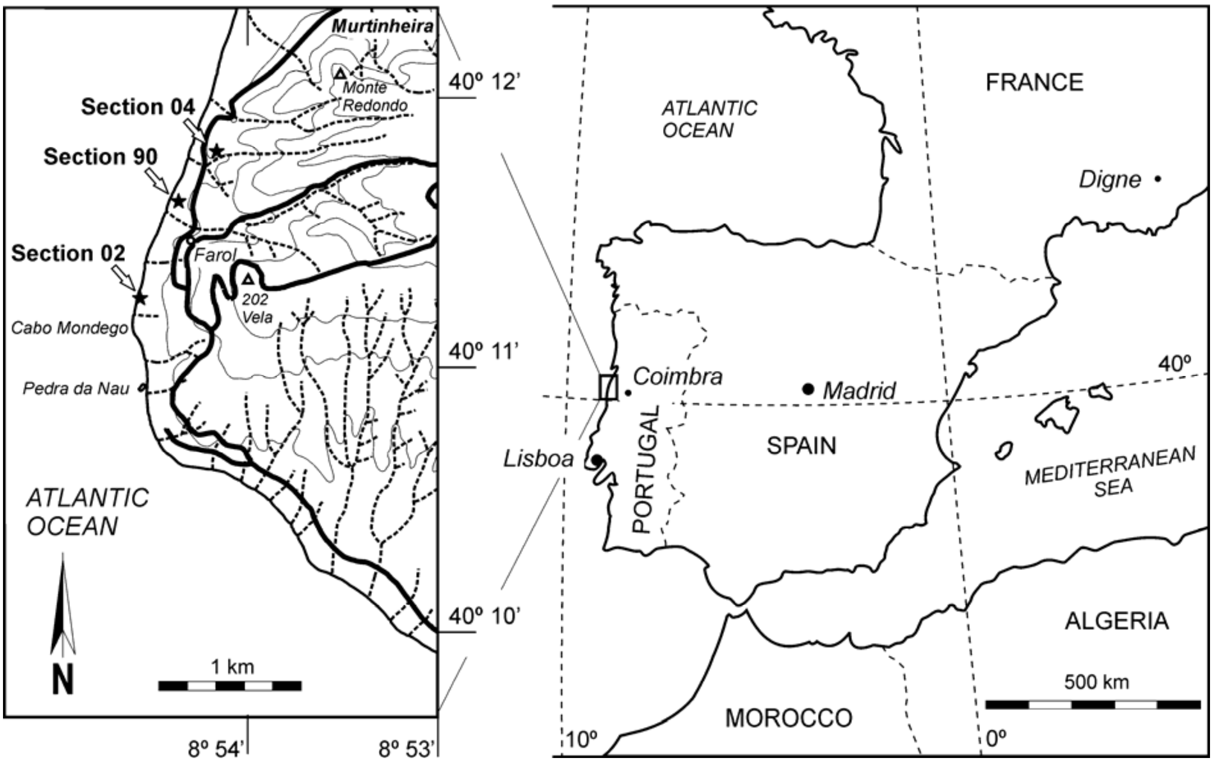


*Fig. 21*. Location maps of three stratigraphic sections of Cabo Mondego (Portugal, from Fernández-López *et al.* 2006a).

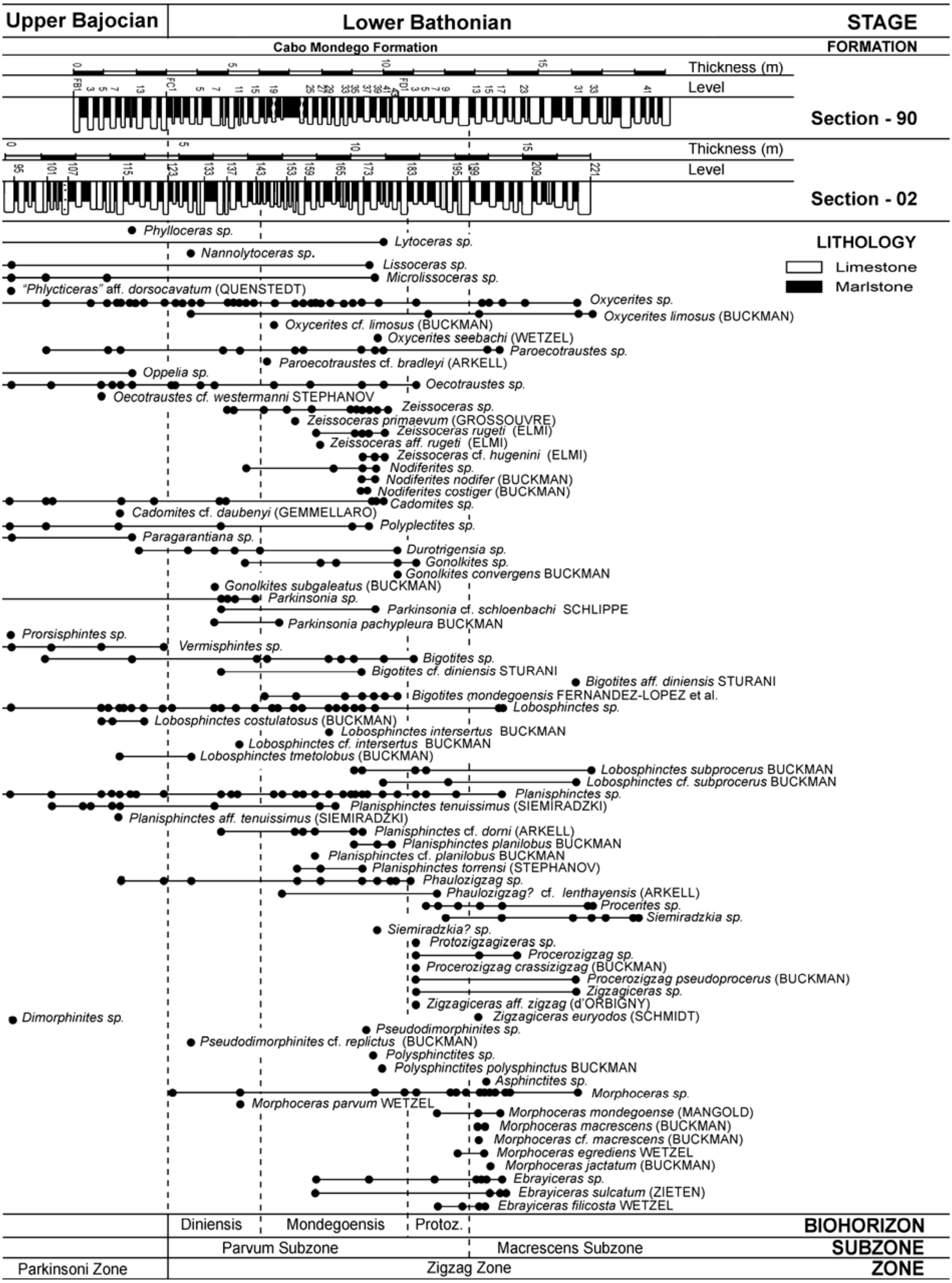


*Fig. 22.* Ammonite biochronostratigraphic data at the Bajocian/Bathonian boundary in the Section-90 and Section-02 of Cabo Mondego (Portugal, from Fernández-López *et al.* 2006ab modified).

## Summary

The leading candidate Global Boundary Stratotype Section and Point for the base of the Bathonian Stage at the Ravin du Bès Section (France) satisfies most of the requirements recommended by the ICS (e.g. in Remane *et al.* 1996, Gradstein *et al.* 2003, Morton 2006, cf. Fig. 23):

- The exposure extends over 13 m in thickness, comprising five metres of fossiliferous levels below the boundary and eight metres above. The stratigraphic succession can be recognized laterally over several hundred metres distance.
- At the Bajocian-Bathonian transition, no vertical (bio-, ichno- or tapho-) facies changes, stratigraphic gaps or hiatuses have been recorded. There is no evidence of taphonomic condensation (i.e. mixture of fossils of different age or different chronostratigraphic units). In relation to the rate of sedimentation, the Bomfordi and Convergens subzones are over 10 m thick.
- Structural complexity, synsedimentary and tectonic disturbances, or important alterations by metamorphism are not relevant constraints in the Bas-Auran area.
- The hemipelagic, bed-scale limestone-marl alternations show a maximum value of biostratigraphic completeness for the Bajocian/Bathonian transition. The Northwest European primary standard Convergens Subzone and the Sub-Mediterranean secondary standard Parvum subzones are in fact precisely coeval in the Bas-Auran area. Through five metres of thickness, forty-six successive ammonoid fossil-assemblages in Ravin du Bès Section belonging to three biohorizons of the Parvum Subzone have been recognized. The Bomfordi Subzone attains a minimum thickness of 5 m and includes 42 successive ammonoid fossil-assemblages.
- The boundary has been characterized by both primary and secondary (auxiliary) biostratigraphic markers. There is a well-preserved, abundant and diverse fossil record across the boundary interval, with key markers (ammonites and nannofossils) for worldwide correlation of the uppermost Bajocian and Lower Bathonian. The section appears to be suitable for biostratigraphic study of microfossils, such as foraminifera, but as yet there are no published studies.
- Regional analyses of sequence stratigraphy and manganese chemostratigraphy are available. A transgressive systems tract associated with a deepening phase and sedimentary starvation, within 3rd and 2nd order deepening/shallowing cycles, was developed in the Bas-Auran area of the French Subalpine Basin, during the Early Bathonian. No data are currently available for strontium isotope ($^{87}Sr/^{86}Sr$ ratio), oxygen isotope ($\delta^{18}O$) or carbon isotope ($\delta^{13}C$) chemostratigraphy.
- The stratigraphic trend in spectral gamma-ray data provides support for an Early Bathonian deepening half-cycle of second order, lacking evidence of stratigraphic gaps at the Bajocian-Bathonian transition.
- Bajocian and Bathonian deposits have been remagnetized with a steady normal polarity. The requirement of suitability for magnetostratigraphy and geochronometry, however, can be indirectly satisfied by reference to the Bathonian magnetostratigraphic scale of Steiner *et al.* (1987, O'Dogherty *et al.* 2006) as defined in the Subbetic Cordillera.
- Volcanogenic deposits suitable for direct radio-isotope dating are not known in the section. According to the data published by Gradstein & Ogg (2004) and Ogg (2004), the age of the Bajocian/Bathonian boundary is 167.7 ± 3.5 Ma in other basins.
- The criteria of accessibility, conservation and protection are assured by the "Réserve Naturelle Géologique de Haute Provence", protected under national law and recognised by UNESCO. The park is managed by the "Centre de Géologie de Digne".
- The Cabo Mondego Section is suggested as the Bathonian ASP within the same GSSP proposal. It provides complementary data about the ammonite succession and biochronostratigraphic subdivision of the Sub-Mediterranean Parvum Subzone and the Northwest European Convergens Subzone, at the basal Bathonian Zigzag Zone. Accessibility, conservation and protection are guaranteed, after the classification of the Cabo Mondego area as a Natural Monument of the Portuguese Republic in 2007.

| The requirements for a GSSP (ICS) | Ravin du Bès Section (Bas-Auran) |
|---|---|
| **GEOLOGICAL REQUIREMENTS** | |
| Exposure over an adequate thickness | Yes |
| Continuous sedimentation. No gaps or condensation close to the boundary | Yes |
| Rate of sedimentation | About 4.5 m for the Parvum Subzone and at least 5 m for the Bomfordi Subzone |
| Absence of synsedimentary and tectonic disturbances | Yes |
| Absence of metamorphism and strong diagenetic alteration | Yes (for macrofossils) |
| **BIOSTRATIGRAPHIC REQUIREMENTS** | |
| Abundance and diversity of well-preserved fossils | Abundant and well preserved ammonites |
| Absence of vertical facies changes at or near the oundary | Yes |
| Favorable facies for long-range biostratigraphic correlations | Yes |
| **OTHER METHODS** | |
| Radioisotopic dating | No information |
| Magnetostratigraphy | No significant result |
| Geochronometry | No information |
| Sequence stratigraphy | Graciansky *et al.* 1993, 1998 |
| Gamma-ray spectrometry | Yes, supporting sequence-stratigraphy results |
| **OTHER REQUIREMENTS** | |
| GSSP indicated by a permanent fixed marker | Yes, if accepted |
| Physical and logistical accessibility | Yes |
| Free access for research | Yes |
| Permanent protection of the site | Part of the European Geopark: "Réserve Naturelle Géologique de Haute Provence" |

*Fig. 23.* Summary of the requirements of the International Commission on Stratigraphy for Ravin du Bès Section (Bas-Auran).

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