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Lower Aptian ammonite and carbon isotope stratigraphy in the eastern Prebetic Domain (Betic Cordillera, southeastern Spain)

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ABSTRACT

Major global palaeobiologic and palaeoenvironmental changes occurred during the Early Aptian. Precise dating and timing of the different events is crucial to determine possible cause-effect relationships between them. In this regard, the combination of biostratigraphic and chemostratigraphic data can provide a very useful tool for time control. So far attempts to correlate the Lower Aptian carbon isotope record and the ammonite zonation yielded contradictory conclusions.

In this paper, we present the results of an integrated analysis of the ammonite stratigraphic distribution and high-resolution carbon isotope profiles from Lower Aptian sections of the eastern Prebetic Domain (Betic Cordillera, southeastern Spain). We recognized, in ascending order, the *Deshayesites oglanlensis*, *Deshayesites forbesi*, *Deshayesites deshayesi*, and *Dufrenoyia furcata* Zones. This succession is the same as that recently identified in the eastern Iberian Chain, and it closely correlates with both standard Mediterranean and Boreal zonations. The carbon isotope record displays the trends globally recognized for the Early Aptian, with two long positive shifts separated by a pronounced negative excursion. Calibration of this isotopic record with the ammonite zonation shows that the age of OAE 1a, which corresponds to the negative excursion and subsequent positive shift, is constrained to the middle/upper part of the *Deshayesites forbesi* Zone.

KEYWORDS **Ammonites. Lower Aptian. OAE 1a. Biostratigraphy. Prebetic Domain. Southeastern Spain.**

INTRODUCTION

Early Aptian times witnessed major global tectonic, palaeoclimatic, palaeoceanographic and palaeobiologic events (Skelton *et al*., 2003). These include enhanced volcanic activity in the Pacific leading to the formation of the Ontong-Java Plateau, large perturbations of the global carbon cycle with widespread episodes of organic-rich sediment deposition, abrupt sea level and temperature changes, biocalcification crisis in both neritic and pelagic organisms, growth and subsequent demise of extensive carbonate platforms.

In past recent years various causal relationships between these phenomena have been suggested (*e.g,* Weissert *et al*., 1998; Wissler *et al*., 2003; Weissert and Erba, 2004; Föllmi *et al*., 2006; Ando *et al*., 2008; Méhay *et al*., 2009). Clearly, a precise dating and timing of the different processes is required in order to test these links. In this regard, the carbon isotope stratigraphy has proven to be a powerful tool for regional to global correlation and, combined with biostratigraphy, may offer a high-resolution temporal framework for accurately placing the palaeobiologic and palaeoenvironmental events.

Menegatti *et al*. (1998) proposed a detailed carbon isotope chemostratigraphic scheme for the Lower Aptian substage that has been successfully correlated with planktonic foraminiferal and calcareous nannofossil zonations (*e.g.,* Bralower *et al*., 1999; Erba *et al*., 1999; Bellanca *et al*., 2002; Gea *et al*., 2003). Until now, available direct calibrations of carbon isotopic records against the ammonite zonation (which provides the highest biostratigraphic resolution for the Lower Aptian interval) show uneven results (Moullade *et al*., 1998, 2000; Wissler *et al*., 2002; Gea *et al*., 2003; Föllmi and Gainon, 2008; Mahanipour *et al*., 2011; Moreno-Bedmar *et al*., 2008, 2009; Malko *et al*., 2010; Mutterlose and Wiedenroth, 2009; Price *et al*., 2008; García-Mondéjar *et al*., 2009; Lehmann *et al*., 2009; Millán *et al*., 2009).

In this paper, we present the outcome of the analysis of the ammonite stratigraphic distribution and high-resolution carbon isotope profiles from Lower Aptian sections of the eastern Prebetic Domain (Betic Cordillera, southeastern Spain). The sedimentary rocks studied are of hemipelagic facies with diverse and abundant ammonites, especially the deshayesitids, the group which serves as the basis for the Lower Aptian standard zonations. The sections studied are well exposed, and they include a complete, continuous, moderately expanded record, free of major condensations in the succession of bio- and chemostratigraphic events. The reliability of the data allowed us to establish an accurate correlation between the ammonite zonation and the carbon isotope record.

GEOLOGICAL SETTING AND SECTIONS STUDIED

All the sections studied are located in the Prebetic Zone (Fig. 1), a tectonic domain that constituted a vast epeiric platform on the passive southern margin of the Iberian

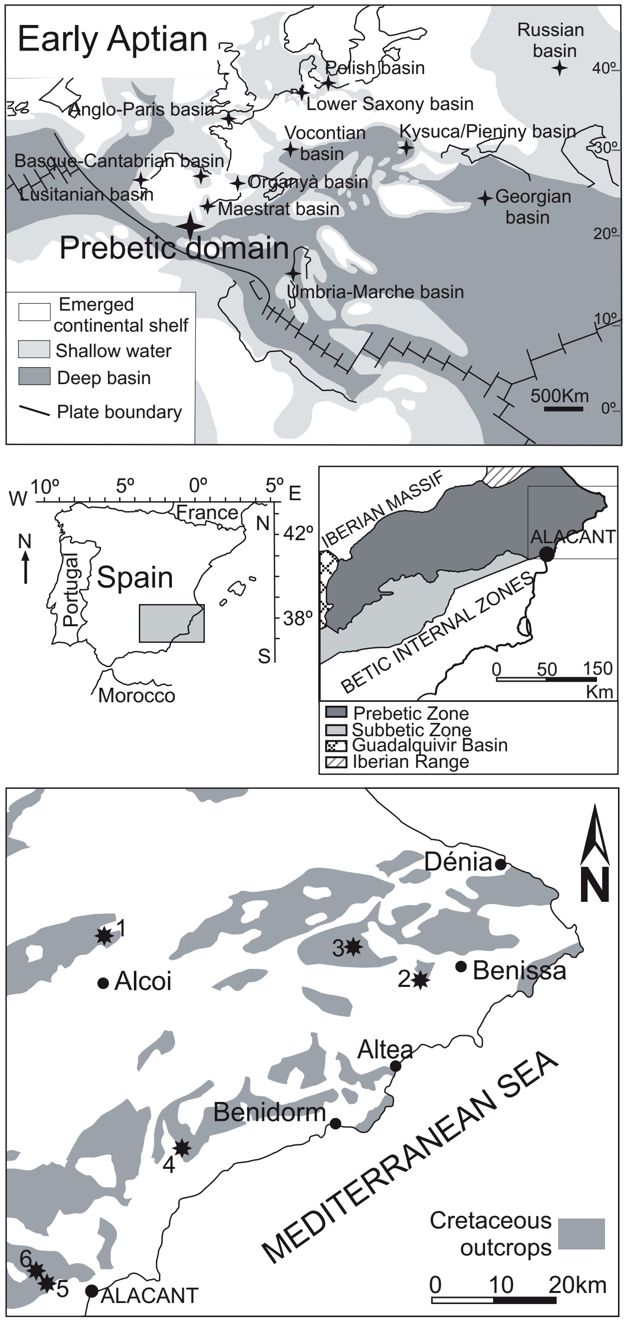


FIGURE 1 | Palaeogeographic reconstruction of the Proto North Atlantic and Tethyan realm during the Early Aptian (Prebetic Domain modified after Masse *et al*., 2000). Simplified geologic map of the Prebetic domain and location of the five sections and outcrops studied: 1) Serra Mariola outcrop, Mas de Llopis, 2) Almadich outcrop, 3) Cau section, 4) Racó Ample section, 5) Font Calent and Font Calent 1 sections, 6) Alcoraia section.

Plate during the Early Cretaceous. This platform extended from shallow carbonate shelf environments in the north to distal hemipelagic environments to the south, which was further connected to a complex pelagic domain (Subbetic Zone).

The sections sampled are mainly composed of green to grey marls, with intermittent marly to sandy limestone beds. Limestones are even parallel to wavy, or even nodular. Microscopically they consist of mudstones, wackestones and packstones. Fine tempestite sandstone beds are also occasionally present in the more distal sections. Ammonites, as well as planktonic and benthonic foraminifera, are abundant, whereas nautiloids, belemnites, bivalves, brachiopods and echinoids are rare. These rocks correspond to the Almadich Formation (Castro, 1998) and have been interpreted as deposited in outer-ramp environments under hemipelagic conditions (Castro, 1998; de Gea, 2004; Castro *et al*., 2008).

The age of the Almadich Fm. varies laterally. It ranges from late Barremian to late Aptian in the southern sections, but towards the north the lower part intergrades with Urgonian facies of the Llopis Formation (Fig. 2), and the upper part is also reported to intergrade into the Seguili Formation, of Urgonian facies as well (Castro, 1998; Castro *et al*., 2008).

For the present study more than 1600 ammonite specimens were collected mostly bed-by-bed in all the sections studied. In general the specimens are sufficiently well preserved to allow identification for biostratigraphic purposes. The ammonite specimens are now housed in the palaeontological collections of the Universities of Barcelona and Granada. They come from the following localities (Fig. 1):

Mas de Llopis (coordinates: 38º45’35”N, 0º28’56”W), on the eastern side of Serra Mariola, 4km WNW of Cocentaina. Although the outcrop conditions do not allow for systematic sampling, the ammonite fauna collected in the Almadich Fm. at that locality reveals the presence

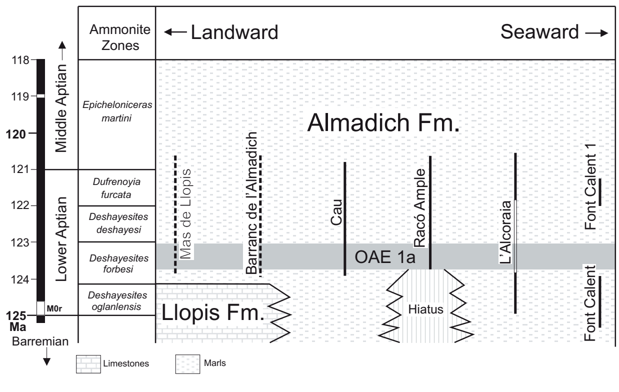


FIGURE 2 | Stratigraphic framework and age relationships of the lower Aptian deposits in the Prebetic domain. Position of OAE 1a is indicated by shaded level.

of the *D. forbesi* (?), *D. deshayesi* and *D. furcata* Zones. The lowermost Aptian is represented by limestones with rudists and orbitolinids of the Llopis Fm. Previous biostratigraphic data on this section were provided by Nicklès (1892), Fallot (1943), Darder (1945), Busnardo *et al*. (1968) and Castro (1998).

Barranc de l’Almadich (coordinates: 38º44’28”N, 0º06’58”W), along a steep slope between the Almadich Gully and the Mirabó Mountain, 1.5km SSW of Benigembla. This site is the type locality of the Almadich Fm., but its lack of exposure, including many observational gaps, prevented from carrying out a detailed sampling. Nevertheless, the *D. forbesi* Zone has been identified immediately above the top of the underlying Llopis Fm., and the *D. deshayesi* and *D. furcata* Zones have also been recognized in superjacent levels. This section was previously described by Castro (1998).

Cau (coordinates: 38º42’14”N, 0º00’19”W), on the western side of the Sella del Cau, 5km WSW of Benissa. This section includes a fairly complete record of the *D. forbesi*, *D. deshayesi* and *D. furcata* Zones. OAE 1a occurs in a dark laminated set of marls towards the middle part of the section. Previous works on the Cau section include those of Darder (1945), Castro (1998), Aguado *et al*. (1999), and de Gea *et al*. (2003). The ammonite stratigraphic distribution in this section is shown in Figure 3.

Racó Ample (coordinates: 38º31’07”N, 0º22’04”W), at the eastern foothills of the Cabeçó d’Or, 2km N of Aigües. The Cabeçó d’Or constitutes the southernmost outcrop of a vast area extending to the NE up to the Altea region. That whole area behaved as a distal swell from the late Valanginian until the earliest Aptian (Granier, 1987; Castro, 1998), so that sediments of this time interval are very reduced or even absent. The Almadich Fm. directly overlies lower Valanginian calcarenites in the section sampled at that site. Ammonites are abundant throughout the section (Fig. 4), which includes the *D. forbesi*, *D. deshayesi* and *D. furcata* Zones. Stratigraphic and palaeontologic data of this area were previously reported by Lillo Beviá (1973a; 1975a, b, c), Estévez *et al*. (1984), Granier (1987) and Castro (1998).

Serra de Fontcalent. Sampling was carried out in two sections (Fig. 5A, B) along the south-eastern slope of this small mountain located 8km W of Alicante. One of the sections (coordinates: 38º21’33”N, 0º34’10”W) spans the Barremian/Aptian boundary interval; the other (coordinates: 38º20’56”N, 0º35’12”W) corresponds to the *D. furcata* Zone. The Lower Cretaceous succession of the Serra de Fontcalent has been analysed by many authors (Nicklès, 1892; Jiménez de Cisneros, 1917; Lillo

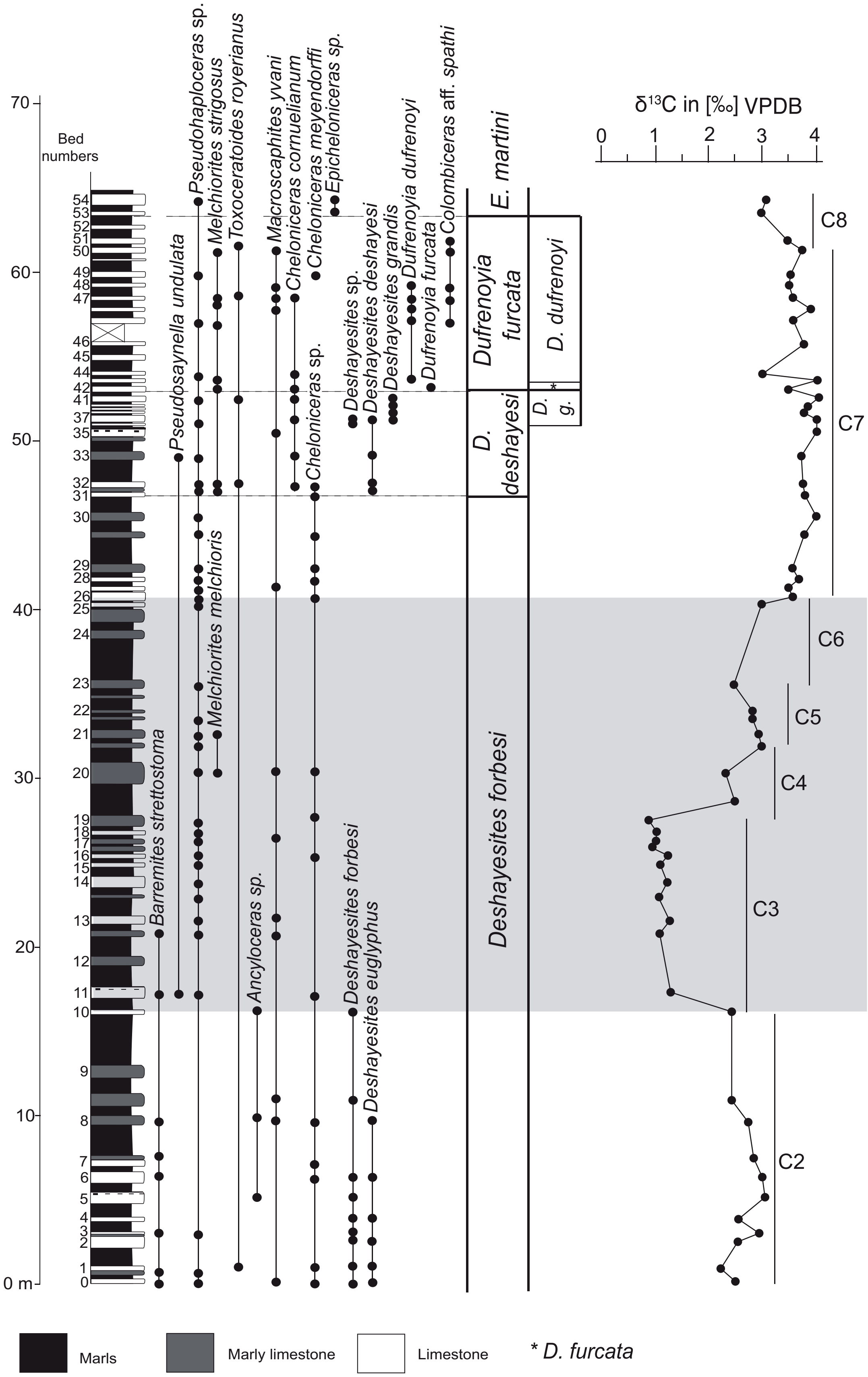


FIGURE 3 | Cau section.

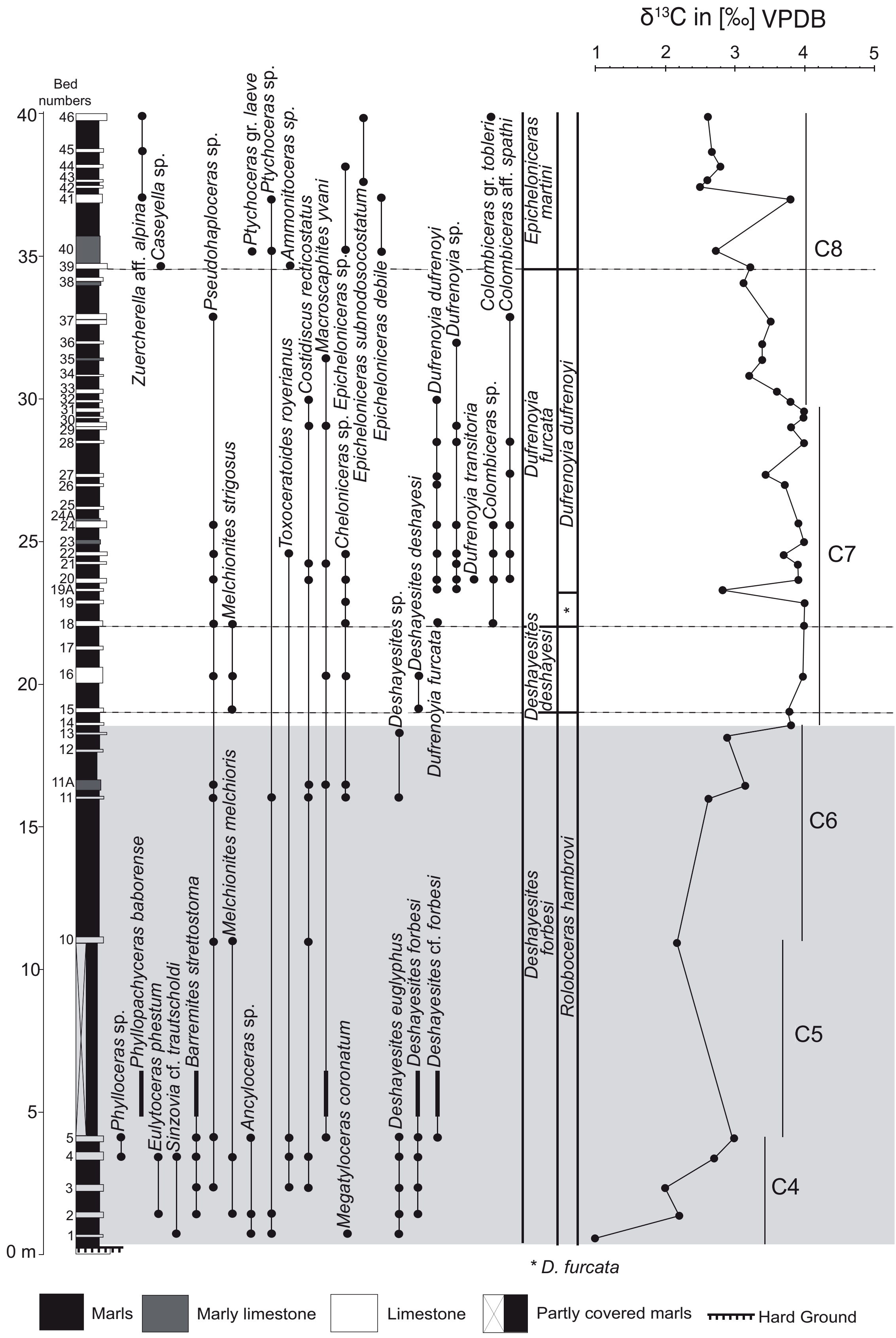


FIGURE 4 | Racó Ample section.

Beviá, 1973b; Rasplus *et al*., 1987; Castro, 1998, Company *et al*., 2004; de Gea, 2004, among others).

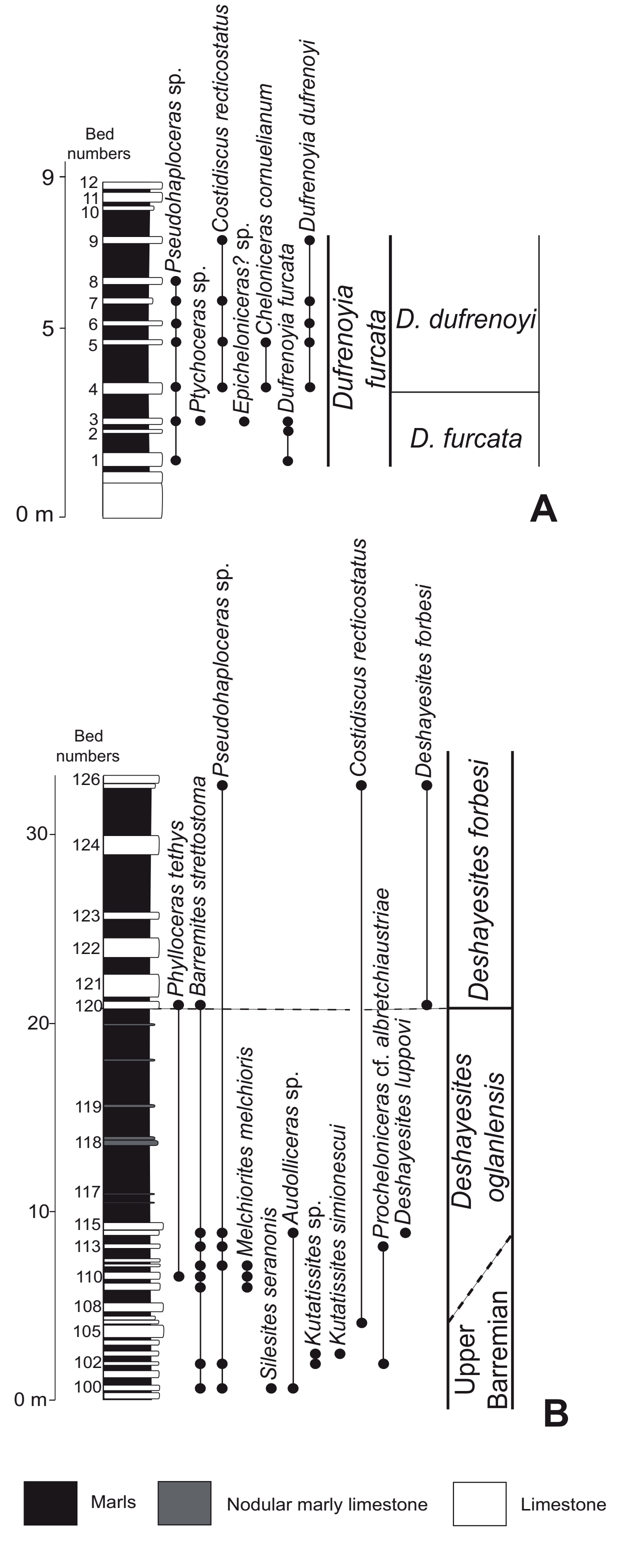


FIGURE 5 | A) FontCalent section. B) FontCalent 1 section.

L'Alcoraia (coordinates: 38º22'25"N, 0º37'04"W), on a small foothill of Serra Mitjana, 12km WNW of Alicante. The section encompasses the whole Lower Aptian, but since it is partly covered by alluvial deposits only the *D. oglanlensis*, *D. forbesi* and *D. furcata* Zones are visible (Fig. 6). The Lower Cretaceous ammonite record of this locality has been the subject of numerous previous studies (Jiménez de Cisneros, 1906, 1917; Wiedmann, 1966a, b; Azéma 1975, 1977; Lillo Beviá, 1973b, 1975a, b, c; Company *et al*., 2004, de Gea, 2004).

AMMONITE BIOSTRATIGRAPHY

The analysis of the ammonite succession in the sampled sections shows that the zonal scheme recently proposed by Moreno-Bedmar *et al*. (2010) for the Lower Aptian of the eastern Iberian Chain can also be satisfactorily applied in the Prebetic Domain. This scheme, which slightly modifies the current standard zonation (Reboulet *et al*., 2009), comprises, from oldest to youngest, the following zones:

Deshayesites oglanlensis Zone

The lower boundary of this zone, which also marks the base of the Aptian stage, is defined by the first occurrence of its index species, *Deshayesites oglanlensis* Bogdanova. This zone was proposed by Raisossadat (2002) in substitution of the former *Deshayesites tuarkyricus* Zone, because *D. oglanlensis* has a wide geographical distribution. This taxon occurs from Spain to Iran, whereas *Deshayesites tuarkyricus* Bogdanova, has been found only in Turkmenistan. This replacement was adopted by the Lower Cretaceous Ammonite Working Group (the "Kilian Group") and introduced in the most recent versions of the standard Mediterranean zonation (Reboulet *et al*., 2006; Reboulet *et al*., 2009).

This zone has been recognized only in the l'Alcoraia and Fontcalent (X Fc) sections, where we have found rich populations of *Deshayesites luppovi* Bogdanova (Fig. 7, A, B; Fig. I A-D Electronic Appendix, available at www.geologica-acta.com). This species was originally reported from the upper part of the *Deshayesites tuarkyricus* Zone and the base of the *Deshayesites weissi* Zone (Bogdanova, 1979, 1983). As all our specimens come from a short stratigraphic interval situated several meters below the first occurrence of *Deshayesites forbesi* Casey (Fig. 8), which characterizes the overlying zone, we assign them to the *Deshayesites oglanlensis* Zone. This interval containing abundant *D. luppovi* was also reported, in a similar stratigraphic position, from the Vocontian basin, where Delanoy (1995, 1997) identified these forms as *Deshayesites* sp. (=*Prodeshayesites* cf. *tenuicostatus* in Delanoy, 1991), and the Subbetic Domain (Aguado *et al*., 1997).

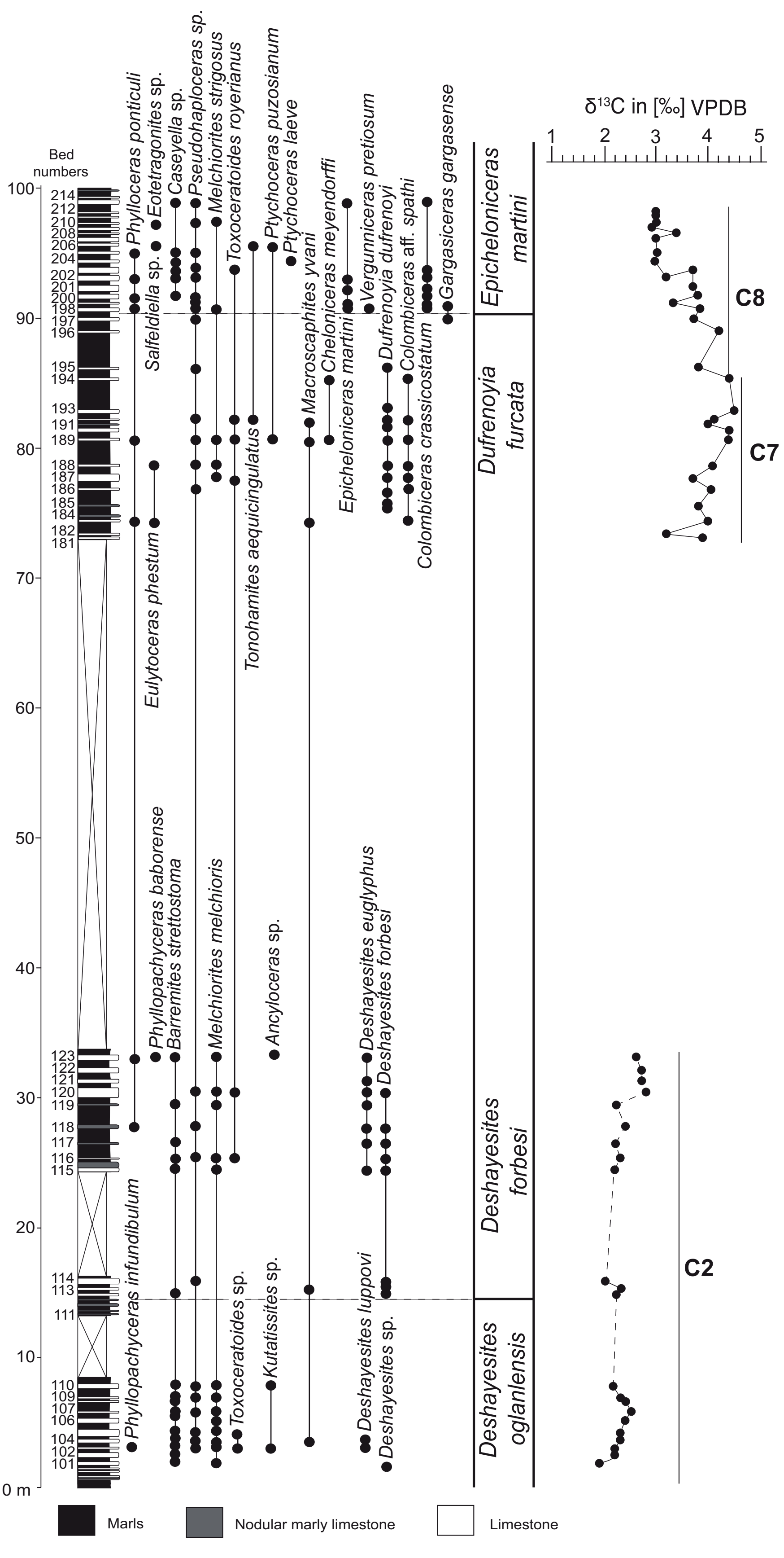


FIGURE 6 | Alcoraia section.

It is worth noting that in the Vocontian basin as well as in the Subbetic Domain, the *D. luppovi* horizon lies shortly above the first appearance of *D. oglanlensis*. Based on such stratigraphic consistency, the lower boundary of the Aptian should also be placed some metres below the *D. luppovi* horizon in the Alcoraia and Fontcalent (X Fc) sections. However, in the absence of age-diagnostic species below this interval, the exact position of the Barremian-Aptian boundary remains uncertain. Indeed, the fauna accompanying *D. luppovi* is mostly composed of taxa inherited from the latest Barremian, which became extinct in this zone, such as *Kutatissites* (Fig. IE) and *Procheloniceras*, together with long-ranging forms, such as *Barremites strettostoma* Uhlig and the genera *Pseudohaploceras*, *Melchiorites* (*Melchiorites melchioris*, Fig. IG), *Toxoceratoides* (*Toxoceratoides* sp., Fig. IG), *Macroscaphites*, *Phyllopachyceras* (*Phyllopachyceras infundibulum*, Fig. IF), and *Hypophylloceras*.

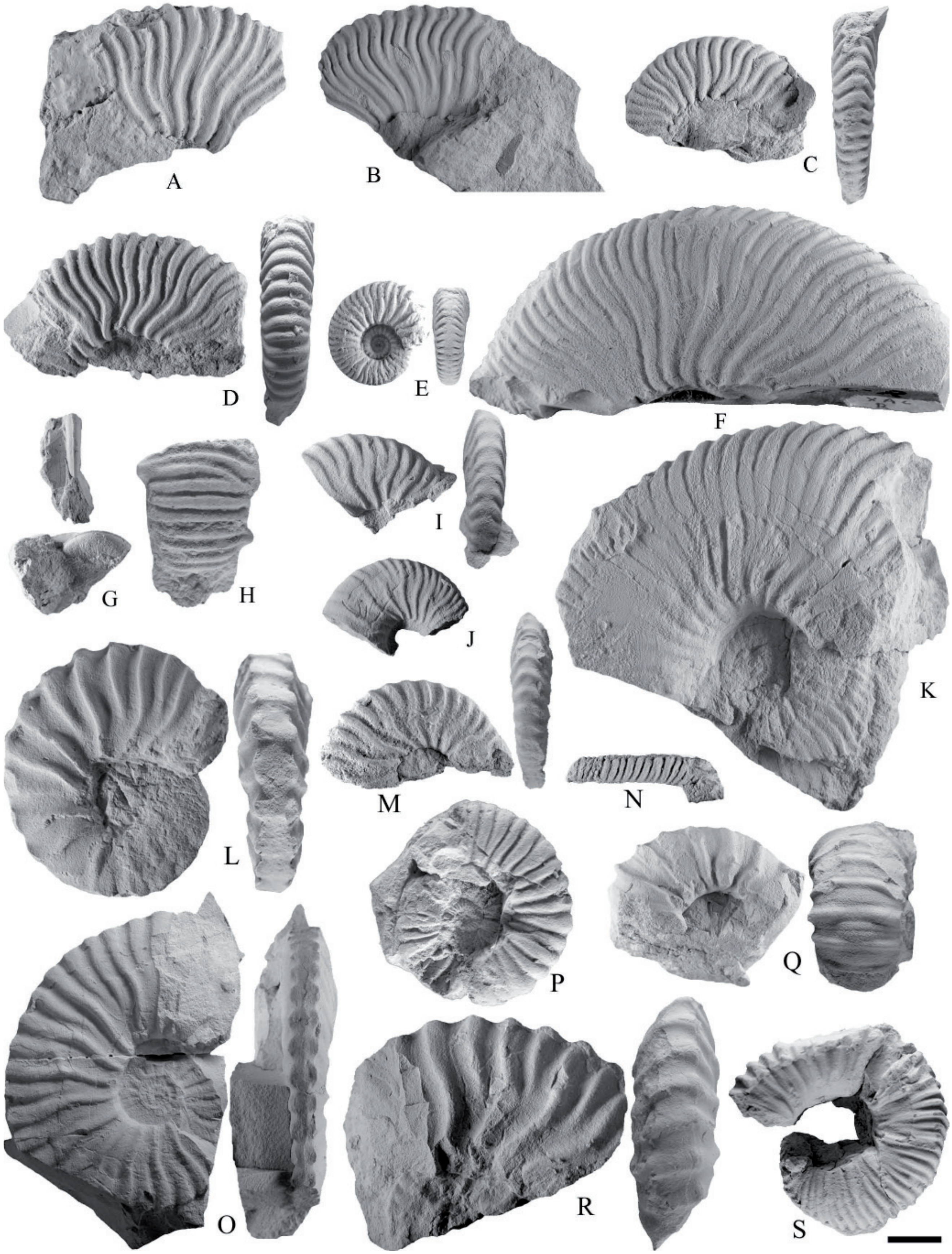
Deshayesites forbesi Zone

The species *Deshayesites weissi* (Neumayr and Uhlig) has been widely used to characterize the second zone of the Aptian stage, as used in all the successive versions of the standard Mediterranean zonation (Hoedemaeker and Bulot, 1990; Hoedemaeker *et al*., 1993; Hoedemaeker *et al*., 1995; Rawson *et al*., 1999; Hoedemaeker and Rawson, 2000; Hoedemaeker *et al*., 2003; Reboulet *et al*., 2006; Reboulet *et al*., 2009). Nonetheless, several authors (Bogdanova and Mikhailova, 2004; Ropolo *et al*., 2006; Reboulet *et al*., 2006; Reboulet *et al*., 2009; García-Mondéjar *et al*., 2009; Moreno-Bedmar *et al*., 2010) have recently questioned the suitability of this species as zonal index. In fact, despite frequent reports of its presence in the Mediterranean province, *D. weissi* is not a well-characterized species, because the original figures (Neumayr and Uhlig, 1881; Koenen, 1902) are difficult to interpret. Furthermore, the type specimens seem to be lost, and their stratigraphic position is unknown. These problems led Moreno-Bedmar *et al*. (2010) to propose the use of *Deshayesites forbesi* Casey as index species of the second zone of the Aptian in their biostratigraphic scheme for the eastern Iberian Chain. This alternative is appropriate also for the Prebetic Domain, where *D. forbesi* (Fig. 7C, D; Fig. II-L; Fig. IIC, E, G-H, K-M, Q; Fig. IIIA-B, E-F) is very well represented by a large number of specimens. This choice allows a direct correlation with the Boreal Realm where *D. forbesi* has also been used as index of the second zone of the Aptian stage in the classic zonation for the English Lower Greensand (Casey, 1961a; Casey *et al*., 1998). Moreover, *D. forbesi* shows close characteristics related to *Deshayesites volgensis* Sazonova, which characterizes the same stratigraphic interval in the Russian Platform (Baraboshkin and Mikhailova, 2002; Bogdanova and Mikhailova, 2004).

The *D. forbesi* Zone has been recognized in the Cau, Racó Ample, Fontcalent (X Fc) and l'Alcoraia sections, and in the Barranc de l'Almadich outcrop. Generally the assemblages from this zone are dominated by deshayesitids. However, they are very scarce, or even absent, in the upper part of the zone in the Cau section coinciding with the presence of deeper, organic-rich sediments. In the other sections, *D. forbesi* and the closely related *D. euglyphus* Casey (Fig. IIA-B, D, F, I-J, N-P; Fig. IIIC-D, G) are the dominant components of the fauna. In contrast, we have only found a single, loose specimen attributable to *D. weissi* (Fig. 7F). It should be noted that in the upper part of the zone in the Racó Ample section, there is occurrence of a few juvenile specimens very similar to *D. forbesi*, but they develop an incipient smooth siphonal band. These specimens, which coexist with typical *D. forbesi*, are here designated as *D.* cf. *forbesi* (Fig. 7E), and interpreted as transitional forms to *D. deshayesi*.

Cheloniceratids are rare and badly preserved, which generally prevents identification to species level. Also worth mentioning is the occurrence of a single fragmentary specimen of *Megatyloceras coronatum* (Rouchadzé) (Fig. 7H) at the base of the Racó Ample section. This markedly contrasts with the assemblages from the eastern Iberian Chain, in which the genera *Roloboceras* and *Megatyloceras* constitute, together with *Pseudosaynella*, the main components of the fauna present in the middle/upper part

FIGURE 7 | A) *Deshayesites luppovi* Bogdanova lateral view of specimen X Ac 104.6, Alcoraia section, *Deshayesites oglanlensis* Zone. B) *Deshayesites luppovi* Bogdanova lateral view of specimen X Fc 114.16, Fontcalent section, *Deshayesites oglanlensis* Zone. C) *Deshayesites forbesi* Casey lateral and ventral view of specimen X AB 3.19, Racó Ample section, *Deshayesites forbesi* Zone. D) *Deshayesites forbesi* Casey lateral and ventral view of specimen X AB 4.56, Racó Ample section, *Deshayesites forbesi* Zone. E) *Deshayesites* aff. *forbesi* Casey lateral and ventral view of specimen X AB 5.31, Racó Ample section, *Deshayesites forbesi* Zone. F) *Deshayesites weissi* (Neuman et Uhlig) lateral view of specimen X Ac, rounded, Alcoraia section, *Deshayesites forbesi* Zone. G) *Sinzovia* cf. *trautscholdi* ventral and lateral view of specimen X AB 1.6, Racó Ample section, *Deshayesites forbesi* Zone. H) *Megatyloceras coronatum* (Rouchadzé) ventral view of specimen X AB 1.1, Racó Ample section, *Deshayesites forbesi* Zone. I) *Deshayesites deshayesi* (d'Orbigny) lateral view of specimen X AB 16.2, Racó Ample section, *Deshayesites deshayesi* Zone. J) *Deshayesites deshayesi* (d'Orbigny) lateral view of specimen X AB 15.1, Racó Ample section, *Deshayesites deshayesi* Zone. K) *Deshayesites grandis* Spath lateral view of specimen X P3 37.2, Cau section, *Deshayesites deshayesi* Zone. L) *Dufrenoyia dufrenoyi* lateral and ventral view of specimen X Fc1 5.8, Fontcalent section, *Dufrenoyia furcata* Zone. M) *Dufrenoyia furcata* lateral and ventral view of specimen X Fc1 3.6, Fontcalent section, *Dufrenoyia furcata* Zone. N) *Tonohamites aequicingulatus* lateral view of specimen X Ac 192.7, Alcoraia section, *Dufrenoyia furcata* Zone. O) *Dufrenoyia dufrenoyi* lateral view of specimen X Fc1 5.18, Fontcalent 1 section, *Dufrenoyia furcata* Zone. P) *Colombiceras* aff. *spathi* lateral view of specimen X P3 50.1, Cau section, *Dufrenoyia furcata* Zone. Q) *Epicheloniceras*? sp. lateral and ventral view of specimen X Fc1 3.12, Fontcalent section, *Dufrenoyia furcata* Zone. R) *Dufrenoyia furcata* lateral and ventral view of specimen X P3 42.1, Cau section, *Dufrenoyia furcata* Zone. S) *Cheloniceras meyendorffi* lateral view of specimen X Ac 189.30, Alcoraia section, *Dufrenoyia furcata* Zone. Scale bar= 1cm.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of the *Deshayesites forbesi* Zone. In fact, Moreno-Bedmar *et al*. (2010) further defined a *Roloboceras hambrovi* Horizon corresponding to that stratigraphic interval. The strong differences between the compositions of the assemblages in both areas can only be explained by taking into account palaeogeographic factors, as the Prebetic sections correspond to more distal environments than the ones from the Iberian domain.

Two fragmentary aconeceratids were collected also from the lowermost part of the Racó Ample section. We tentatively attribute these specimens to the species *Sinzovia trautscholdi* (Sinzow) (Fig. 7G). This species has been very rarely reported in the Mediterranean province, but it is a common component of the *Deshayesites volgensis* Zone assemblages in the Russian Platform (see, for instance, Baraboshkin and Mikhailova, 2002).

Desmoceratids are abundant in the studied sections, and mostly belong to the genera *Pseudohaploceras* (*Pseudohaploceras* sp., Fig. IVA), *Melchiorites* (*Melchiorites melchioris*, Fig. IIIJ-L) and *Barremites*. The species *Barremites strettostoma* (Uhlig) (Fig. IIIH-I, O-Q), which appear in the Upper Barremian, has its last occurrence within the *Deshayesites forbesi* Zone. It is succeded by the morphologically close species *Pseudosaynella undulata* (Sarasin) (Fig. IIIR), which first appears in the middle/upper part of the zone (=*Roloboceras hambrovi* Horizon).

Deshayesites deshayesi Zone

The "Zone à *Hoplites Deshayesi* et *Ancyloceras Matheroni*" was first introduced by Jacob (1908) to refer to the entire Bedoulian. In the current use, the *Deshayesites deshayesi* Zone covers a much more restricted stratigraphic interval between the first occurrences of *Deshayesites deshayesi* (d'Orbigny) and *Dufrenoyia furcata* (Sowerby), respectively. We recognized this biostratigraphic interval in the Cau and Racó Ample sections, and in the Mas de Llopis and Barranc de l'Almadich outcrops. Assemblages from this zone are mainly composed of deshayesitids and desmoceratids.

Deshayesitids are represented by *D. deshayesi* (Fig. 7I-J; Fig. IVE-F, J-K), *D. grandis* (Spath) (Fig. 7K, Fig. IVD, G; Fig. VA, G), *D. latilobatus-involutus* group (Fig. IVI), and *Deshayesites* sp. (Fig. IVL). The species *D. deshayesi* was very widely and differently interpreted in the old literature before Casey (1961a, 1964) definitely fixed its taxonomic status and clarified its actual stratigraphic position. According to this author, in the English Lower Greensand, *D. deshayesi* would only be present in the lower half of its zone (=*Cheloniceras parinodum* Subzone), whereas the upper part would be characterized by the occurrence of *D. grandis*. The *D. grandis* Subzone was later recognized also in southeastern France (Ropolo *et al*., 2000, 2006; Dutour, 2005) and, consequently, it was introduced in the latest versions of the standard Mediterranean zonation (Reboulet *et al*., 2006; Reboulet *et al*., 2009). In the Cau section, we also found *D. grandis* in the upper part of the zone, above typical *D. deshayesi.*

As found in lower levels, desmoceratids are also common components of the fauna of the *Deshayesites deshayesi* Zone where they are mainly represented by the genera *Pseudohaploceras* (*Pseudohaploceras* sp., Fig. VIA) and *Melchiorites*. In this zone, the species *Melchiorites melchioris* (Tietze), which appears in the Upper Barremian and is still present in the *Deshayesites oglanlensis* and *Deshayesites forbesi* Zones, is replaced by *Melchiorites strigosus* (Fallot) (Fig. VD). This taxon persists until the *Epicheloniceras martini* Zone, in the Middle Aptian (see also Dutour, 2005). The genus *Pseudosaynella* also has its last occurrences in the *Deshayesites deshayesi* Zone (see also Moreno-Bedmar *et al*., 2010).

Other groups, like cheloniceratids, ancyloceratids (*Toxoceratoides royerianus*, Fig. IVH), macroscaphitids, phylloceratids and lytoceratids are scarcer, and biostratigraphically less significant. Cheloniceratids are, in general, not well preserved and only the species *Cheloniceras cornuelianum* (Fig. VH) has been positively identified in these beds. However, this species seems to have a long stratigraphic range, as it has been reported from the *Deshayesites forbesi* Zone (=*Deshayesites weissi* Zone, Bogdanova and Tovbina, 1994; Delanoy, 1995), up to the base of the middle Aptian *Epicheloniceras martini* Zone (Ropolo *et al*., 2008). Among the ancyloceratids, we have identified *Toxoceratoides royerianus* (d'Orbigny) and *Hamiticeras carcitanense* (Matheron). The former species, or closely related forms, are found in our sections from the *Deshayesites forbesi* Zone up to the *Dufrenoyia furcata* Zone. *H. carcitanense* has previously been reported from the *Deshayesites deshayesi* Zone (Ropolo *et al*., 2000; Moreno, 2007), but also from the *Epicheloniceras martini* Zone (Conte, 1995). We found this species both in the *Deshayesites deshayesi* Zone of the Mas de Llopis outcrop, and in the *Epicheloniceras martini* Zone of the Racó Ample section.

Dufrenoyia furcata Zone

Jacob (1908) was the first to use a "Sous-zone à *Oppelia nisus* et *Hoplites furcatus*", which he placed at the base of the Gargasian. As currently interpreted, the *Dufrenoyia furcata* Zone constitutes the uppermost subdivision of the Lower Aptian, even though some controversies have recently arisen on this point (Conte, 1995; Atrops and Dutour, 2002; Dutour, 2005; Reboulet *et al*., 2006; Ropolo *et al*., 2006).

We recognized the *Dufrenoyia furcata* Zone in all the localities studied. The lower boundary of this zone is marked by the appearance of the genus *Dufrenoyia*, which entirely replaces the genus *Deshayesites* characteristic of infrajacent levels. Dutour (2005), in his study on the Aptian of south-eastern France, proposed to subdivide the *Dufrenoyia furcata* Zone into two subzones featured by the consecutive occurrence of *Dufrenoyia furcata* (Sowerby) and *Dufrenoyia dufrenoyi* (d'Orbigny). This subdivision has subsequently been recognized in the eastern Iberian Chain (Moreno-Bedmar *et al*., 2010), and can also be identified in the Prebetic Domain (Fig. 8). In the sections we analysed, *D. furcata* (Fig. 7M, R; Fig. VE) occurs within a very short stratigraphic interval at the base of the zone, and is rapidly replaced by *D. dufrenoyi* (Fig. 7L, O; Fig. VB-C, F; Fig. VIB-H; Fig. VII B-D) that characterizes the rest of the unit.

The genus *Colombiceras* is another important component of the assemblages of this zone. It is a member of the family Parahoplitidae, and is usually considered as characteristic of the middle Aptian. However, its occurrence in the *Dufrenoyia furcata* Zone, or equivalent levels, has been consistently reported from different geographic areas (Demay and Thomel, 1986; Barragán-Manzo and Méndez-Franco, 2005; Dutour, 2005; Barragán and Maurrasse, 2008; Moreno-Bedmar *et al*., 2010). In the sections studied, *Colombiceras* is present throughout the *Dufrenoyia furcata* Zone. It is represented by coarse-ribbed specimens of *Colombiceras* aff. *spathi* Humphrey (Fig. 7P; Fig. VIIG, I), similar to *Colombiceras spathi*, as interpreted by Barragán (2001) and Barragán and Maurrasse (2008).

Cheloniceratids are less frequent, represented by *Ch. cornuelianum*, which appears in the *Deshayesites deshayesi* Zone, and extends into the *Dufrenoyia furcata* Zone. In addition, a few specimens of *Cheloniceras meyendorffi* (d'Orbigny) (Fig. 7S) were found in the upper beds of the zone in the l'Alcoraia and Cau sections. This species, which already shows some transitional characters to the genus *Epicheloniceras*, has previously been used to characterize the upper part of the *Tropaeum bowerbanki* Zone in southern England (Casey, 1961a; Casey *et al*., 1998), and the upper part of the *Dufrenoyia furcata* Zone in southeastern France (Ropolo *et al*., 2008). Also worth mentioning is our finding, near the base of the zone in the Fontcalent (X Fc_1) section, of a few single-ribbed and ventro-laterally tuberculated cheloniceratids (Fig. 7Q; Fig. VIIE) that recall some small-sized (microconch?) forms of *Epicheloniceras* usually coming from higher levels (see Casey, 1962).

Less significant components of the assemblages from this zone include, among others, the genera *Costidiscus*

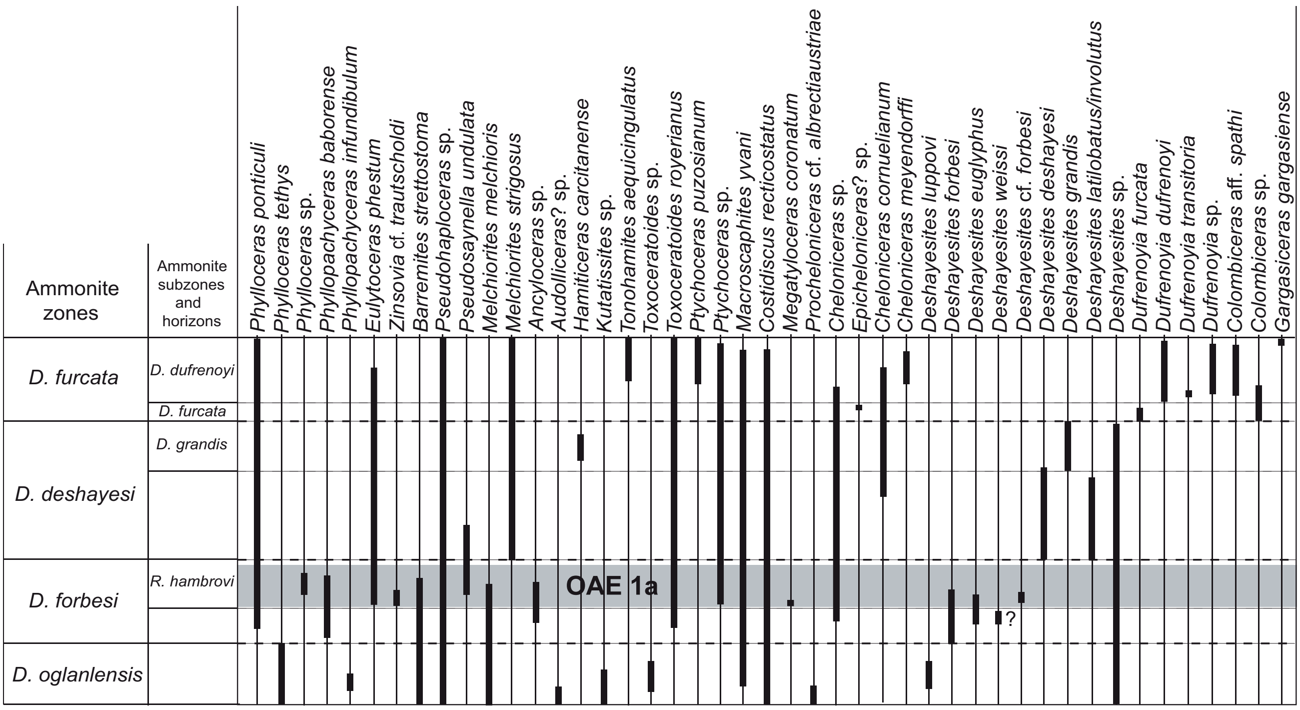

FIGURE 8 | Range of the forty-five species recognized in the Prebetic domain. Gray level indicates position of OAE 1a.

(*Costidiscus recticostatus*, Fig. VIIN) and *Macroscaphites* (*Macroscaphites yvani*, Fig. VIIH), which seem to become extinct at the end of this zone. There is also *Tonohamites aequicingulatus* (Koenen) (Fig. 7N), which was reported from equivalent levels in southern England (Casey, 1961b).

The upper boundary of the *Dufrenoyia furcata* Zone, which coincides with the base of the Middle Aptian, is defined by the first occurrence of the genus *Epicheloniceras*. A conspicuous faunal turnover takes place at that level. Unlike the observations reported by Casey *et al*. (1998), and Dutour (2005), the sections studied did not show any overlap between the stratigraphic ranges of the genera *Dufrenoyia* and *Epicheloniceras*, because *Dufrenoyia* disappeared before the first recorded *Epicheloniceras*. The first specimens of this genus, such as *E. debile* Casey (Fig. VIIIA-B) and *E. martini* (d'Orbigny) (Fig. VIIID), occur together with *Colombiceras crassicostatum* (d'Orbigny) (Fig. VIIIG), which replaces *C.* aff. *spathi*, and *Gargasiceras gargasense* (d'Orbigny). These two species, however, were reported from the *Dufrenoyia furcata* Zone by Dutour (2005). Other forms appearing near the base of the *Epicheloniceras martini* Zone comprise *Vergunniceras pretiosum* (d'Orbigny) and *Caseyella* sp. (Fig. VIIIH-M, O-P). The latter taxon, which is rather frequent in the l'Alcoraia section, is a desmoceratid of Caribbean affinities originally identified as *Uhligella jacobi* (Burckhardt), and reported from equivalent levels in southeastern France by Dutour (2005). In contrast, the genus *Aconeceras* is markedly absent in our sections, both in the *Dufrenoyia furcata* Zone and the *Epicheloniceras martini* Zone.

CARBON ISOTOPE STRATIGRAPHY. CALIBRATION AGAINST THE AMMONITE ZONATION

A total of 153 bulk rock samples were analyzed for stable carbon isotope ratios from the Cau, Racó Ample and l'Alcoraia sections. The samples were treated with H_3PO_4 (90%) at 70ºC and the liberated CO_2 was analyzed with a Thermo Finnigan MAT-252 stable isotope ratio mass spectrometer at the laboratory of the Unitat de Medi Ambient (Serveis cientificotècnics de la Universitat de Barcelona). The isotope results are expressed in ‰ versus VPDB standard, with a precision of ±0.03 for the samples of the Cau section, ±0.02 for the samples of the Racó Ample section, and ±0.01 for the samples of the l'Alcoraia section. The data previously published by de Gea *et al*. (2003) for the Cau section have been substituted here by a denser record.

The carbon isotope curves of the three sections can be easily correlated as they show the globally observed trends, which implies that measured values are primary and therefore suitable for $\delta^{13}C$ stratigraphy. Moreover, the chemostratigraphic segments defined by Menegatti *et al*. (1998), and subsequently widely applied (Bralower *et al*., 1999; Erba *et al*., 1999; Bellanca *et al*., 2002; de Gea *et al*., 2003; Heimhofer, 2004; Herrle *et al*., 2004; Ando *et al*., 2008; Heldt *et al*., 2008; Li *et al*., 2008; Michalík *et al*., 2008; García-Mondéjar *et al*., 2009; Millán *et al*., 2009; Moreno-Bedmar *et al*., 2009), can also be easily identified. This enables a direct, high-resolution calibration of the chemostratigraphic record with the proposed ammonite zonation. The results obtained can be seen in Figure 9. The isotopic curves of the Roter Sattel reference section (Menegatti *et al*., 1998) and the Cassis-La Bédoule stratotype (Moullade *et al*., 1998, 2000; Kuhnt *et al*., 2000; Renard *et al*., 2005) are also plotted in the figure for comparison. The ammonite biostratigraphic zonation shown has been reinterpreted following the considerations of Moreno-Bedmar *et al*. (2009).

In the lowermost Aptian (*Deshayesites oglanlensis* Zone and lower part of the *Deshayesites forbesi* Zone), the ^{13}C curves show no significant trend, and values oscillate between 1.9‰ and 3.0‰ in both l'Alcoraia and Cau sections. This rather stable phase corresponds to segment C2 of Menegatti *et al*. (1998) and Erba *et al*. (1999), and can also be easily recognized in the Cassis-La Bédoule section (beds 70-129), and in the Angles section (interval A2 of Wissler *et al*., 2002).

A strong negative shift in $\delta^{13}C$ values is detected in the lower part of a predominantly marly interval in the Cau section (bed 10). The carbon isotope values fall by about 1.5‰, reaching minima of 0.9-1.0‰, which persist during the middle part of the *Deshayesites forbesi* Zone. This interval distinctly correlates with the long negative excursion of $\delta^{13}C$, between beds 129 and 146, in the Casis-La Bédoule section (Moullade *et al*., 1998, 2000; Kuhnt *et al*., 2000; Renard *et al*., 2005). In both cases, the extension of the excursion and its structure are very similar. This interval would correspond to the segment C3 of Menegatti *et al*. (1998) and Erba *et al*. (1999). The strongly reduced thickness of this negative excursion in the Roter Sattel and Cismon sections (and many others elsewhere) could be explained by the existence of a hiatus or a strong condensation in sedimentation at this stratigraphic level (Renard *et al*., 2005).

Following the negative excursion, the curve shows a markedly positive trend leading the $\delta^{13}C$ values to ~3.5‰, both in the Cau section (beds 19-26) and at the base of the Racó Ample section (beds 1-14). This interval is structured in three short steps that can be paralleled with segments C4, C5 and C6 of Menegatti *et al*. (1998): an initial abrupt positive shift, followed by a middle stable phase at ~2.5-3‰, and a final sloping increase up to ~3.5‰. A very similar pattern occurs in the Cassis-La Bédoule section (beds 146-158). The age of this positive excursion can be established with accuracy because the genus *Megatyloceras* is present

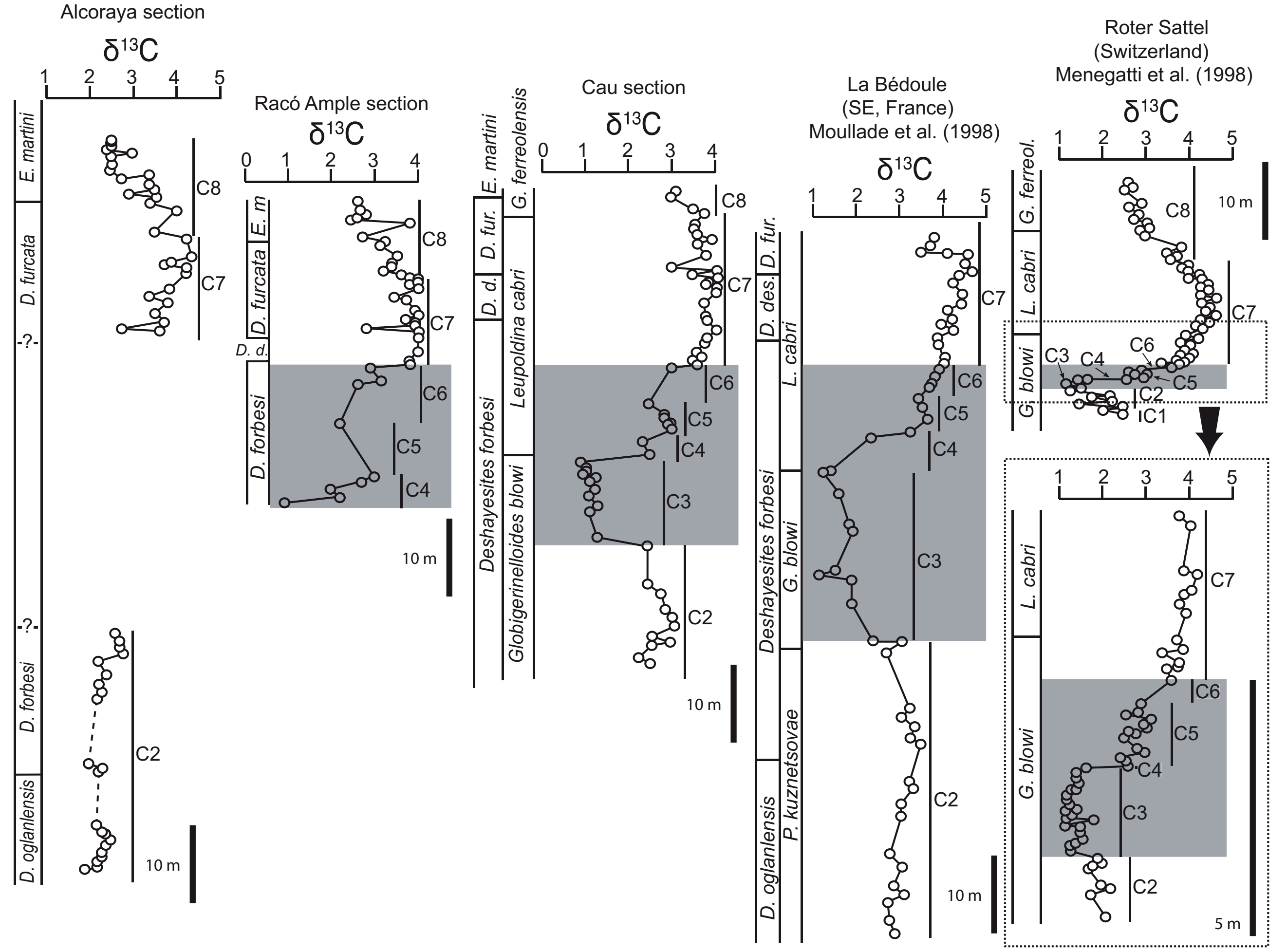

FIGURE 9 | Isotopic curves of the sections studied in the Prebetic domain at Alcoraia, Racó Ample, and Cau. These curves are compared with the reference sections of the Cassis-La Bédoule, France (Moullade *et al.*, 1998, 2000; Kuhnt *et al.*, 2000; Renard *et al.*, 2005), and Roter Sattel, Switzerland (Menegatti *et al.*, 1998). The ammonite biostratigraphy of the Cassis-La Bédoule section has been reinterpreted in agreement with arguments discussed by Moreno-Bedmar *et al.* (2009). Gray level indicates position of OAE 1a.

at the base of this interval in the Racó Ample section, and throughout it in the Cassis-La Bédoule area (Ropolo *et al*., 2000, 2008) as well as in the eastern Iberian Chain (Moreno-Bedmar *et al*., 2008, 2009). According to Casey *et al*. (1998), this genus is restricted to the uppermost part of the *Deshayesites forbesi* Zone (= *Deshayesites annelidus* Subzone).

As usually interpreted, the organic-rich sediments related to OAE1a extend throughout the interval corresponding to the negative excursion and subsequent abrupt positive shift of the $\delta^{13}C$ curve, *i.e.* segments C3 to C6 (Erba, 1999; Bellanca *et al*., 2002; Li *et al*., 2008). Therefore, we can constrain the age of this global event to the middle/upper part of the *Deshayesites forbesi* Zone, thus corroborating similar findings by Moreno-Bedmar *et al*. (2008, 2009) in the eastern Iberian Chain.

The carbon isotope curves reach their highest values (~3.5-4‰) in a plateau interval analogous to segment C7 of Menegatti *et al*. (1998) that extends from the top of the *Deshayesites forbesi* Zone to the upper part of the *Dufrenoyia furcata* Zone. This relatively stable phase is interrupted in all the sections analyzed by a sharp negative peak (by ~-1‰) near the base of the *D. furcata* Zone (Fig. IX). A comparable negative shift has been recorded at the top of the Cassis-La Bédoule section (beds 173-176), in an equivalent stratigraphic position (Fig. IX). In addition, Herrle *et al*. (2004) documented a short negative excursion of $\delta^{13}C$ coinciding with the Niveau Blanc in the Vocontian Basin (Fig. IX). The age of this bed has long remained uncertain (Dauphin, 2002), but recent records permit to attribute it to the lower part of the *Dufrenoyia furcata* Zone (Dutour, 2005).

Finally, from the upper part of the *Dufrenoyia furcata* Zone, the carbon isotope values show a progressive decrease that continues in the *Epicheloniceras martini* Zone. This negative trend corresponds to segment C8 of Menegatti *et al*. (1998).

CONCLUSIONS

Lower Aptian hemipelagic sediments of the Almadich Fm. (eastern Prebetic Domain (southeastern Spain) include abundant and diverse ammonite fauna, particularly rich in deshayesitids, the key group used for biostratigraphic zonation of this interval. Analysis of the ammonite stratigraphic distribution in several systematically sampled sections show that the zonal scheme proposed by Moreno-Bedmar *et al*. (2010) for the Lower Aptian of the Maestrat basin is also applicable to other Mediterranean basins, such as the Prebetic domain. This scheme, which slightly modifies and refines the current standard zonation (Reboulet *et al*., 2009), comprises the following units in ascending order: *Deshayesites oglanlensis* Zone, *Deshayesites forbesi* Zone (with *Roloboceras hambrowi* Horizon in its middle/upper part), *Deshayesites deshayesi*, and *Dufrenoyia furcata* Zones (subdivided into a lower *D. furcata* Subzone and an upper *D. dufrenoyi* Subzone). This work provides further precision in the identification and dating of other biostratigraphically significant events, mainly based on desmoceratids, which can also be used to further characterize some of these units.

The ammonite data have been correlated with high resolution carbon isotope records from the same sections. The geochemical records reproduce the global trends observed for the Early Aptian interval, which is characterized by two positive shifts separated by a marked negative excursion. The lower positive shift correlates with the *Deshayesites oglanlensis* Zone and the lower part of the *Deshayesites forbesi* Zone. The negative excursion and the subsequent abrupt positive shift, which generally coincide with the occurrence of organic rich sediments related to the OAE 1a, correspond to the middle and upper part of the *Deshayesites forbesi* Zone, respectively. These results thus confirm previous findings (Moreno-Bedmar *et al*., 2008, 2009) in the eastern Iberian Chain. The upper positive interval extends throughout the *Deshayesites deshayesi* Zone and most of the *Dufrenoyia furcata* Zone, showing a short negative spike near the base of the latter zone.

The integration of ammonite and carbon isotope stratigraphic data provides a high resolution temporal framework for accurately placing the major palaeoenvironmental and palaeobiologic events that took place during the Early Aptian.

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ELECTRONIC APPENDIX

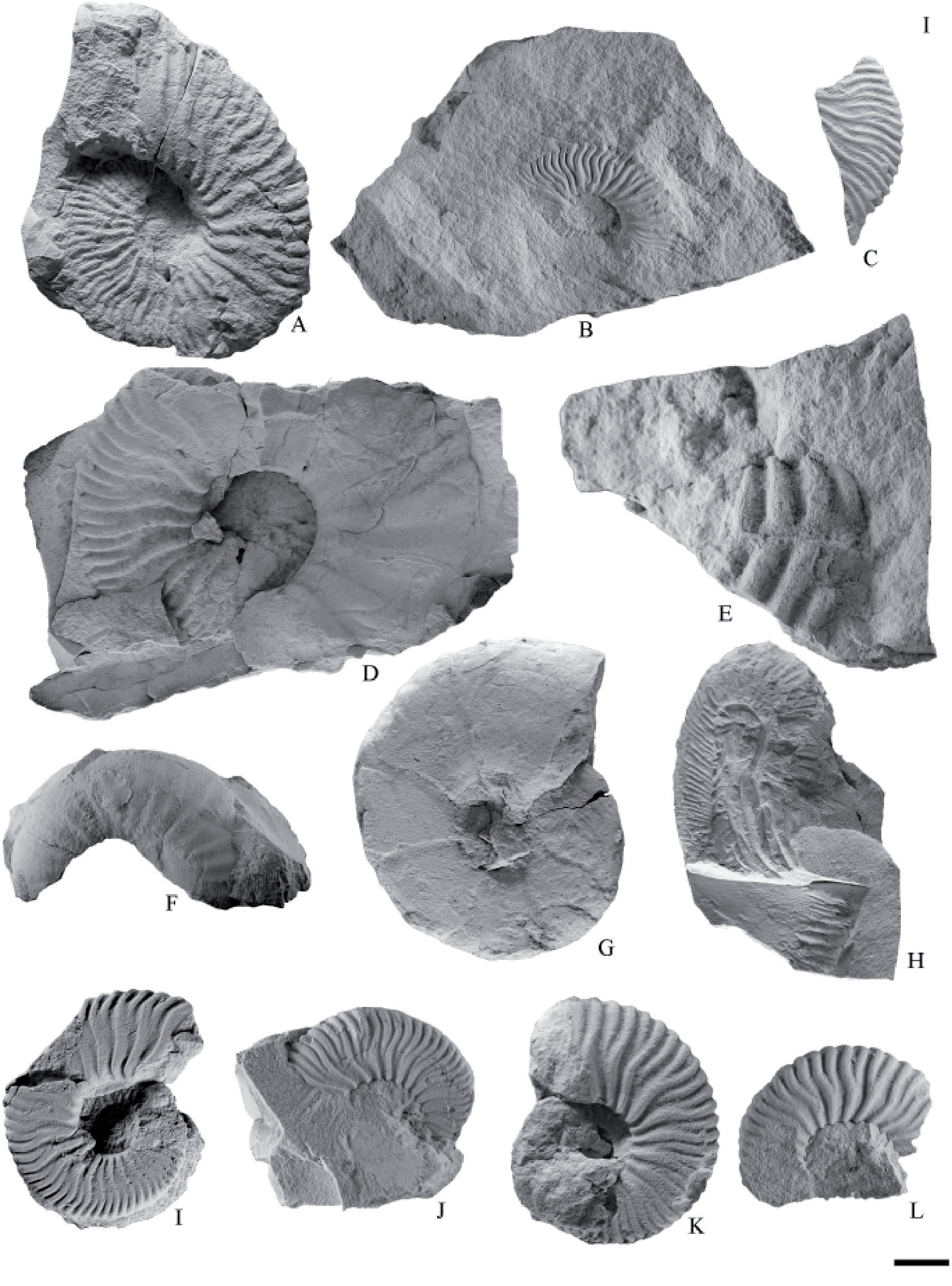

FIGURE I | A) *Deshayesites luppovi* lateral view of specimen X Ac 104.23, Alcoraia section, *Deshayesites oglanlensis* Zone. B) *Deshayesites luppovi* lateral view of specimen X Fc 114.4, Font Calent section, *Deshayesites oglanlensis* Zone. C) *Deshayesites luppovi* lateral view of specimen X Fc 114.17, Font Calent section, *Deshayesites oglanlensis* Zone. D) *Deshayesites luppovi* lateral view of specimen X Ac 104.3, Alcoraia section, *Deshayesites oglanlensis* Zone. E) *Kutatissites* sp. ventral region X Ac 110.12, Alcoraia section, *Deshayesites oglanlensis* Zone. F) *Phyllopachyceras infundibulum* lateral view of specimen X Ac 103.20, Alcoraia section, *Deshayesites oglanlensis* Zone. G) *Melchiorites melchioris* lateral view of specimen X Ac 107.6, Alcoraia section, *Deshayesites oglanlensis* Zone. H) *Toxoceratoides* sp. lateral view of specimen X Ac 103.27, Alcoraia section, *Deshayesites oglanlensis* Zone. I) *Deshayesites forbesi* lateral view of specimen X P3 0.2, Cau section, *Deshayesites forbesi* Zone. J) *Deshayesites forbesi* lateral view of specimen X Ac 120.5, Alcoraia section, *Deshayesites forbesi* Zone. K) *Deshayesites forbesi* lateral view of specimen X AB 2.51, Racó Ample section, *Deshayesites forbesi* Zone. L) *Deshayesites forbesi* lateral view of specimen X AB 2.7, Racó Ample section, *Deshayesites forbesi* Zone. Scale bar= 1cm.

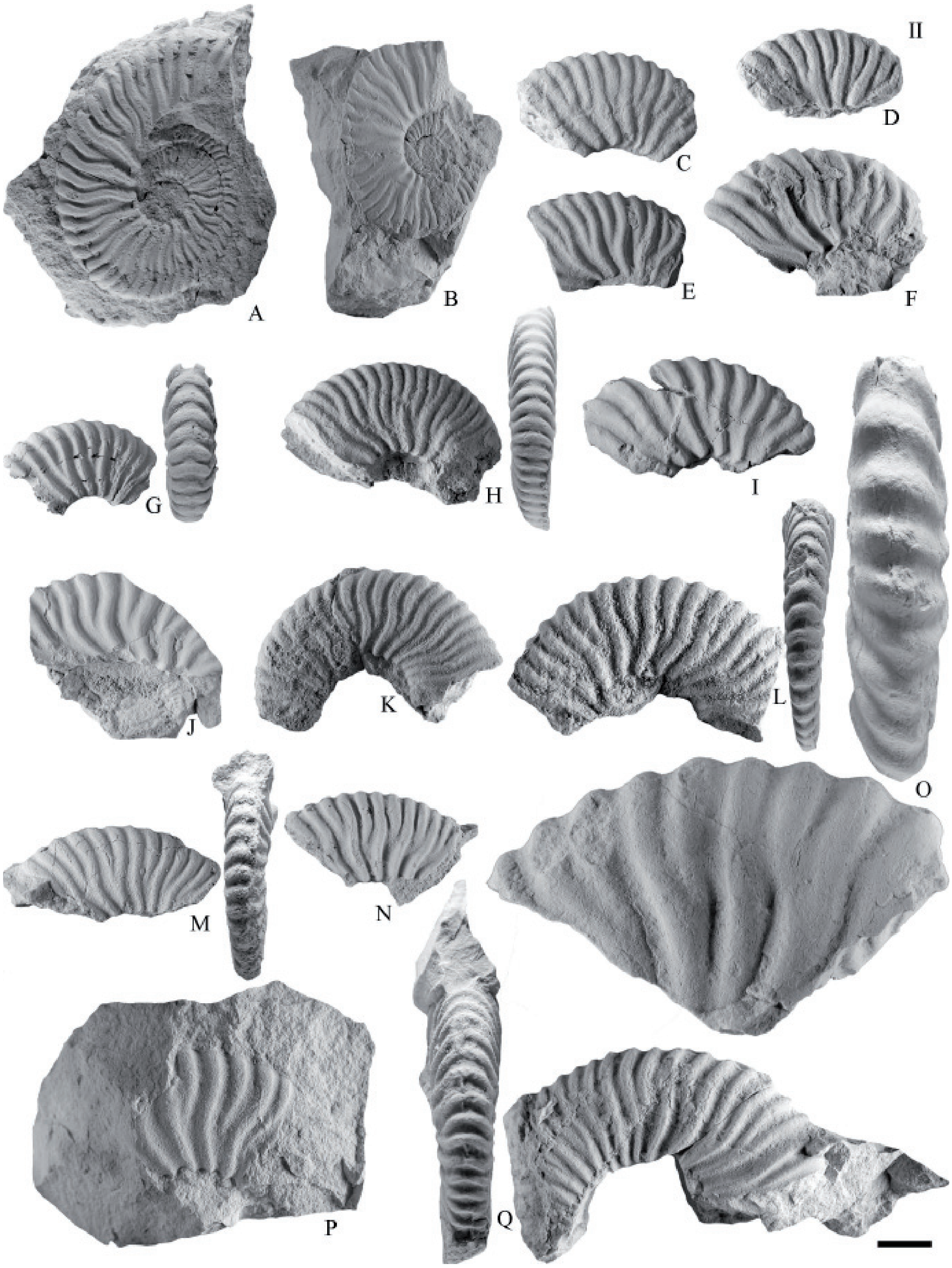

FIGURE II | A) *Deshayesites euglyphus* lateral view of specimen X Ac 117.1, Alcoraia section, *Deshayesites forbesi* Zone. B) *Deshayesites euglyphus* lateral view of specimen X Ac 115.1, Alcoraia section, *Deshayesites forbesi* Zone. C) *Deshayesites forbesi* lateral view of specimen X P3 2.2, Cau section, *Deshayesites forbesi* Zone. D) *Deshayesites euglyphus* lateral view of specimen X AB 1.2, Racó Ample section, *Deshayesites forbesi* Zone. E) *Deshayesites forbesi* lateral view of specimen X Ac 118.2, Alcoraia section, *Deshayesites forbesi* Zone. F) *Deshayesites euglyphus* lateral view of specimen X Ac 115.17. G) *Deshayesites forbesi* lateral and ventral view of specimen X AB 3.14, Racó Ample section, *Deshayesites forbesi* Zone. H) *Deshayesites forbesi* lateral view of specimen X AB 5.12, Racó Ample section, *Deshayesites forbesi* Zone. I) *Deshayesites euglyphus* lateral view of specimen X P3 0.4, Cau section, *Deshayesites forbesi* Zone. J) *Deshayesites euglyphus* lateral view of specimen X Ac 118.15, Racó Ample section, *Deshayesites forbesi* Zone. K) *Deshayesites forbesi* lateral view of specimen X AB 2.6, Racó Ample section, *Deshayesites forbesi* Zone. L) *Deshayesites forbesi* lateral and ventral view of specimen X AB 2.8, Racó Ample section, *Deshayesites forbesi* Zone. M) *Deshayesites forbesi* lateral and ventral view of specimen X AB 2.11, Racó Ample section, *Deshayesites forbesi* Zone. N) *Deshayesites euglyphus* lateral view of specimen X Ac 115.14, Alcoraia section, *Deshayesites forbesi* Zone. O) *Deshayesites euglyphus* lateral view of specimen X AB 2.18, Racó Ample section, *Deshayesites forbesi* Zone. P) *Deshayesites euglyphus* lateral view of specimen X AB 4.54, Racó Ample section, *Deshayesites forbesi* Zone. Q) *Deshayesites forbesi* ventral and lateral view of specimen X AB 4.45, Racó Ample section, *Deshayesites forbesi* Zone. Scale bar= 1cm.

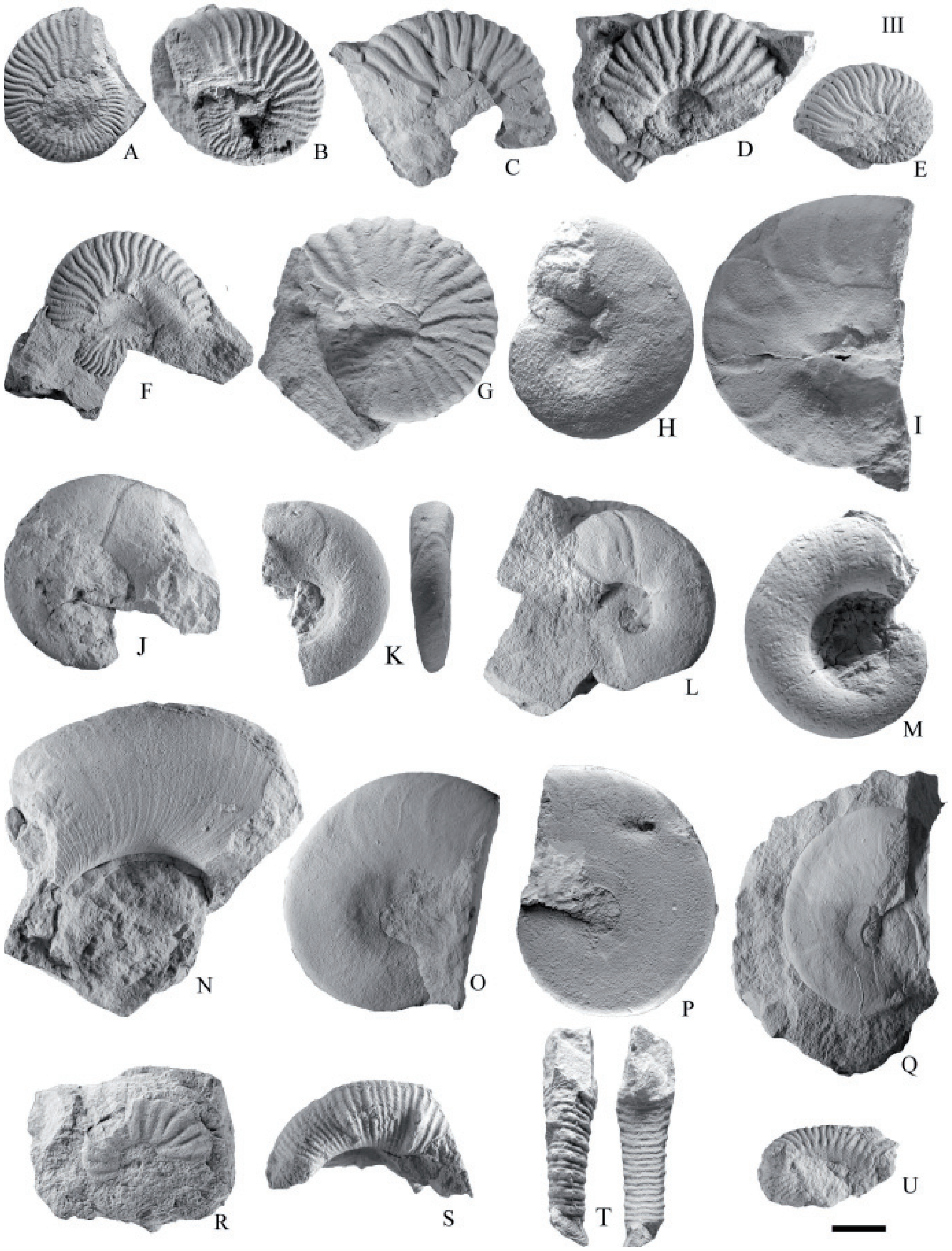

FIGURE III A) *Deshayesites forbesi* lateral view of specimen X AB 4.35, Racó Ample section, *Deshayesites forbesi* Zone. B) *Deshayesites forbesi* lateral view of specimen X AB 4.46, Racó Ample section, *Deshayesites forbesi* Zone. C) *Deshayesites euglyphus* lateral view of specimen X AB 5.18, Racó Ample section, *Deshayesites forbesi* Zone. D) *Deshayesites euglyphus* lateral view of specimen X AB 4.68, Racó Ample section, *Deshayesites forbesi* Zone. E) *Deshayesites forbesi* lateral view of specimen X AB 4.64, Racó Ample section, *Deshayesites forbesi* Zone. F) *Deshayesites forbesi* lateral view of specimen X AB 5.11, Racó Ample section, *Deshayesites forbesi* Zone. G) *Deshayesites euglyphus* lateral view of specimen X P3 3.1, Cau section, *Deshayesites forbesi* Zone. H) *Barremites strettostoma* lateral view of specimen X AB 3.20, Racó Ample section, *Deshayesites forbesi* Zone. I) *Barremites strettostoma* lateral view of specimen X P3 8.3, Cau section, *Deshayesites forbesi* Zone. J) *Melchiorites melchioris* lateral view of specimen X AB 4.25, Racó Ample section, *Deshayesites forbesi* Zone. K) *Melchiorites melchioris* lateral and ventral view of specimen X AB 2.3, Racó Ample section, *Deshayesites forbesi* Zone. L) *Melchiorites melchioris* lateral view of specimen X Ac 123.12, Alcoraia section, *Deshayesites forbesi* Zone. M) *Eulytoceras phestum* lateral view of specimen X AB 4.81, Racó Ample section, *Deshayesites forbesi* Zone. N) *Eulytoceras phestum* lateral view of specimen X AB 2.14, Racó Ample section, *Deshayesites forbesi* Zone. O) *Barremites strettostoma* lateral view of specimen X P3 11.3. P) *Barremites strettostoma* lateral view of specimen X P3 11.5, Cau section, *Deshayesites forbesi* Zone. Q) *Barremites strettostoma* lateral view of specimen X Ac 119.7, Alcoraia section, *Deshayesites forbesi* Zone. R) *Pseudosaynella undulata* lateral view of specimen X P3 11.1, Cau section, *Deshayesites forbesi* Zone. S) *Ancyloceras* sp. lateral view of specimen X AB 1.5, Racó Ample section, *Deshayesites forbesi* Zone. T) *Toxoceratoides royerianus* ventral and dorsal view of specimen X AB 4.10, Racó Ample section, *Deshayesites forbesi* Zone. U) *Toxoceratoides royerianus* lateral view of specimen X AB 3.5, Racó Ample section, *Deshayesites forbesi* Zone. Scale bar= 1cm.

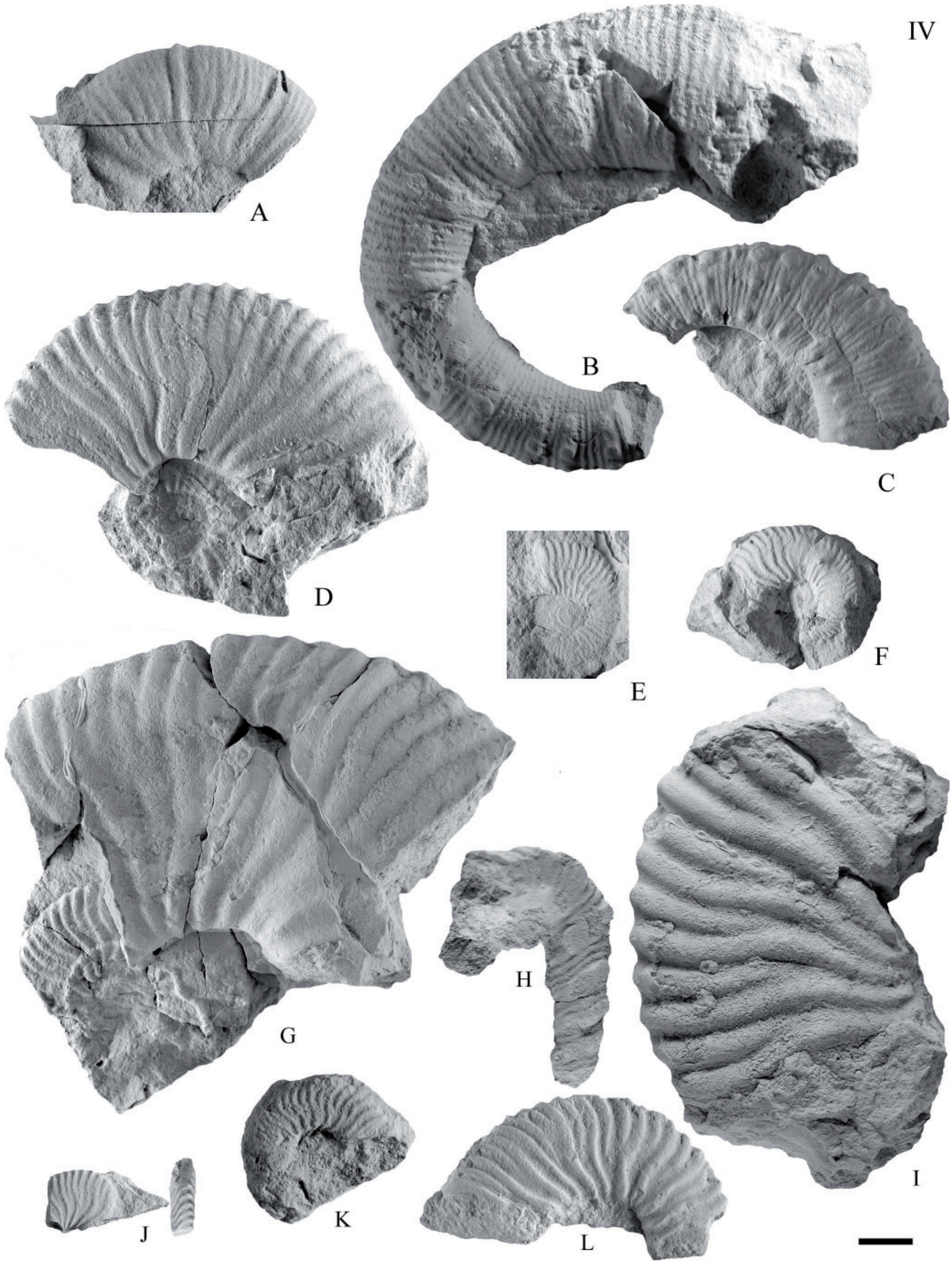

FIGURE IV | A) *Pseudohaploceras* sp. lateral view of specimen X AB 5.21, Racó Ample section, *Deshayesites forbesi* Zone. B) *Ancyloceras* sp. lateral view of specimen X AB 5.2, Racó Ample section, *Deshayesites forbesi* Zone. C) *Ancyloceras* sp. lateral view of specimen X P3 5.5, Cau section, *Deshayesites forbesi* Zone. D) *Deshayesites grandis* lateral view of specimen X P3 39.2, Cau section, *Deshayesites deshayesi* Zone. E) *Deshayesites deshayesi* lateral view of specimen X P3 31.2, Cau section, *Deshayesites deshayesi* Zone. F) *Deshayesites deshayesi* lateral view of specimen X P3 37.7, Cau section, *Deshayesites deshayesi* Zone. G) *Deshayesites grandis* lateral view of specimen X P3 37.16, Cau section, *Deshayesites deshayesi* Zone. H) *Toxoceratoides royerianus* lateral view of specimen X P3 32.17, Cau section, *Deshayesites deshayesi* Zone. I) *Deshayesites latilobatus*/*involutus* group lateral view of specimen SM-111-2, Mas de Llopis, Serra Mariola, *Deshayesites deshayesi* Zone. J) *Deshayesites deshayesi* lateral view of specimen X AB 15.4, Racó Ample section, *Deshayesites deshayesi* Zone. K) *Deshayesites deshayesi* lateral view of specimen X P3 31.4, Cau section, *Deshayesites deshayesi* Zone. L) *Deshayesites* sp. lateral view of specimen X P3 37.14, Cau section, *Deshayesites deshayesi* Zone. Scale bar= 1cm.

FIGURE V | A) *Deshayesites grandis* lateral view of specimen X P3 39.1, Cau section, *Deshayesites deshayesi* Zone. B) *Dufrenoyia dufrenoyi* ventral view of specimen X Ac 192.17, Alcoraia section, *Dufrenoyia furcata* Zone. C) *Dufrenoyia dufrenoyi* lateral view of specimen X Ac 192.56, Alcoraia section, *Dufrenoyia furcata* Zone. D) *Melchiorites strigosus* lateral view of specimen X AB 15.5, Racó Ample section, *Deshayesites deshayesi* Zone. E) *Dufrenoyia furcata* ventral view of specimen X Fc1 2.1, Font Calent section, *Dufrenoyia furcata* Zone. F) *Dufrenoyia dufrenoyi* ventral view of specimen X P3 46B.8, Cau section, *Dufrenoyia furcata* Zone. G) *Deshayesites grandis* lateral and ventral view of specimen SM-111-7, Mas de Llopis, Serra Mariola, *Deshayesites deshayesi* Zone. H) *Cheloniceras cornuelianum* lateral view of specimen X P3 32.3, Cau section, *Deshayesites deshayesi* Zone. Scale bar= 1cm.

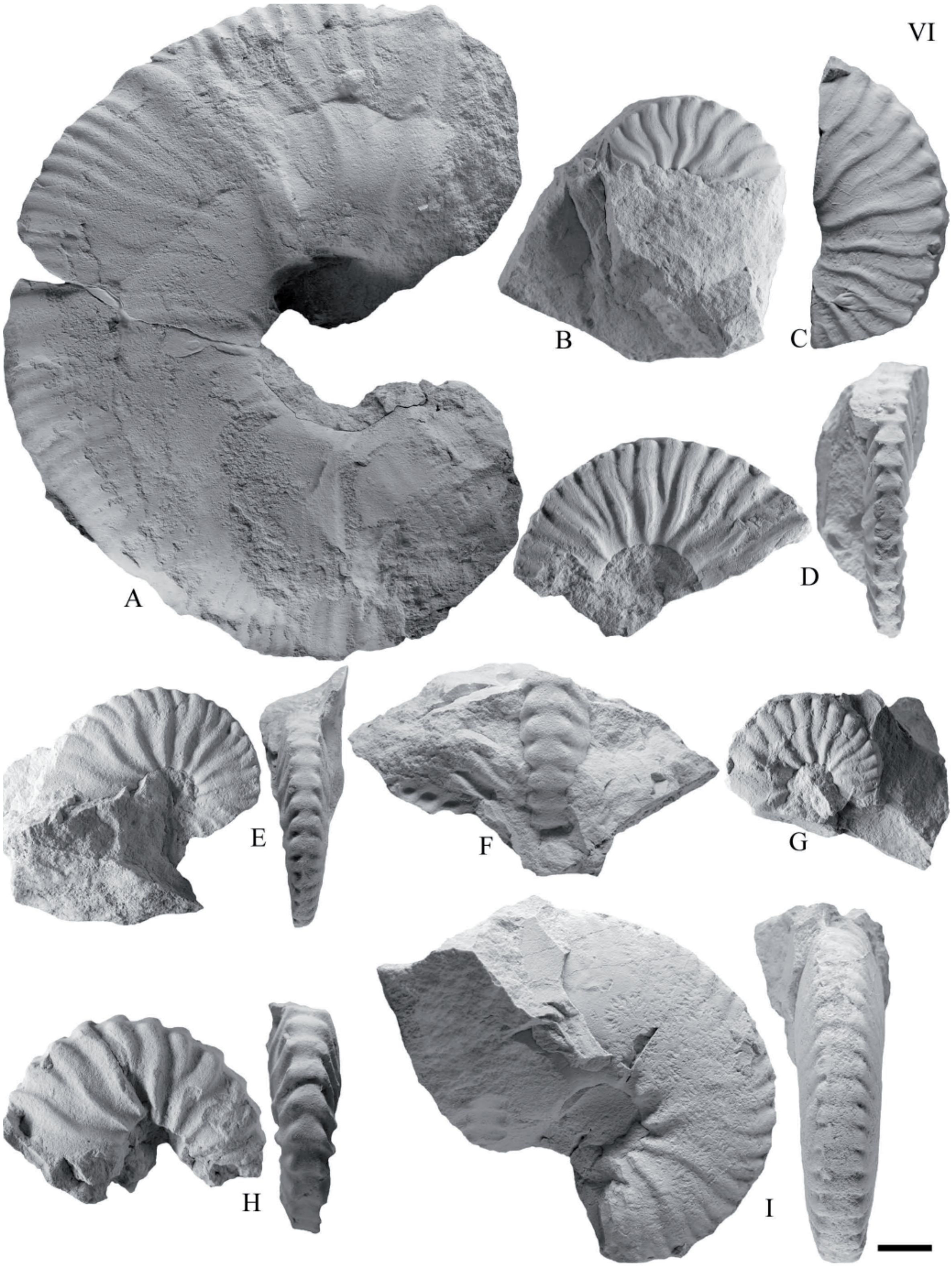

FIGURE VI A) *Pseudohaploceras* sp. lateral view of specimen X P3 32.8, Cau section, *Deshayesites deshayesi* Zone. B) *Dufrenoyia dufrenoyi* lateral view of specimen X AB 19A.5, Racó Ample section, *Dufrenoyia furcata* Zone. C) *Dufrenoyia dufrenoyi* lateral view of specimen X P3 46B.8, Cau section, *Dufrenoyia furcata* Zone. D) *Dufrenoyia dufrenoyi* lateral and ventral view of specimen X P3 46B.5, Cau section, *Dufrenoyia furcata* Zone. E) *Dufrenoyia dufrenoyi* lateral and ventral view of specimen X AB 20.3, Racó Ample section, *Dufrenoyia furcata* Zone. F) *Dufrenoyia dufrenoyi* ventral view of specimen X AB 20.9, Racó Ample section, *Dufrenoyia furcata* Zone. G) *Dufrenoyia dufrenoyi* lateral view of specimen X AB 24.3, Racó Ample section, *Dufrenoyia furcata* Zone. H) *Dufrenoyia dufrenoyi* lateral and ventral view of specimen X AB 22.9, Racó Ample section, *Dufrenoyia furcata* Zone. I) *Dufrenoyia transitoria* lateral and ventral view of specimen X AB 20.18, Racó Ample section, *Dufrenoyia furcata* Zone. Scale bar= 1cm.

FIGURE VII | A) *Dufrenoyia* sp. lateral view of specimen X AB 29.5, Racó Ample section, *Dufrenoyia furcata* Zone. B) *Dufrenoyia dufrenoyi* lateral view of specimen X AB 19A.1, Racó Ample section, *Dufrenoyia furcata* Zone. C) *Dufrenoyia dufrenoyi* lateral and ventral view of specimen X AB 24.8, Racó Ample section, *Dufrenoyia furcata* Zone. D) *Dufrenoyia dufrenoyi* lateral and ventral view of specimen X Ac 192.48, Alcoraia section, *Dufrenoyia furcata* Zone. E) *Epicheloniceras*? sp. lateral and ventral view of specimen X Fc1 3.14, Font Calent 1 section, *Dufrenoyia furcata* Zone. F) *Phylloceras ponticuli* lateral view of specimen X Ac 189.33, Alcoraia section, *Dufrenoyia furcata* Zone. G) *Colombiceras* aff. *spathi* lateral and ventral view of specimen X Ac 188.8, Alcoraia section, *Dufrenoyia furcata* Zone. H) *Macroscaphites yvani* lateral view of specimen X Ac 183.15, Alcoraia section, *Dufrenoyia furcata* Zone. I) *Colombiceras* aff. *spathi* lateral view of specimen X P3 47.20, Cau section, *Dufrenoyia furcata* Zone. J) *Toxoceratoides royerianus* lateral view of specimen X Ac 189.31, Alcoraia section, *Dufrenoyia furcata* Zone. K) *Ptychoceras* sp. lateral view of specimen X Fc1 3.25, Font Calent 1 section, *Dufrenoyia furcata* Zone. L) *Eulytoceras phestum* lateral view of specimen X Ac 183.29, Alcoraia section, *Dufrenoyia furcata* Zone. M) *Toxoceratoides royerianus* lateral view of specimen X Ac 189.32, Alcoraia section, *Dufrenoyia furcata* Zone. N) *Costidiscus recticostatus* lateral view of specimen X Fc1 5.8, Font Calent 1 section, *Dufrenoyia furcata* Zone. Scale bar= 1cm.

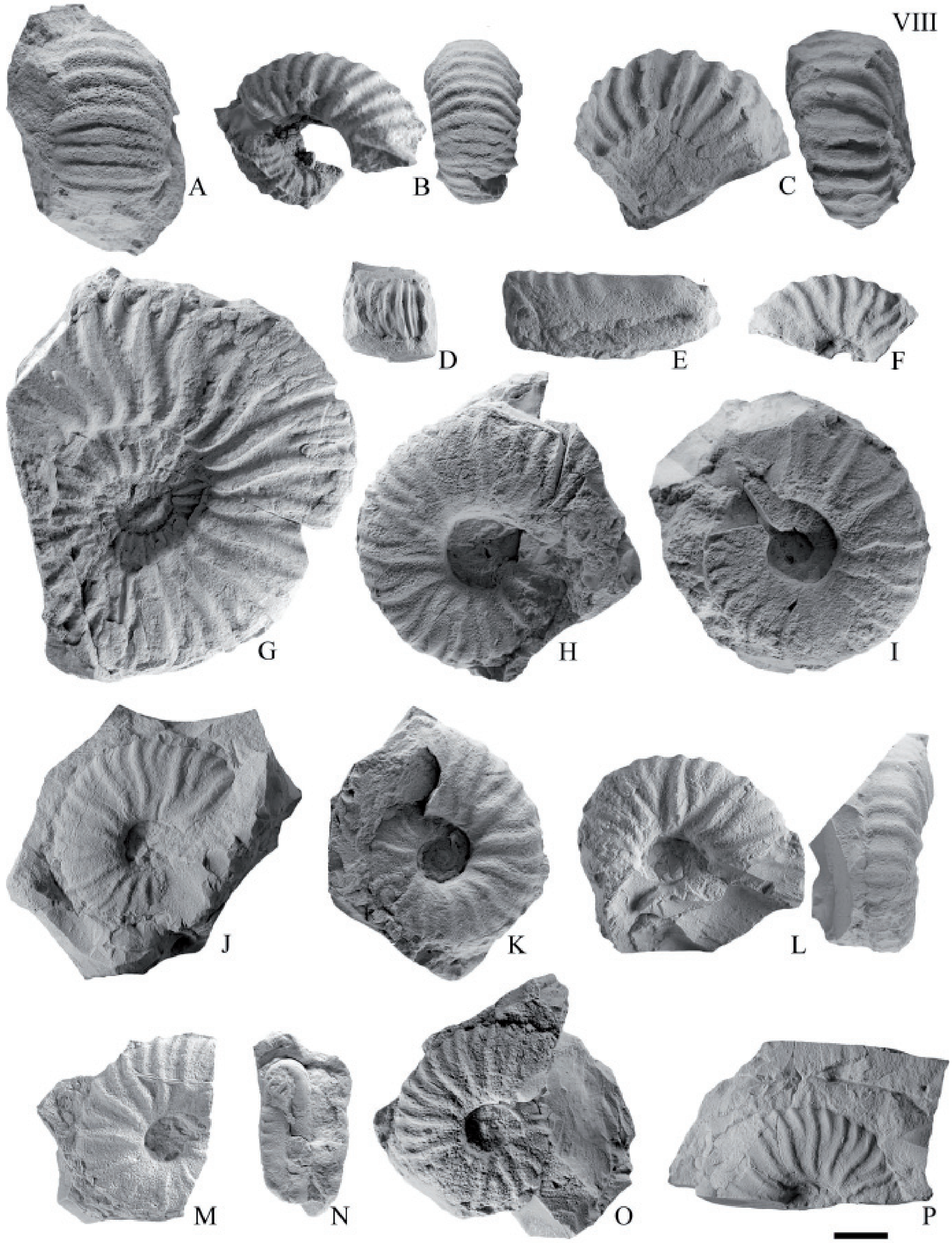

FIGURE VIII A) *Epicheloniceras debile* ventral view of specimen X AB 41.1, Racó Ample section, *Epicheloniceras martini* Zone. B) *Epicheloniceras debile* lateral and ventral view of specimen X AB 41.9, Racó Ample section, *Epicheloniceras martini* Zone. C) *Epicheloniceras* sp. lateral and ventral view of specimen X AB 44.1, Racó Ample section, *Epicheloniceras martini* Zone. D) *Epicheloniceras martini* ventral view of specimen X Ac 202.2, l'Alcoraia section, *Epicheloniceras martini* Zone. E) *Ptychoceras* sp. lateral view of specimen X AB 40.2, Racó Ample section, *Epicheloniceras martini* Zone. F) *Caseyella* sp. lateral view of specimen X Ac 200.24, l'Alcoraia section, *Epicheloniceras martini* Zone. G) *Colombiceras crassicostaum* lateral view of specimen X Ac 199.1, l'Alcoraia section, *Epicheloniceras martini* Zone. H) *Caseyella* sp. lateral view of specimen X Ac 200.20, l'Alcoraia section, *Epicheloniceras martini* Zone. I) *Caseyella* sp. lateral view of specimen X Ac 203.4, l'Alcoraia section, *Epicheloniceras martini* Zone. J) *Caseyella* sp. lateral view of specimen X Ac 200.46, l'Alcoraia section, *Epicheloniceras martini* Zone. K) *Caseyella* sp. lateral view of specimen X Ac 200.14, l'Alcoraia section, *Epicheloniceras martini* Zone. L) *Caseyella* sp. lateral view of specimen X Ac 200.6, l'Alcoraia section, *Epicheloniceras martini* Zone. M) *Caseyella* sp. lateral view of specimen X Ac 200.39, l'Alcoraia section, *Epicheloniceras martini* Zone. N) *Ptychoceras laeve* lateral view of specimen X Ac 204.1, l'Alcoraia section, *Epicheloniceras martini* Zone. O) *Caseyella* sp. lateral view of specimen X Ac 200.5, l'Alcoraia section, *Epicheloniceras martini* Zone. P) *Caseyella* sp. lateral view of specimen X Ac 200.29, l'Alcoraia section, *Epicheloniceras martini* Zone. Scale bar= 1cm.

IX

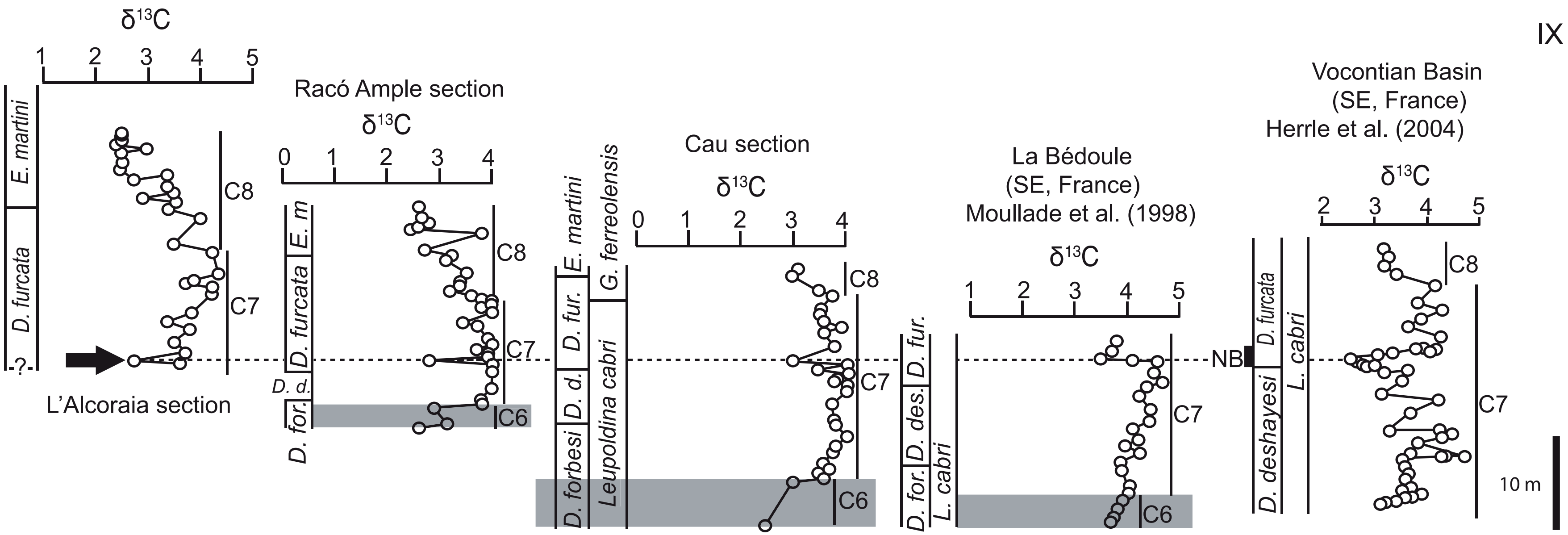

FIGURE IX | Detail of the isotopic curves of the Alcoraia, Racó Ample and Cau sections studied in the Prebetic domain. These curves are compared with the reference sections of Cassis-La Bédoule, France (Moullade *et al.*, 1998, 2000; Kuhnt *et al.*, 2000; Renard *et al.*, 2005) and the Vocontian basin (Herrle *et al.*, 2004). A sharp negative peak, near the base of the *Dufrenoyia fucata* Zone, is compared in these four sections (see the arrow).

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