Updated calpionellid zonation around the Jurassic–Cretaceous boundary in NE Algeria ("Ravin Bleu" site, Batna Mountains): A potential regional stratotype for the North Africa Maghrebian Ranges

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Abstract: In NE Algeria and the Tunisia–Algeria border chains, detailed stratigraphic investigations across the Jurassic–Cretaceous boundary (JKB) are scarce and this important stratigraphic interval remains poorly known. This work attempts fulfilling this gap of our knowledge on the JKB successions in this area. It represents unpublished data on calpionellid zonations, based on bed-by-bed sampling, of two sections from the "Ravin Bleu" site of Batna Mountains. In the Jebel Kasserou and J. Bou Merzoug study sections, most of the standard Upper Tithonian–lowermost Valanginian calpionellid zones and subzones are first identified here. Their limits correspond to main calpionellid bioevents allowing to recognize a new Alpelliptica Subzone of the Calpionella Zone in the Lower–Middle Berriasian; subsidiary bioevents being useful to delimit six horizons in the Upper Tithonian Crassicollaria Zone and two others in the Middle Berriasian Elliptica Subzone. All these biostratigraphic units are correlated with their lateral equivalents in other Tethyan sections, mainly from Morocco, Tunisia, SE France, Spain, the Carpathian Ranges and the Balkanides. Chitinoidellid and most of the calpionellid species from Eastern Algeria are first illustrated here. In addition to their easy access and good outcrops, the continuous, complete and thick marine study successions are devoid of strong diagenetic alteration, synsedimentary features and tectonic effects. The "Ravin Bleu" site is proposed herein as a potential reference section for the JKB interval in the North Africa Maghrebian Ranges of the SW Tethys Margin.

Keywords: Jurassic–Cretaceous boundary, calpionellid zonation, NE Algeria, Batna Mountains, "Ravin Bleu" site, regional stratotype

Introduction

Considering the recommendations of the ICS (International Commission on Stratigraphy) (Remane et al. 1996), a particular attention has been paid to fix a boundary point within a well-defined stratotype (GSSP, Global Standard Section and Point) for the Berriasian stage around the Jurassic–Cretaceous boundary (JKB) interval. Among the stratigraphic biomarkers used for the definition of the Tithonian–Berriasian boundary; calpionellids have been considered as excellent tools, and the base of the Alpina Subzone as the primary marker for the Berriasian lower limit (Wimbledon et al. 2020). In Algeria, pioneer works on ammonite and calpionellid zonations have been focused on the western part of the country (e.g. Atrops et al. 1983; Benest et al. 1993; Atrops & Benest 1994; and references therein). However, in Eastern Algeria, available data on the relatively scarce JKB successions are still imprecise. To our knowledge, only two published old papers (Donze et al. 1974; Aïssaoui et al. 1982) may constitute basic references for calpionellid zonations around the JKB interval in this sector. No calpionellid figurations are available as no detailed calpionellid subzones were identified.

This work comes within the scope of litho- and biostratigraphic revisions leading to interregional correlations with the relatively well dated series of Tunisia and Morocco. We particularly focus on the uppermost Jurassic and lowermost Cretaceous units of the Jebel Bou Merzoug (RB.I), and Jebel Kasserou (RB.II) section of the "Ravin Bleu" site (Batna Mountains, Batna area, NE Algeria). It aims at: (1) a first detailed zonation using calpionellid biomarkers as promising tools; (2) checking the validity of this biozonation and corresponding bioevents with regard to regional charts established in the neighbouring South Tethys Maghrebian areas and their equivalents from North Tethyan sites; (3) first illustrating the main calpionellid and chitinoidellid specimens; and (4) discussing the suitability of the investigated site as a potential regional stratotype for the Maghrebian JKB interval.

Location and structural context of the study sections

Between the Mediterranean Sea, to the North, and the Saharan Platform, to the South, the E–W trending Maghrebian orogenic Belt of North-West Africa comprises (Fig. 1A):

- The Northern Tell-Rif Alpine chain, a part of the Maghrebides that extends north-eastwards to Sicily and South Italy, mainly composed of South-verging fold and thrust structures, and characterized by the occurrence of flysch deposits and High-Pressure metamorphism;
- The E–W and ENE–WSW elongated Atlassic domain, including the High and Middle Atlas of Morocco, the Algerian Saharan Atlas and Aurès Mountains, and the Tunisian Atlas. This wide domain is characterized by weaker general

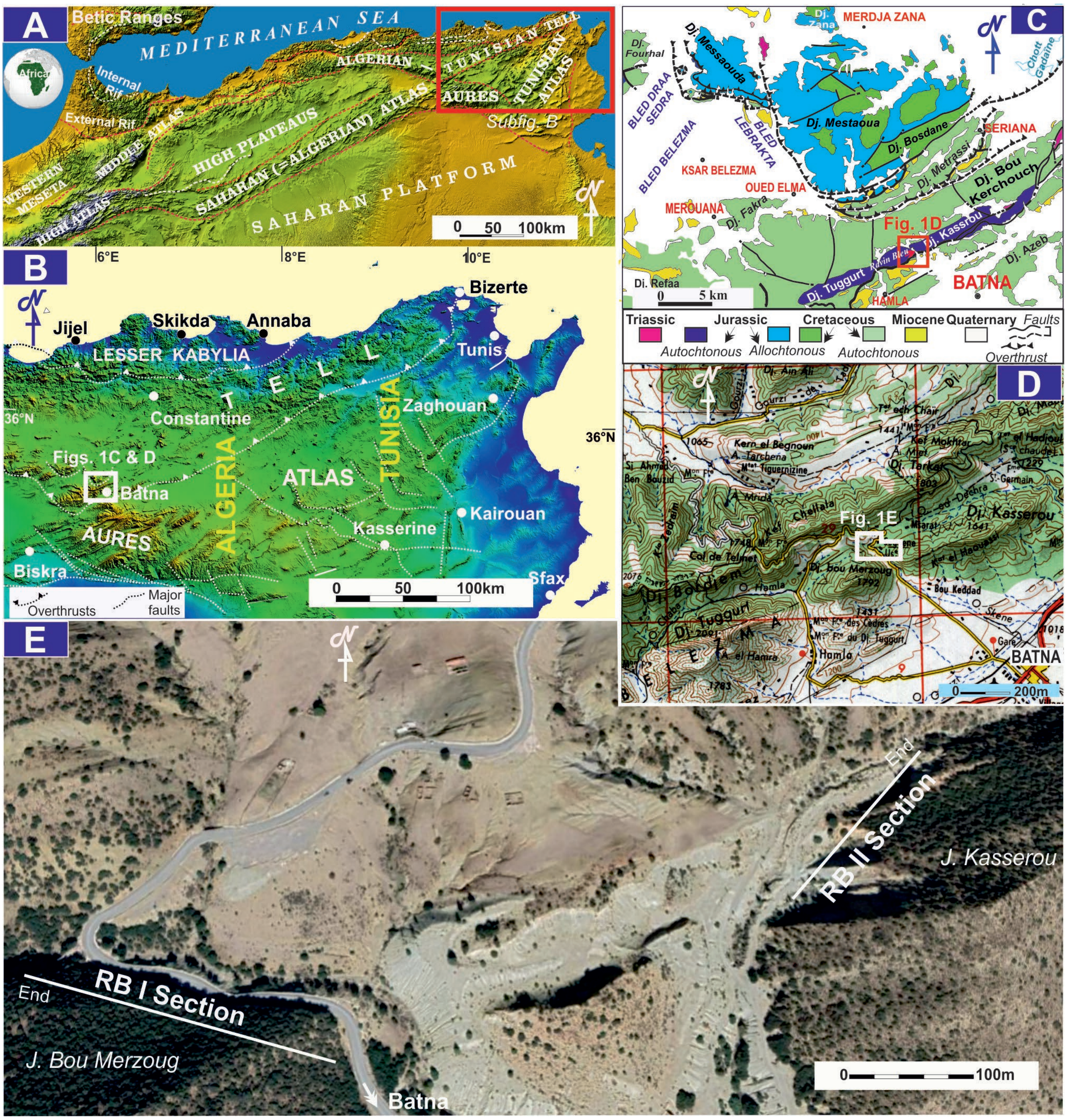

Fig. 1. A — Structural map of North-West Africa showing the main geological domains. **B** — Map of North-East Algeria and Tunisia, and location of the study area. **C** — Simplified geological map of the study area (after Vila 1980). **D** — Topographic map of the study area (Topographic map of Merouana (ex. Corneille), Scale : 1/50,000. Sheet Nr 172. Editions of the French Ministry of Public Works and Transports, Geographic Service of Army, National Geographic Institute, 1961). **E** — "Google Earth" aerian view of the study area and location of the study sections RB.I and RB.II.

shortening structures with an overall steep dip, separated from the Saharan Platform by the South-Atlasic major fault extending from Agadir, in Morocco, to the Gabès area in Tunisia.

Between these structural domains, a pre-Atlassic transitional zone includes the Batna Mountains that extend north-eastward to the Chebket Sellaoua, in Algeria, and the Tunisian North-Western thrust sheets of Ghardimaou and adjacent areas (Fig. 1B). The Jebel Tuggurt–Bou Merzoug–Kasserou NE–SW alignment, object of this study, belongs to the Batna Mountains of this transitional domain. It is cut by a major NE–SW fault affecting both the Jurassic core and successive units as well as lateral Miocene transgressive series (Fig. 1C). This structure is interpreted as the effect of superimposed "Atlas" and "Alpine" tectonic events of Middle-Late Eocene and Upper Miocene age, respectively (e.g. Frizon de Lamotte et al. 1998). As a result, the Jebel Bou Merzoug–Kasserou chain is considered as a fault-propagation fold, developed above a Triassic evaporitic "décollement" plan and altered by a secondary Alpine-aged break through (*ibid*).

To reach easily this study site, we can take the N5 national ring road that bypasses the town of Batna (Fig. 1D) from which another W5 road branches off at the level of the Kechida industrial Zone, heading NW towards the villages of Wadi el Ma and Marouana through the Jebel Chlaala. About 5 km from the junction, this W5 road crosses the gorge separating the relieves of Jebel Kasserou (1641 m) and Jebel Bou Merzoug (1792 m). On both sides of this road and adjacent ravine, the Jebel Bou Merzoug (RB.I) and Jebel Kasserou (RB.II) sections of the "Ravin Bleu" site (Fig. 1E) were sampled, at the respective GPS coordinates: 35°35'56.832"N, 6°6'47.160"E (RB.I) and 35°35'47.364"N, 6°6'34.740"E (RB.II).

Material and methods

The study sections were bed-by-bed sampled. A total of 179 thin sections has been made and observed under a polarized Zeiss microscope and photographed by a Canon incorporated camera. Only beds bearing relatively well preserved calpionellid specimens are matched with their content in Figs. 2 and 3, illustrating the calpionellid distribution for each study section.

Calpionellid specimen determinations and corresponding zones in both sections are separately made by two of us (I. Ch., M. B.) and taxonomic interpretations took into account restored oblique sections of calpionellids as recently proposed by Boughdiri et al. (2020). Obtained biostratigraphic results are then cross-checked and an agreement was made on the exact bed under which a given limit can be traced.

Calpionellid zones and subzones are considered as "interval" biostratigraphic units, the base of each is placed considering the first appearance (FO) of index species, cross-checked by characteristic associations, and (or) complemented by the abundance of marker taxa. Subsidiary calpionellid bioevents allow to distinguish stratigraphic intervals within subzones, to each a "Horizon" rank is assigned for detailed correlation purposes. The reference scales used here are mainly those of Remane (1963) and Remane et al. (1986). For correlations purposes and complementary data, we referred to regional charts proposed by Allemann et al. (1971); Le Hégarat & Remane (1968), for SE France; Oloriz et al. (1995), for SE Spain; Pop (1994, 1997, 1998), Reháková & Michalík (1997), Michalík & Reháková (2011), for the Carpathian Ranges; Lakova et al. (1999), Lakova & Petrova (2013), and Petrova et al. (2019), for the western Balkan chains; Boughdiri et al. (2009) and Ben Abdesselam et al. (2010), for the Tunsian Atlas; Benzaggagh & Atrops (1995a, b, 1997), Benzaggagh et al. (2010) and Benzaggagh (2020), for the Moroccoan Prerif and Mesorif. Thin sections are stored in the Stratigraphy and Sedimentology Laboratory of the Earth Science Department of the Faculty of Sciences of Bizerte (Tunisia).

Results

The lithological succession, calpionellid-bearing beds and zonation bioevents for each of the study sections are presented here (Figs. 2, 3). Considering the complementarity of these sections, a synthetic chart is proposed for the whole site as a basis for interregional correlations.

Lithological successions, calpionelid distribution and zonations

The Jebel Bou Merzoug RB.I section

The general lithology of this section consists of alternations of grey blue limestone beds and greenish to blue marly levels. The relative thickness of these lithological components allows to distinguish two main carbonate informal units (RB.I-A and RB.I-C) separated by a well individualized more marly interval (RB.I-B).

The RB.I-A unit (beds 55–215; 129.37 m) is composed of dark blue limestone beds alternating with greenish blue marl intervals. The first chitinoidellids represented by *Chitinoidella* aff. *boneti* Doben (Fig. 4A), *Ch. elongata* Pop and *Ch. hegarati* Sallouhi et al. were observed within the bed 64; *Ch. carthagensis* Sallouhi et al. (Fig. 4B) first occurring higher, in the bed 80. This association allows identifying the lower limit of the Boneti Subzone of the Chitinoidella Zone traced below the bed 64. Since no chitinoidellid association characterizes the lowermost beds of the unit RB-A (RB.I-55–63), this lower limit of the Boneti Subzone is also considered here as a possible marker for the upper Dobeni Zone and Lower–Upper Tithonian transition.

Higher, in the beds 69, 111 and 122, a few calpionellid forms, close to the *Praetintinnopsella andrusovi* Borza group, are observed (Fig. 4C, D). However, their scarcity, state of conservation and doubtful taxonomic interpretation do not allow to confidently delimit a possible Praetinnopsella Zone.

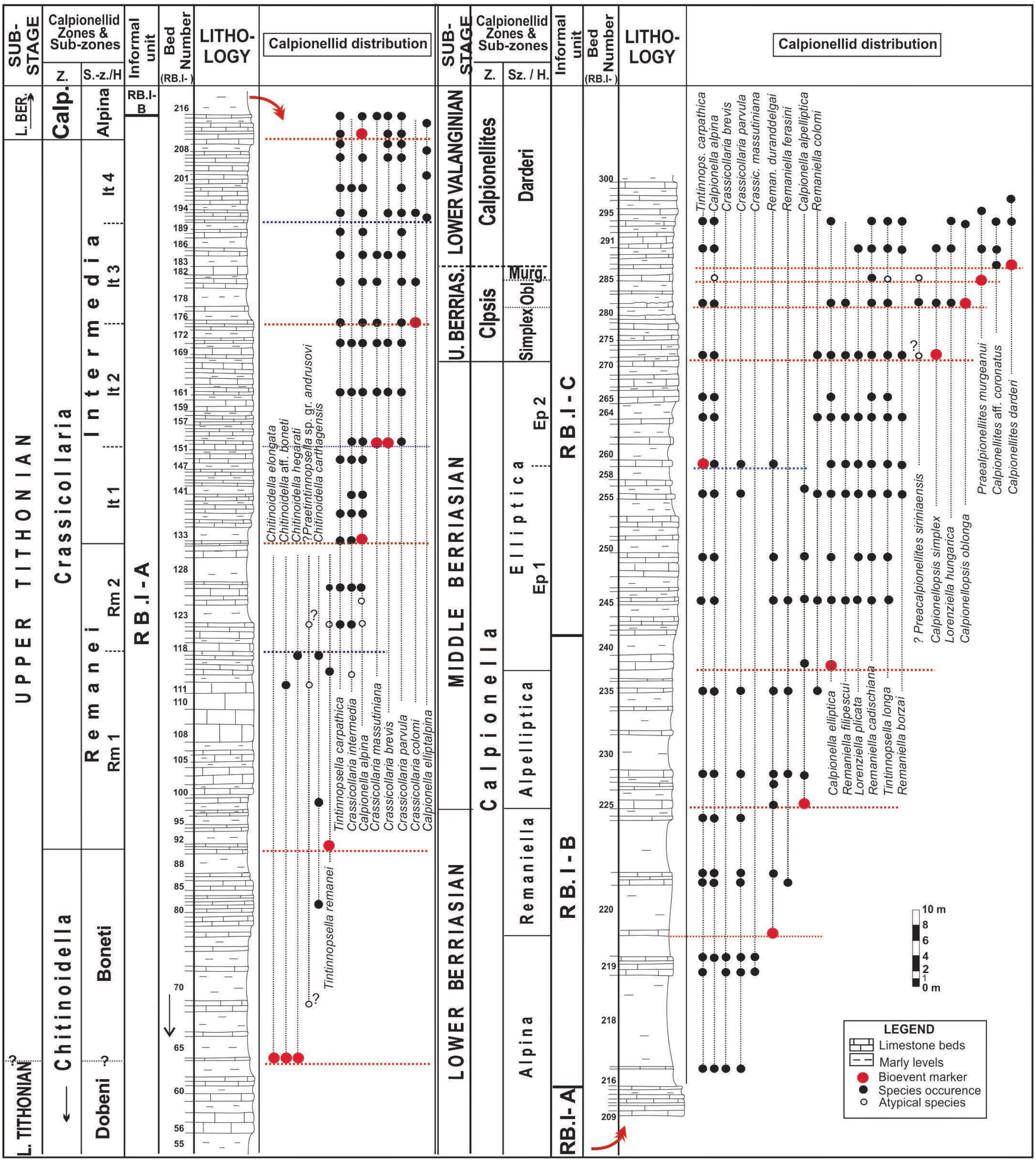

Fig. 2. Lithological succession, calpionellid distribution and biozonation of the RB.I section.

The first occurrence (FO) of hyaline calpionellids represented by *Tintinnopsella remanei* Borza (Fig. 4E) is noted within the bed 90 which allows tracing the base of the Remanei Subzone of the Crassicollaria Zone *sensu* Remane et al. (1986) (=Subzone A1 of Remane (1963)) below this bed 90. In parallel, considering the last occurrence (LO) of chitinoidellids in the bed 117, two stratigraphic intervals within the Remanei Subzone can be delimited. The first transitional horizon (Rm1: RB.I-90–117) yields the last chitinoidellids, *T. remanei*, ?*Praetintinnopsella* sp. gr. *andrusovi* and atypical primitive calpionellids mainly represented by small *C. alpina* and *T. intermedia.* The second horizon (Rm2: RBI-118–131) is restricted to beds where chitinoidellids are totally absent with the occurrence of first typical hyaline calpionellids.

Upsection, big-sized *Calpionella alpina* Lorenz (=*C.* "*grand-alpina*" Nagy) (Fig. 4F) are observed within the bed 132, at the base of which the lower limit of the Intermedia Subzone of calpionellids can be traced. This subzone extends up to the bed 210 that marks the base of the overlying Calpionella Zone. It is subdivided into four horizons considering three characteristic bioevents: (1) the quasi-simultaneous appearance of *Crassicollaria brevis* Remane and *Cr. massutiniana* (Colom (Fig. 4K) in RB.I-151; (2) the FO of *Cr. colomi* Pop (Fig. 4L) in RB.I-152, and 3) the FO of large, somewhat elongated forms of *Calpionella alpina* Lorenz (= *Calpionella elliptalpina* Nagy) (Fig. 4H) in RB.I-209. These horizons are designated: It1 (RB.I-132–151), It2 (RB.I-152–174), It3 (RB.I-175–189) and It4 (RB.I-190–209).

To the topmost of the RB.I-A unit, a notable abundance of isometric small-sized *Calpionella alpina* (Fig. 4G) is observed since the bed 210 at the base of which we place herein the lower limit of the Alpina Subzone (Calpionella Zone) of calpionellids *sensu* Remane et al. (1986) (= "B" Zone of Remane (1963)). Correlated with the base of the lowermost Berriasian Jacobi Zone of ammonites (Enay & Geyssant 1975; Cecca et al. 1989; Benzaggagh & Atrops 1995a), this limit is also considered as the primary marker of the Jurassic–Cretaceous boundary (Wimbledon 2017).

The mainly carbonate unit RB.I-A is overlain by a thick more marly interval with rare limestone intercalations (= Unit RB.I-B; beds 216–240; 57.18 m). This unit starts with marl/limestone alternations (beds 216–222; 34 m) where calpionellid associations of the base consist of sporadic occurrences of rare *Cr. massutiniana* (Colom), still present in the Calpionella Zone, together with abundant *C. alpina*, *Cr. parvula* and scarcer *Tintinnopsella carpathica*. The first specimens of *Remaniella duranddelgai* Pop (Fig. 4O) in the bed 219, and mark the base of the Remaniella Subzone. This is confirmed by the FO of *R. ferasini* (Catalano) (Fig. 4N) in the bed 221. A bit Higher, the bed 225 yields the first *Calpionella alpelliptica* Nagy (Fig. 4I) indicating the lower limit of the Alpelliptica Subzone, newly proposed here and considered as a reliable equivalent of the "B3" Subzone of Benzaggagh et al. (2012) and the "Alpina/Alpelliptica" Subzone of Benzaggagh (2020).

Higher, the first appearance of *C. elliptica* Cadisch (Fig. 4J) was noted in the bed 239. This is followed by the FO of *R. cadischiana* (Colom) together with *Tintinnopsella* aff. *longa* (Colom) (Fig. 4S) and *Lorenziella hungarica* Knauer and Nagy (Fig. 4W) within the upper part of the bed 249. These bioevents allow tracing the lower limit of the Elliptica Subzone (Calpionella Zone) below the bed 239.

Through this subzone, the bed 259 is mainly characterized by the relative abundance of large *Tintintinnopsella carpathica* (Fig. 4M) prevailing over diverse forms of *C. alpina*. This bioevent allows to separate two horizons within the Elliptica Subzone (Ep1: RB.I-240–258; Ep2: RBI-259–270). Both horizons are correlated with the respective "C1" and "C2" stratigraphic intervals of Benzaggagh et al. (2010, 2012), and the "Elliptica–Alpina" and "Elliptica–Carpathica" Subzones of Benzaggagh (2020).

To the topmost of the study section, the bed 271 is characterized by the first *Calpionellopsis simplex* (Colom) (Fig. 4U), accompanied by scarce atypical forms close to *Praecalpionellites siriniaensis* Pop (Fig. 4X), that marks the lower limit of the Calpionellopsis Zone. Within this Zone, the base of the Oblonga Subzone can be traced below the bed 281 where the index species *Calpionellopsis oblonga* (Colom) was observed.

The last sampled beds of the RB.I-C unit, over a thickness of 13 meters preceding the first sandstone bed of the overlying Flysch deposits, show the FO of *Praecalpionellites murgeanui* (Pop) in the bed 285, that of *Calpionellites darderi* (Colom) (Fig. 4R, V) and *Calpionellites* aff. *coronatus* (Fig. 4Y) within the beds 287 and 295. In this latter bed, *R. borzai* Pop (Fig. 4Q) and *Remaniella catalanoi* Pop are also a part of the association. The first bioevent indicates the base of the Murgeanui Subzone, traced below the bed 285. Two meters higher, the lower limit of the Darderi Subzone (Calpionellites Zone) is placed below the bed 287. This latter limit can also be correlated with the Berriasian–Valanginian transition.

The J. Kasserou RB.II-section

This section exhibit the same general lithology of the J. Bou Merzoug RB.I section. Similarly, the relative thickness of limestone beds and marly levels allows to distinguish two informal units RB.II-B (beds 1–60; 56 m) and RB.II-C (beds 61–140; 52 m); both being of the same facies than RB.I-B and RB.I-C of the above-described RB.I section.

In the lowermost part of the section (beds 2–12a), the calpionellid association includes a constant occurrence of *T. carpathica*, *C. alpina* and *Cr. parvula*. Upsection, the same biozonation procedure applied to the RB.I section serves to identify the calpionellid key bioevents. In fact, the FO of *Remaniella duranddelgai* and *R.* aff. *colomi* (Fig. 4T) within the lowermost bed of RB.II.12b indicates the Remaniella Subzone of the Calpionella Zone. Hence, the succession below this bed 12b is attributed to the Alpina Subzone (Calpionella Zone). *Calpionella alpelliptica* appears in the bed 28 as does *C. elliptica* within the bed 53 of the same unit. On this basis, the lower limit of the Alpelliptica Subzone is placed below the bed 28 and its upper limit below the bed 53.

Considering the relative abundance of large *Tintinnopsella carpathica* in the bed RB.II-113, the Elliptica Subzone is subdivided into two horizons (Ep1: RB.II-61–112 and Ep2: RB.II-113–119). The FO of *Cps. simplex* within the bed 120 marks the base of the Simplex Subzone (Calpionellopsis Zone); the upper limit of this latter Subzone (= base of the Oblonga Subzone) being traced below the bed 124 where the FO of *Cps. oblonga* and accompanying *Lorenziella hungarica* is observed. To the topmost of the section, the bed RB.II-133 marks the FO of *Praecalpionellites murgeanui* and *Praec. siriniaensis* indicating the base of the D3 Subzone of Le Hégarat and Remane (1968). Within the upper part of the limestone bed 135, were observed the first *Calpionellites darderi* together with *Cptes*. aff. *coronatus*; both indicating the lower limit of the Darderi Subzone.

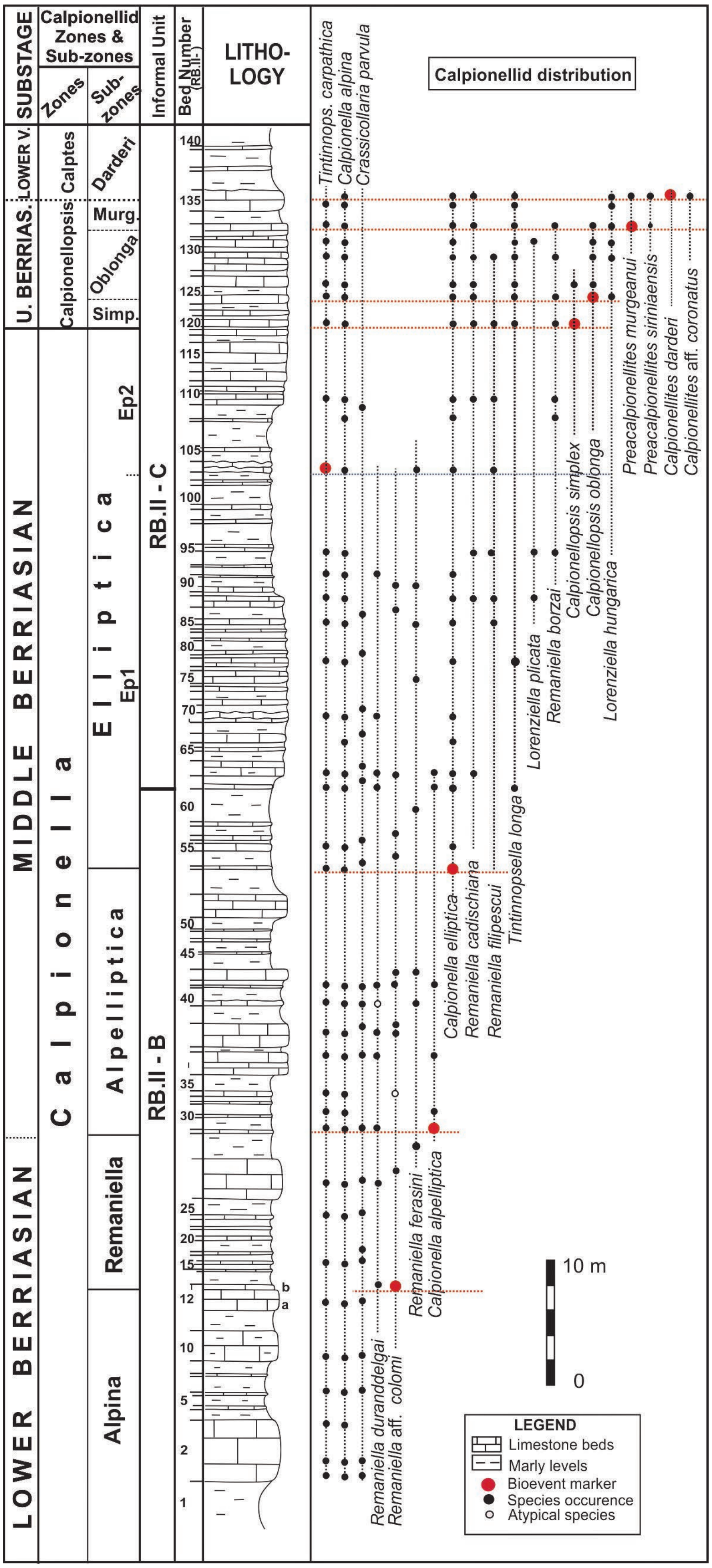

Fig. 3. Lithological succession, calpionellid distribution and biozonation of the RB.II section.

Identified zones from NE Algeria, calpionellid content and correlations

Figure 5 illustrates a preliminary synthesis of the calpionellid distribution and key bioevents through the complementary sections RB.I and RB.II, and the corresponding identified biozones. This regional chart needs to be completed (improved) considering further data gathered in neighboring sections of NE Algeria.

Chitinoidella Zone (Boneti Subzone)

As introduced by Enay & Geyssant (1975) and defined by Grandesso (1977), this zone corresponds nearly to the total range of microgranular-walled chitinoidellids, and its upper limit coincides with the base of the Crassicollaria Zone. It was subdivided by Borza (1984) into the Dobeni and Boneti Subzones.

In the Jebel Bou Merzoug section, only the Boneti Subzone was identified by large-sized *Chitinoidella* aff. *boneti*, *Ch*. *carthagensis*, *Ch*. *elongata* and *Ch*. *hegarati*. Its upper limit coincides with the FO of *Tintinnopsella remanei*. No small chitinoidellis of the Dobeni Subzone were documented from the lowermost beds of the section which is considered here as of a probable Dobeni Subzone age. Scarce *Praetintinnopsella*-like forms were documented in the upper part of the Boneti Subzone and may extend higher through the lower part of the Crassicollaria Zone. However, their scarcity and doubtful taxonomic interpretation do not allow to trace the lower limit of a possible Praetintinnopsella Zone with certainty as proposed by Pop (1994), Reháková & Michalík (1997), Lakova et al. (1999) and Petrova et al. (2019). Hence, the Boneti Subzone of these latter authors, and that of Benzaggagh et al. (2012) and Benzaggagh (2020) are nearly correlatives (Fig. 5); it is a probable equivalent of the beds yielding the calpionellid "Association I" of Oloriz et al. (1995).

Crassicollaria Zone

Defined by Allemann et al. (1971) as an equivalent of the "A" Zone of Remane (1963, 1971), its lower limit corresponds to the FO of hyaline-walled calpionellids, and its upper part is defined by the base of the overlying Calpionella Zone. In the Jebel Bou Merzoug section, it can be suddivided into the Remanei and Intermedia Subzones. Secondary bioevents allow to distinguish stratigraphic intervals, erected here as "horizons", biostratigraphic units of a lower rank than subzones, which may serve as precious markers for detailed correlation purposes.

Remanei Subzone

As an equivalent of the "A1" Subzone of Remane (1963, 1971), the Remanei Subzone (Remane et al. 1986) was defined by the FO of *Tintinnopsella remanei* and, a bit later, by the first small *Tintinnopsella carpathica*. This bioevent is considered here as a mark for the base of the Remanei Subzone which upper limit coincides with the FO of large-sized varieties of *Calpionella alpina* (=*C. grandalpina* Nagy). In the RB.I section, the LO of chitinoidellids and the FO of *Tintinnopsella remanei* are diachronic so that a transitional interval where overlap the first *T. remanei* and last chitinoidellids can be identified. In fact, the Remanei Subzone of the RB.I section can be subdivided into two horizons (Rm1 and Rm2, Fig. 5) with distinct associations. The first includes an overlap of the still present *Chitinoidella boneti* group, primitive *Cr. intermedia* and *T. carpathica*, and *Tintinnopsella remanei*; the second association gathering small- and medium-sized calpionellids of the *C. alpina* and *T. intermedia* group with a total absence of chitinoidellids. These two successive horizons can be correlated with at least the upper part of "A0" Horizon plus the "Tintinnopsella–Intermedia" stratigraphic interval of Benzaggagh (2000). The Rm1 Horizon is a probable correlative of the Praetintinnopsella Zone as defined in the South Carpathian Ranges and West Balkan Chains, and the passage levels between the "Assosciations I and II" of Oloriz et al. (1995). The Rm2 Horizon can be correlated with the "A1" Subzone *sensu* Remane (1963, 1971), and the Remanei Subzone of Remane et al. (1986), Pop (1994), Lakova et al. (1999), Lakova & Petrova (2013) and Petrova et al. (2019).

Intermedia Subzone

As defined by Remane et al. (1986) and accepted here, this subzone starts with the FO of *Calpionella* "*grandalpina*" Nagy and is considered as an equivalent of the "A2+A3" subzones of Remane (1963, 1971). Its upper limit corresponds to the base of the overlying Calpionella Zone. It is mainly characterized by a rich association of crassicollarians (*Crassicollaria brevis*, *Cr. massutiniana*, *Cr. intermedia*). In the RB.I section, its lowermost part includes exclusively *C. alpina* and *Cr. intermedia*, which are followed by the quasi-simultaneous appearance of *Cr. brevis* and *Cr. massutiniana*. This latter bioevent allows to distinguish two horizons (It1; 12.5 m and It2; 15.6 m), that can be correlated with the lower and upper parts of the "A2" Subzone of Remane (1963, 1971), "Intermedia–Alpina" stratigraphic interval of Benzaggagh (2020), lower Massutiniana Subzone of Lakova et al. (1999), Lakova & Petrova (2013) and Petrova et al. (2019), Brevis Subzone of Reháková & Michalík (1997) and the beds yielding the calpionellid "Association III" of Oloriz et al. (1995). Higher, through the Intermedia Subzone of the Jebel Bou Merzoug section, the FOs of *Cr. colomi* and *Cr. parvula* serve to delimit the base of a third horizon (It3; 13.1 m) mainly characterized by a notable increase in the *Cr. massutiniana* and *Cr. brevis* relative proportions. The upper limit of this horizon coincides with the FO of *C. elliptalpina* Nagy that marks the base of the last horizon (It4; 10.3 m) of the Intermedia Zone. The It3 and It4 horizons can be correlated with the lower and upper parts of the "A3" Subzone of Remane (1963, 1971). They also correspond to the "Brevis–Massutiniana" and "Elliptalpina–Parvula" stratigraphic intervals of Benzaggagh (2020), Colomi Subzone of Pop (1994) and Reháková & Michalík (1997), and upper Massutiniana Subzone of Lakova & Petrova (2013) and Petrova et al. (2019).

Calpionella Zone

This zone starts with the *acme* of small sphaerical variety of *C. alpina,* also considered as a primary marker for the Jurassic–Cretaceous boundary (Wimbledon 2017). Its upper part is determined by the base of the Calpionellopsis Zone. It is subdivided here into the Alpina, Remaniella, newly recognized Alpelliptica, and Elliptica Subzones.

Alpina Subzone

It is mainly characterized by a low calpionellid diversity with abundant *C. alpina* and *Cr. parvula* and fewer *T. carpathica*. The majority of the other crassicollarians notably decline but still show sporadic occurences at its lower part. The abrupt appearance of species of the genus *Remaniella* defines the upper limit of this subzone.

Remaniella Subzone

It starts with the first specimens of *Remaniella duranddelgai* Pop and *R. colomi* Pop. Representatives of *C. alpina* are mainly of a medium size but a recurrence of scarce large-sized specimens is also noted. In both study sections of the "Ravin bleu" site, *R. ferasini* Pop appears later and its use as a subzone index is discussable; a "Duranddelgai" Subzone designation seems more appropriate. The upper limit of the Remaniella Zone is marked by a sudden appearance of large-sized calpionellids of the *C. alpina* group but with a slightly longer lorica approaching that of *C. elliptica* (=*C. alpelliptica* Nagy) which marks the overlying newly proposed Alpelliptica Subzone. The Remaniella Subzone in the RB.I section is a correlative of the lower Ferasini Zone of Pop (1994) and Reháková & Michalík (1997), and lower Remaniella Subzone *sensu* Remane et al. (1986), Boughdiri et al. (2006, 2009), Lakova & Petrova (2013) and Petrova et al. (2019). It can be correlated with the "Alpina–Remaniella (B2)" Subzone of Benzaggagh (2020).

Alpelliptica Subzone

Newly identified in NE Algeria, this subzone can be easily correlated with the "B3" Subzone of Benzaggagh and Atrops (1995b) and the "Alpina–Alpelliptica" Subzone of

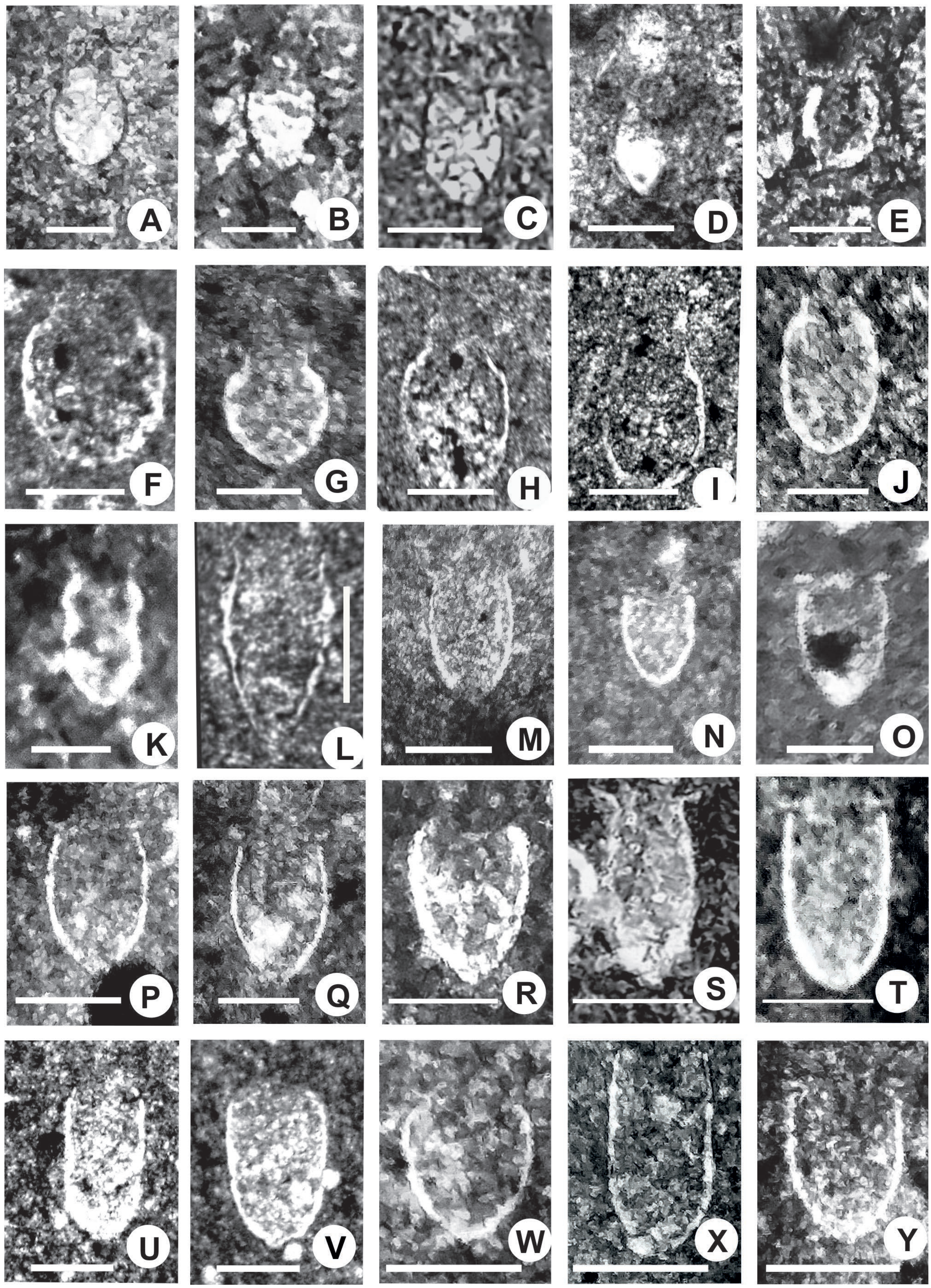
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Fig. 4. Chitinoidellid and Calpionellid species of the study sections. **A** — *Chitinoidella* aff. *boneti* Doben, RB.I-64, Chitinoidella Zone, Boneti Subzone, Upper Tithonian. **B** — *Chitinoidella carthagensis* Sallouhi et al., RB.I-81, Chitinoidella Zone, Boneti Subzone, Upper Tithonian. **C, D:** ?*Praetintinnopssella* sp. gr. *andrusovi* Borza, **C** — RB.I-111, Crassicollaria Zone, Remanei Subzone (Rm1 Horizon), Upper Tithonian; **D** — RB.I-122, Crassicollaria Zone, Remanei Subzone (Rm2 Horizon), Upper Tithonian. **E** — *Tintinnopsella remanei* Borza, RB.I-113, Crassicollaria Zone, Remanei Subzone (Rm1 Horizon), Upper Tithonian. **F** — Large form of *Calpionella alpina* Lorenz (= *Calpionella* "*grandalpina*" Nagy), RB.I-137, Crassicollaria Zone, Intermedia Subzone (It1 Horizon), Upper Tithonian. **G** — Small sphaerical form of *Calpionella alpina* Lorenz, RB.I-205, Crassicollaria Zone, Intermedia Subzone (It4 Horizon), Upper Tithonian. **H** — Elongated form of *Calpionella alpina* Lorenz (=*Calpionella elliptalpina* Nagy), RB.I-193, Crassicollaria Zone, Intermedia Subzone (It4 Horizon), Upper Tithonian. **I** — *Calpionella alpelliptica* Nagy, RB.I-229, Calpionella Zone, Alpelliptica Subzone, Middle Berriasian. **J** — *Calpionella elliptica* (Cadisch), RB.I-259, Calpionella Zone, Elliptica Subzone (Ep2 Horizon), Midle Berriasian. **K** — *Crassicollaria massutiniana* (Colom), RB.I-132, Crassicollaria Zone, Intermedia Subzone (It1 Horizon), Upper Tithonian. **L** — *Crassicollaria colomi*, RB.I-179, Crassicollaria Zone, Intermedia Subzone (It3 Horizon), Upper Tithonian. **M** — *Tintinnopsella carpathica* (Murgeanu and Filipescu), RB.I-281, Calpionellopsis Zone, Oblonga Subzone, Upper Berriasian. **N** — *Remaniella ferasini* (Catalano), RB.I-229, Calpionella Zone, Alpelliptica Subzone, Middle Berriasian. **O** — *Remaniella duranddelgai* Pop, RB.I-229, Calpionella Zone, Alpelliptica Subzone, Middle Berriasian. **P** — *Remaniella colomi* Pop, RB.II-41, Calpionella Zone, Alpelliptica Subzone, Middle Berriasian. **Q** — *Remaniella borzai* Pop, RB.I-295, Calpionellites Zone, Darderi Subzone, Lower Valanginian. **R** — *Calpionelllites darderi* (Pop), RB.I-287, Calpionellites Zone, Darderi Subzone, Lower Valanginian. **S** — *Tintinnopsella* aff. *longa* (Colom), RB.I-271, Calpionellopsis Zone, Simplex Subzone, Upper Berriasian. **T** — *Remaniella* aff. *colomi* Pop, RB.I-263, Calpionella Zone, Elliptica Subzone (Ep2 Horizon). **U** — *Calpionellopsis simplex* (Colom), RB.I-291, Calpionellites Zone, Darderi Subzone, Lower Valanginian. **V** — *Calpionellites darderi* (Colom), RB.I-293, Calpionellites Zone, Darderi Subzone, Lower Valanginian. **W** — *Lorenziella hungarica* (Knauer and Nagy), RB.I-281, Calpionellopsis Zone, Oblonga Subzone, Upper Berriasian. **X** — *Praecalpionelllites siriniaensis* (Pop), RB.I-287, Calpionellites Zone, Darderi Subzone, Lower Valanginian.. **Y** — *Calpionellites* aff. *coronatus* Trejo, RB.I-297, Calpionellites Zone, Darderi Subzone, Lower Valanginian. Scale bar: 50µm.

Benzaggagh (2020). It mainly includes *C. alpina*, *Cr. parvula*, small- to medium-sized *T. carpathica*, *Remaniella durandelgai*, *R. colomi* and *R. ferasini*. It is considered here as a correlative of the upper part of the Ferasini or Remaniella Subzones as defined in Romania, Slovakia and Bulgaria (Fig. 5). Its upper boundary is defined by the FO of *C. elliptica*.

Elliptica Subzone

The lower limit of this subzone corresponds to the FO of *Calpionella elliptica* Cadisch and its upper limit coincides with the base of the Calpionellopsis Zone. In NE Algeria, the marker bioevent is accompanied by the FO of *Remaniella filipescui*, *R. cadishiana* and *Lorenziella plicata*. Its upper part is marked by a change in *T. carpathica* morphology where large-sized, somewhat elongated forms prevail over *C. alpina*, allowing to distinguish two horizons Ep1 and Ep2. These horizons are correlatives of the "Elliptica–Alpina (C1)" and "Elliptica–Carpathica (C2)" Subzones of Benzaggagh (2020); only the upper Ep2 Horizon being a reliable equivalent of the "C" Subzone of Remane (1963, 1971).

Calpionellopsis Zone

Of a diverse calpionellid content, the lower limit of this zone is defined by the FO of the index genus represented by *Calpionellopsis simplex*. It includes *C. elliptica*, *C. alpina*, *T. carpathica*, *Remaniella filipescui*, *R. cadischiana* and *Lorenziella*. Its upper limit corresponds to the base of the Calpionellites overlying Zone. It is subdivided here into the Simplex, Oblonga and Murgeanui Subzones.

Simplex Subzone

It is the equivalent of the "D1" Subzone of Le Hégarat and Remane (1968). In NE Algeria, added to the relatively abundant index species, the genus *Remaniella* is less frequent but diversified (*R. filipescui*, *R. cadischiana*, *R. borzai* and *R. colomi*). *C. alpina*, *C. elliptica, T. carpathica* and *Lorenziella* are relatively rare. At this stratigraphic level, the early appearance of the genus *Praecalpionellites* represented by the *siriniaensensis* group is worth of a preliminary particular attention as far as its phyletic relationships are concerned. The upper limit of this subzone coincides with the FO of *Cpsis*. *oblonga*.

Oblonga Subzone

Introduced by Remane et al. (1986), this subzone had been considered as an equivalent of the "D2+D3" Subzones of Le Hégarat and Remane (1968), until Pop (1994) restricted it to the interval defined by the FOs of *Cps. oblonga* and *Cps. murgeanui*, a correlative of the unique "D2" Subzone of Le Hégarat and Remane (1968), as also admitted in this work. Calpionellid diversity is high with abundant *Lorenziella hungarica*, *Tintinnopsella carpathica*, *T. longa* and *Remaniella cadischiana*. Scarcer *Clpsis*. *simplex* of the underlying subzone is noted. This subzone corresponds to the "Oblonga–Simplex (D1)" Subzone of Benzaggagh (2020), and the Oblonga Subzone of Pop (1994), Reháková & Michalík (1997), Lakova & Petrova (2013) and Petrova et al. (2019).

Murgeanui Subzone

Its lower limit is defined by the FO of *Calpionellipsis murgeanui* and its upper limit by the base of the Calpionellites Zone. Among the *Calpiollopsis* representatives, *Cpsis*. *murgeanui* is frequent and the *Cpsis. oblonga* prevails over *Cpsis. Simplex*. *Tintinnopsella longa* and *L. hungarica* are scarcer. This subzone is a correlative of the "D3" Subzone of Le Hégarat & Remane (1968), Murgeanui Subzone of Pop (1994), Reháková & Michalík (1997), Lakova & Petrova (2013) and Petrova et al. (2019), and the "Oblonga–Preacalpionellites" Subzone of Benzaggagh (2020).

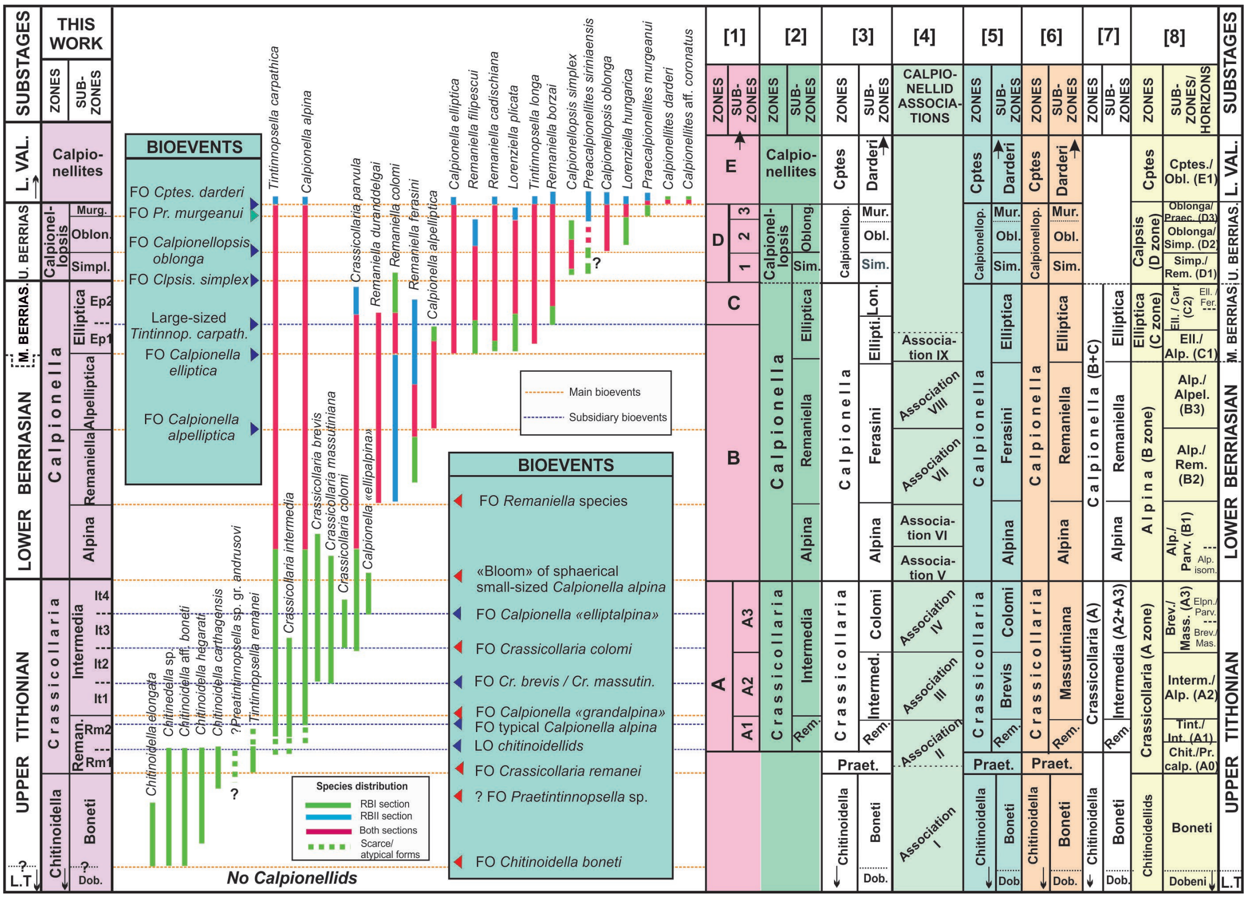

Fig. 5. A synthesis chart of Upper Tithonian–Lowermost Valanginian calpionellid distribution in NE Algeria. Regional zonations after: [1]: Remane (1963, 1971); [2]: Remane et al. (1986); [3]: Pop (1994); 4: Oloriz et al. (1995); [5]: Reháková & Michalík (1997); [6]: Lakova et al. (1999), Lakova & Petrova (2013) and Petrova et al. (2019); [7]: Boughdiri et al. (2009); [8]: Benzaggagh (2020).

Calpionellites Zone (Darderi Subzone)

This zone corresponds nearly to the total range of the *Calpionellites* genus; it is considered as an equivalent of the "E" Zone of Le Hégarat & Remane (1968). In NE Algeria, only the lower part of the Darderi Subzone is identified on the basis of the FO of *Calpionellites darderi* accompanied by *Ctes.* aff. *coronatus*. In addition to the association of the uppermost Berriasian Murgeanui Subzone, the Darderi Subzone includes scarce *C. elliptica*, *R. cadischiana*, *R. borzai*, *T. longa*, *L. hungarica* and *Praecalpionellites murgeanui*. It can be correlated with the "E1" Subzone of Le Hégarat & Remane (1968) and the "Oblonga–Praecalpionellites" Subzone of Benzaggagh (2020).

Discussion

Regional correlations (Fig. 6)

Donze et al. (1974) proposed a calpionellid biozonation through a profile (Fig. 6C) in the same site of the two study sections the sampling of which benefited from former industrial works in a quarry long ago exploited in the area.

The correlation of the section of Donze et al. (1974) with the study sections (Fig. 6A, B) shows that Donze et al. sampled a section which no longer exists, but likely composed of a lithological succession close to that of the of RB.II section, and the upper part of RB.I (units RB.I-B and RB.I-C). Despite some difficulties in precise lithological correlations due to different sampling procedures, only minor differences concerning the limit positions of the Berriasian calpionellid zones can be revealed. However, our zonation is in disagreement with that proposed by Donze et al. (1974) for the uppermost beds of the correlated sections. In fact, these authors mentioned ammonite faunas indicating the Paramimounum Subzone of Upper Berriasian gathered in their sample RB 21 (Fig. 6C). About sixty meters higher (their beds 25–26), Donze et al. (1974) confirm the late Berriasian age (Boissieri Zone) by the occurrence of the index species, *Fauriella boissieri*. In addition, Donze et al. (1974) reported calpionellid species from the same interval, including *Calpionellopsis simplex* of the "D" Zone of Le Hégarat & Remane (1968), also assigning a late Berriasian age ("D1" Subzone of the same authors) to the beds with sandstone intercalations of the flysch deposits.

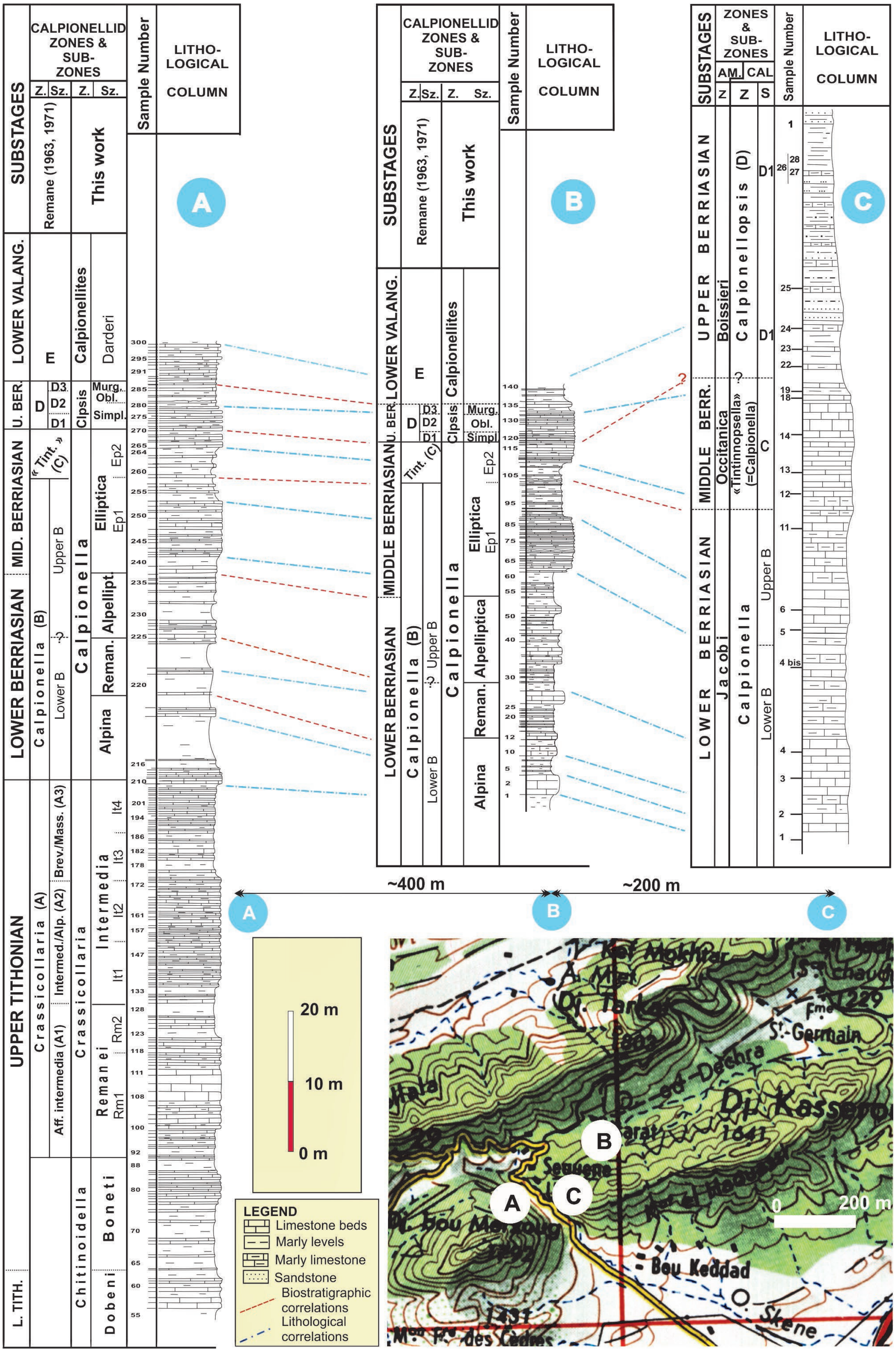

Fig. 6. Biostratigraphic correlation between the RB.I-section (A), the RB.II-section (B) and the section after Donze et al. (1974) (C).

In contrast, our calpionellid zonation places the lower limit of the Calpionellopsis Zone (=lower Upper Berriasian) within the upper part of the carbonate units RB.I-C and RB.II-C, both levels being correlatable with Donze et al. beds close to their sample RB14 (Fig. 6C). Moreover, the D/E calpionellid Zone limit in the two study sections is located at the topmost of the units RB.I-C and RB.II-C, just before the first sandstone beds of the overlying flysch deposits. This limit was not identified by Donze et al. (1974) and the same lithological markers of flysch deposits are clearly reported in their sampled section (beds 24–28, Fig. 6C). The possibility of facies lateral variations between the three correlated sections can not be envisaged here since these sections are very close (*ca* 200 m far from each other, Fig. 6). To explain this divergence in age assignments, one can consider the fact that the Upper Berriasian ammonite specimens mentioned by Donze et al. (1974) would not be gathered *in situ* and may come from their underlying carbonate levels RB12-18. Only a bed-by-bed sampling of the intercalated carbonate beds of the thick lower Cretaceous flysch deposits in the study section; accompanied by precise ammonite gatherings, may confirm, bring the adequate solution and propose a precise Ammonite/Calpionellid calibration for the study sections of NE Algeria.

"Ravin Bleu" site as a potential regional stratotype of the Jurssic–Cretaceous boundary: comparisons with sections from the Maghrebian ranges

The continuous stratigraphic succession and the excellent Upper Jurassic–Lower Cretaceous outcrops invited us to compare them with lateral equivalent sections from Tunisia, Western Algeria and Morocco. Are mainly considered here the quality of the Tithonian–Berriasian units around the JKB as far as accessibility, continuity of sedimentation and completeness of the well dated sites are concerned.

In NW Algeria, the ammonite-bearing Jurassic formations of the Tellian basin and its foreland co-eval series (Tiaret area) were the subject of a detailed calpionellid (and ammonite) zonations (e.g. Atrops & Benest 1984, 1986, 1993, 1994; Atrops et al. 1983, 1991; Benest et al. 1993). Among these well dated open marine sections, those of the jebels Bechtout and Bou Rhedou (North Tiaret area) and the Ouarsenis Great-Peak (Telemcen region) include the JKB-interval aged marl/limestone alternations of the Rharda Formation. In this area, the Ouarsenis section is the most complete and thick, but includes dilated marly levels and mainly pseudonodular limestone packages marking a sedimentary change within the upper part assigned to the "A" calpionellid Zone of Remane (1963, 1971).

In NE Morocco, foreland of the Rif Chain, and the Morocco–Algerian confines, the Beni Snassen massive Tithonian Hariga and Ouled Mimoun formations pass laterally into the Bou-Rhennja limestones and marly limestones (Cattanéo 1987). In these areas, Jurassic sequences are of inner shelf depositional environments as indicated by the thick calcareous sequences, without pelagic microfauna and with sporadic siliciclastic intercalations, and beared algae and benthic foraminifera usually used for biostratigraphic stage delimitations.

In the Internal Prerif and the Mesorif zones (External Rif) of northern Morocco, the Kimmeridgian and Lower Tithonian form a carbonate bar called Msila Formation, in the Internal Prerif Zone, and El Gouzat Formation, in the Mesorif Zone (Benzaggagh 1988). This bar is encased by two formations: the "Ferrysch", a 1500-m thick siliciclastic sequence dated as Callovian–Oxfordian, and the marly and marly limestone series (500 m) of Upper Tithonian–Barremian age. The Upper Jurassic carbonate series are intensely dislocated by the Cenozoic tectonics forming, in the Internal Prerif and Mesorif zones, alignments of moderate-sized blocks called "sofs". In the Internal Prerif Zone (Msila Formation), Benzaggagh (1988, 2000) identified the main ammonite zones and subzones for the Kimmeridgian–Lower Tithonian and the Upper Tithonian–lowermost Berriasian ammonite zones in the marly-limestone alternations of El Haraïk Formation. For the late Tithonian–Berriasian time interval, a calpionellid (Benzaggagh & Atrops 1995a, b) and a ammonite (Benzaggagh & Atrops 1997) charts that fit the Mediterranean standards were proposed. Among the most complete and continuous Kimmeridgian–Lower Berriasian succession of the Prerif Zone, dated by ammonites and calpionellids, are those of the Msila (Eastern Internal Prerif) and Moulay Bouchta regions. However, the majority of the Upper Jurassic–Lower Cretaceous succession in these areas do not exhibit the whole Upper Tithonian–Berriasian sequence but are either tectonically base-cut-out (lack of Upper Tithonian) or top-cut-out (lack of Berriasian–Lower Valanginian). This led the authors to sample complementary subsections to reconstruct the Tithonian–Valanginian whole synthetic series. Despite their fine zonations, none of the examined sections fits the recommended characteristics to be considered as a regional reference.

To the Eastern part of the Maghrebian chain, the Tunisia Atlassic successions, studied by Donze et al. (1975), Memmi et al. (1989), Boughdiri et al. (2005, 2006, 2009) and Oloriz et al. (2006) and Ben Abdesselam et al. (2011), are also affected by regional tectonics with synsedimentary features in the Tunisian "Dorsale" (NE Tunisia) and the Tunisian "Trough" (NW Tunisia). In the "North–South Axis" of Central Tunisia, the uppermost Jurassic successions are dolomitic (upper Nara Formation) and the Berriasian Sidi Khalif Formation consists mainly of thick marly levels topped by the siliciclastic deposits of the Meloussi and Boudinar formations (e.g. Memmi 1967; Busnardo et al. 1976, 1981; M'Rabet 1987; Boughdiri et al. 1999, among others). None of all these northern and central Tunisia successions is worth being considered as a Maghrebian regional stratotype.

Considering the above-mentioned comparisons, we can state that the Jebel Bou Merzoug RB.I section of NE Algeria fits better the characteristics of a reference section at the regional scale of the North Africa Maghrebian Ranges.

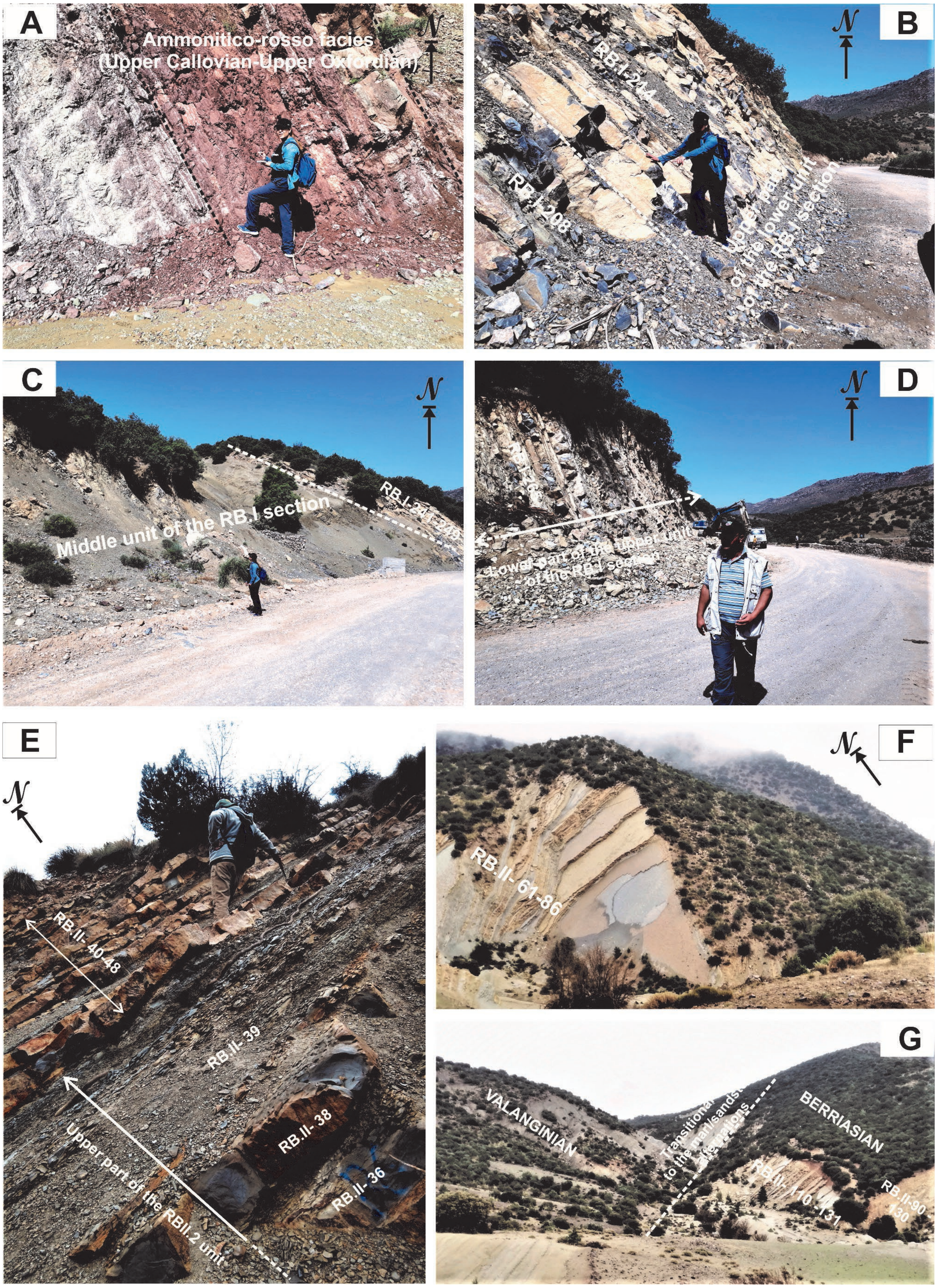

Fig. 7. Photographs of Upper Jurassic–lowermost Valanginian units of the study sections, illustrating their exceptional outcrop quality and easy access. **A** — Ammonitico-rosso facies underlying the study sections. **B** — The lower unit RB.I-A of Jebel Bou Merzoug. **C** — The middle unit RB.I-B. **D** — The upper unit RB.I-C. **E** — The transition between middle (RB.II-B) and upper (RB.II-C) unit of the J. Kasserou RB.II-section. **F** — The upper carbonate unit RB.II-C. **G** — Transitional beds between the RB.II-C unit and Valanginian marl/sandstone alternations.

In fact, compared to the "Ouarsenis Great Peak" section formerly proposed as a West-Mediterranean stratotype by Atrops et al. (1991), the "Ravin Bleu" site meets better the guidelines of Remane et al. (1996) for the establishment of a GSSP. In fact, added to its easy access and excellent outcrops (Fig. 7A–G), this continuous and thick section does not exhibit any synsedimentary and/or tectonic features, as it is devoid of diagenetic alteration and metamorphism signatures. Around the JKB interval, the limits of zones and subzones identified herein by means of calpionellids, as widespread and valuable biomarkers, can also be determined in further works by interpolation using auxiliary markers. No vertical or lateral litho- and biofacies changes at or close to the Upper Tithonian–Berriasian interval boundaries were observed. Except for its relatively reduced uppermost part, no gap and no condensation features were evidenced in both study sections so that the sedimentation rate is sufficient for the separation of successive key calpionellid bioevents. Hence, all these outcrop quality and facies characteristics allow promising long-range biostratigraphic correlations.

Furthermore, of a particular relevance is the fact that, considering the whole Jurassic sequences of the study sections, all examined formations can be easily correlated with lateral equivalents in the "Tunisian Dorsale" (NE Tunisia). Nevertheless, they are different from those of the "Tunisian Trough" (NW Tunisia) by the lack of a well-marked biosiliceous series, recently dated by radiolarians as Bajocian–Oxfordian (Cordey et al. 2005; Boughdiri et al. 2007). Furthermore, in the Tunisia–Algeria confine areas, the carbonated Kimmeridgian–Berriasian (*p.p.*) series are topped by a thick marl/sandstone alternations of flysch deposits, starting around the uppermost Berriasian–lowermost Valanginian time interval. This is interpreted as an important sedimentary event, also described in other sections from the Mediterranean area. When this event is replaced in a wider Tethyan geodynamic context aiming to explain its diachronic onset and the related controlling factors, it may be correlated at a long distance and potentially considered as an added important criterion for the JKB definition.

Conclusion

The updated stratigraphy of two sections from the "Ravin bleu" site of Batna Mounts (NE Algeria) allows to identify five calpionellid zones and eleven subzones in the Upper Tithonian–lowermost Valanginian interval. This zonation is based on calpionellid bioevents and associations that confirm their stratigraphic potential, already demonstrated in other areas from the Mediterranean Tethys. The Upper Tithonian Chitinoidella and Crassicollaria zones include the successive Boneti, and the Remanei and Intermedia Subzones, respectively. The Calpionella Zone of Lower and Middle Berriasian are subdivided into the Alpina, Remaniella, newly defined Alpelliptica and Elliptica Subzones. Subsidiary bioevents allow identifying six Horizons within the Upper Tithonian Crassicollaria Zone and two others in the Elliptica Zone (Middle Berriasian). These are first identified in Algeria and correlated with their Tethyan lateral equivalents, mainly from Morocco. Nevertheless, their definition remains provisional waiting for a formal validation after: (1) being documented from a wider sector, and (2) a wide consensus among specialists. The Berriasian–Valanginian transition lies within the limit between the Calpionellopsis Zone gathering the Simplex, Oblonga and Murgeanui Subzones (Upper Berriasian), and the lowermost Valanginian Calpionellites Zone represented here by its lower Darderi Subzone.

The new data and related zonation provided here lead to propose the "Ravin Bleu" site of the Batna Mountains in NE Algeria as a regional stratotype for the interval around the JKB in the Maghrebian Ranges. In fact, to our knowledge, no complete, continuous and well exposed section from Tunisia, Morocco and Western Algeria, devoid of local tectonic effects and/or resedimentation features, includes the whole Upper Tithonian–Lower Valanginian interval.

Further efforts may be deployed within a larger stratigraphic frame that integrates chemostratigraphy and magnetostratigraphy investigations for the well exposed study sections. In fact, from the Atlassic Ranges of the Maghreb, NE Algeria constitutes a promising key sector not yet (or not well) investigated for the Jurassic–Cretaceous boundary biozonation purposes. The correlation of the Jurassic–Cretaceous boundary successions in NE Algeria with those well dated in Northern Tunisia and their Western lateral equivalents in North Central and Western Algeria and Morocco, are of particular relevance for replacing the Maghrebian Jurassic–Cretaceous boundary successions within their wider Tethys geodynamic context.

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