
Stratigraphy and biostratigraphy (charophytes) of the marine-terrestrial transition in the Upper Eocene of the NE Ebro Basin (Catalonia, Spain)

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| A B S T R A C T |

The onset of endorheic sedimentation in the Ebro Basin is a prominent feature of the basin's evolution and has recently been characterized as a rapid event occurring in the Early Priabonian. In the north-eastern part of the basin this event coincides with the deposition of the Artés Formation (Fm.), mainly built up by red beds of alluvial origin. The marine-continental boundary has been poorly studied up to now in the so-called Lluçanès area, and what was previously thought to be the base of the Artés Fm. is actually a transitional unit, which we define as the Sant Boi Formation, which covers the underlying marine Milany Depositional Sequence and passes laterally to the Terminal Complex, extending over 15km along the eastern margin of the Ebro Basin. The Sant Boi Fm. is formed by up to 15-20m of alternating siltstones and lutite, grading upwards to brackish and lacustrine marls and lignite, and represents deposition in a brackish to freshwater floodplain. It is characterized biostratigraphically by the fossil charophyte assemblage *Harrisichara lineata*, *Harrisichara vasiformis-tuberculata* and *Nodosochara jorbae*, from the middle part of the Priabonian. In contrast, the overlying red beds of the Artés Fm. are characterized by assemblages containing *Harrisichara tuberculata*, *Nodosochara jorbae* and *Lychnothamnus longus* from the Late Priabonian. These results are largely consistent with recent magnetostratigraphic studies performed south of the studied area, and have enabled us to refine the stratigraphy of the marine-continental transition in the north-eastern Ebro Basin.

KEYWORDS | Charophyta. Biostratigraphy. Ebro Basin. Eocene. Oligocene.

INTRODUCTION

The continentalization of the Ebro Basin has been a matter of debate in recent years. This event has been described as occurring over a relatively short time, affecting the entire basin at the beginning of the Priabonian (Costa et al., 2010). In the north-easternmost part of the basin (Lluçanès area) the

boundary has traditionally been located at the top of the deltaic sandstone with reefal limestones of the Sant Martí Xic Formation (Fm.) (Reguant, 1967). However, new geological mapping, along with stratigraphic and biostratigraphic analyses of an overlying and previously poorly known transitional unit, called here the Sant Boi Fm., led us to revisit previous assumptions on the continentalization of this part of the Ebro Basin.

Not only is the lithostratigraphy of the study area confusing, but the dating of the last marine deposits of the eastern Ebro Basin has also been controversial. Magnetostratigraphy studies by Burbank et al. (1992) and Taberner et al. (1999) assigned the uppermost marine and transitional rocks to Upper Bartonian and Lower Priabonian (chron C17n). Biostratigraphic studies based on foraminifera (Serra-Kiel et al., 2003) also assigned the uppermost marine and transitional rocks to the Upper Bartonian-Lower Priabonian (Shallow Benthic Zones 18 and SBZ 19?). However, recent studies on calcareous nannofossils have revealed that only Priabonian marine rocks occur in this upper part of the stratigraphic record (Zones NP18 and NP19-20) which were correlated with chron C16/16n.2n (Casella and Dinarès-Turell, 2009). Biostratigraphic studies of continental fossils, mainly charophytes and vertebrate remains, from the central part of the eastern Ebro Basin (Igalada-Jorba area) have attributed the youngest marine units to the Upper Eocene (Anadón et al., 1987, 1992; Choi, 1989; Feist et al., 1994). Furthermore, palaeomagnetic dating has recently been performed in this area, attributing the youngest marine rocks to chron C16 (Costa et al., 2010). In contrast, biostratigraphic markers from the marine-continental transition in the northeastern part of the basin have been poorly studied up to now. In the Lluçanès area fossil charophytes have only been reported by Colom et al. (1970), who found the species *Harrisichara lineata* in the Sant Boi Fm.

Resampling the Lluçanès area has enabled us to document a rich charophyte flora of biostratigraphic interest, which sheds new light on the dating of the continentalization of the Ebro Basin in this area. The new biostratigraphic data are significant in comparison to other margins of the Ebro Basin, where an equivalent stratigraphic situation occurs i.e. in the Riu Boix Fm., south of Igualada (Ramírez et al., 1991) and the Campodarbe Fm., Huesca province (Canudo et al., 1988). The whole of these data will allow us to test the hypothesis of a rapid continentalization of the Ebro Basin in the Priabonian from a biostratigraphic point of view, as drawn from magnetostratigraphic data.

GEOLOGICAL SETTING

The Ebro Basin is the triangular-shaped southern foreland basin of the Pyrenean Range (Fig. 1). The origin of the Ebro Basin is related to flexural subsidence due to the collision between the Eurasian and Iberian plates from the Late Cretaceous to the Miocene. Maximum compression occurred during the Palaeocene and Eocene and resulted in the superposition of a number of thrust sheets in the south Pyrenean central zone. The main structures display an E-W orientation and the deformation progressed south- and westwards in parallel with the basin depositional centres,

the lowermost sedimentary sequences being incorporated into the successive thrust sheets (Puigdefàbregas et al., 1992).

The south Pyrenean foreland basin infill includes marine and continental rocks that range from the Upper Cretaceous to the Upper Eocene. Later, exclusively non-marine facies were recorded. During most of the Palaeogene the basin formed an Atlantic gulf. This situation lasted until the Late Eocene, when uplift in the western Pyrenees led to the final isolation from the Atlantic Ocean and the definitive onset of endorheic sedimentation in the Ebro Basin (Puigdefàbregas et al., 1992).

The study area is located in the north-eastern part of the Ebro Basin (Fig. 1). The Palaeogene sedimentary succession in this part of the basin is divided into nine depositional sequences related to the emplacement of the south Pyrenean thrust sheets and linked to two major relative sea level rises, in the Ilerdian (Early Eocene) and Bartonian (Middle-Late Eocene) (Puigdefàbregas et al., 1986). According to these authors, thrust cyclicity and evaporite events allow differentiation of the basin-fill into three main depositional cycles. The first cycle includes the Cadí, Corones, Armàncies and Campdevàdol sedimentary sequences and coincides with the submarine emplacement of the upper thrust sheets. The second sedimentary cycle includes the Bellmunt and Milany sequences (Lutetian and Bartonian) and coincides with the development of an antiformal stack of thrust sheets in the central Pyrenees. This structure induced deltaic progradation

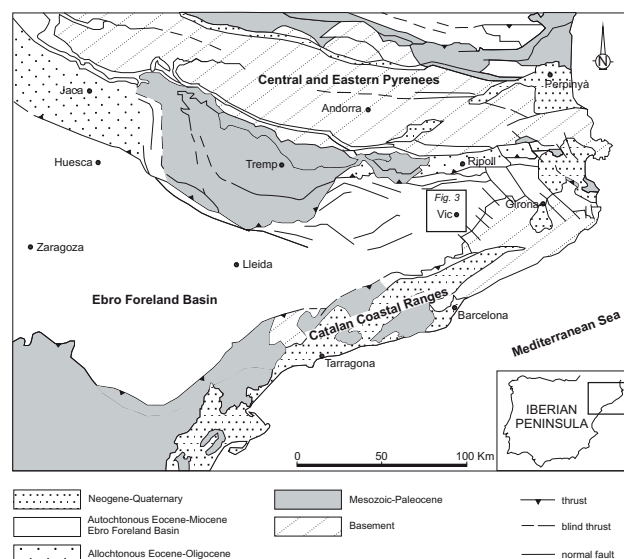


FIGURE 1 | Geological sketch of the eastern part of the Ebro Foreland Basin showing the location of the area studied (modified from Vergés et al., 1998).

and contemporaneous migration of the basin depocentre southwards. At the same time, the Catalan Coastal Chain was tectonically active and contributed to basin infill with well-developed fan delta progradation systems (e.g. Montserrat and Sant Llorenç del Munt fan deltas). This tectonic activity led to the final restriction of the basin and the deposition of the second evaporite plug during the Late Eocene. This evaporitic event (Cardona sequence) is the last marine episode in the southern Pyrenean foreland basin, which became purely endorheic afterwards.

The third cycle includes the Solsona and younger Ebro Basin sequences. It coincides with the southward thrusting and final emergence of the Vallfogona thrust, which carried the former piggyback thrust sheets. These thrust sheets supplied clastic sediments to the alluvial fans that were laterally connected with lacustrine areas in the centre of the basin (Puigdefàbregas et al., 1986).

The closure of the Ebro Basin to marine influence is a significant event of the basin evolution. In the north-eastern part of the basin, where the influence of both the Pyrenees and the Catalan Coastal Chain became superposed, facies related to the definitive onset of the endorheic sedimentation are relatively different to other parts of the basin. In this area, the last fully marine deposits belong to the deltaic sandstones of the Sant Martí Xic Fm., which is composed of low order sequences related to deltaic progradation (Barnolas et al., 1988; Barnolas, 1992). This formation grades basinwards to the prodelta marls of the Vic Fm. (Reguant, 1967) which is equivalent, towards the south, to the Igualada Fm. (Ferrer, 1971). These deposits mark the top of the Milany sedimentary sequence (Fig. 2).

The rocks overlying the Sant Martí Xic Fm. include mainly transitional deposits of diverse sedimentological features, which are bounded by regional unconformities and have been grouped in the so-called Terminal Complex (Fig. 2). This unit, defined by Travé (1992) and Travé et al. (1996), is made up of sandstones of the La Noguera Fm. (Reguant, 1967), anoxic marls, limestones including freshwater stromatoliths, and gypsum, representing the progressive infilling of the basin and its final shift to non-marine conditions. Three carbonate units have been recognized and represent three successive shallowing-upward carbonate platforms interlayered with prograding siliciclastic sediments. Moreover, a characteristic freshwater stromatolithic limestone is abundant in some levels along the entire margin of the basin (Travé et al., 1996). In the south-eastern part of the basin, the Terminal Complex passes laterally and is overlain by the Òdena Gypsum Fm. This formation may represent the marginal equivalent of the central basin halite and sylvinite deposits of the Cardona Fm. The stratigraphic position of these units, intercalated between the marine Milany and the continental

Solsona depositional sequences, suggests that the Terminal Complex and the aforementioned evaporites belong to an intermediate sequence which has been controversially considered Late Bartonian or Early Priabonian in age. Recent studies on calcareous nannofossils have revealed the presence of the Lower Priabonian in marine rocks of this part of the basin and these have been assigned to C16/C16n.2n chron (Casella and Dinarès-Turell, 2009).

Overlying this marine-continental transition, the infill of the Eastern Ebro Basin consists of 1000m thick alluvial and lacustrine deposits. Continental deposits are composed of thick upper Eocene-Oligocene sequences dominated by different lacustrine systems, which developed in the inner basinal zones and were fed by marginal alluvial fan systems. Five lacustrine systems consisting of mudstones and carbonates, evaporite and minor coals, have been recognized in the Upper Eocene to Upper Oligocene sequences of the Eastern Ebro Basin (Anadón et al., 1989). In the studied area, the Artés Fm. defined by Ferrer (1971) is widely represented. This sedimentary unit is generally built up by red beds with alternating siltstone and coarse sandstone bodies, showing typical palaeochannel features. Intercalated in the Artés Fm. there are thin lacustrine grey limestone and marl deposits with abundant charophytes, ostracodes and small limnic gastropods. The sedimentary and stratigraphic features of the Artés Fm. are related to mid to distal alluvial fan systems.

Chronological constraints of the continental sedimentary units overlying the Cardona Fm., i.e. red beds of the Artés Fm. in the Solsona Depositional Sequence, are provided by charophyte and mammal biostratigraphic data and magnetostratigraphy. The oldest known vertebrate fossil assemblage in the easternmost basin area comes from the locality of Sant Cugat de Gavadons, which indicates a Late Eocene age for the basal part of the Artés Fm., according to Anadón et al. (1987). Fossil charophyte flora and vertebrate fauna from the neighbouring locality of Santpedor and the more distant locality of Rocafort de

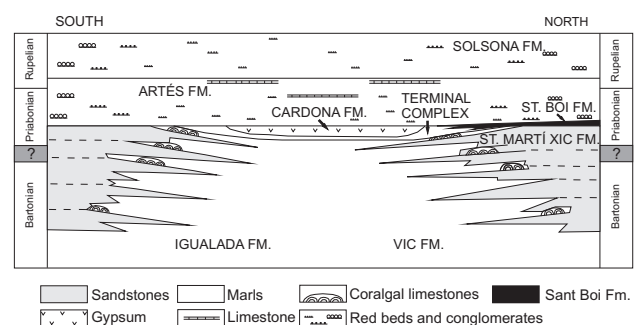


FIGURE 2 | Stratigraphic framework of the Eocene in the South Pyrenean foreland basin near Vic (modified from Serra-Kiel and Travé, 1995).

Queralt also indicate a Late Eocene age (Anadón et al., 1987, 1992; Choi, 1989; Feist et al., 1994). However, Early Oligocene vertebrate fossils have been found in Santpedor as well (Arbiol and Sáez, 1988). Also charophyte flora and preliminary magnetostratigraphic data from the Jorba-La Panadella section indicate an early Late Eocene to Oligocene age (Choi, 1989; Anadón et al., 1992; Feist et al., 1994; Barberà et al., 2001). New magnetostratigraphic data show that the transition from marine to continental sedimentation was a rapid event occurring in the Late Priabonian (Costa et al., 2010). Continentalization of the basin was related to the seaway closure that resulted from the uplift of the western Pyrenees and was coincident with a mid-amplitude eustatic sea-level low with a maximum at 36.2Ma, correlated with chron C16n (Costa et al., 2010).

MATERIAL AND METHODS

Grey mudstones and marls of Palaeogene transitional and lacustrine deposits of six stratigraphic sections were sampled systematically near the villages of Sant Boi de Lluçanès, Sobremunt, Sant Bartomeu del Grau, Oristà and Santa Maria d'Oló (Fig. 3). All sections are located in the Lluçanès area, near Vic, about 60km northeast of Barcelona (Catalonia, Spain). The two sections sampled in Sant Boi de Lluçanès were El Perers and Serrat Rodó. The first section crops out along the BV-4608 road (base coordinates 42°03'14.7"N and 02°10'E, top coordinates 42°03'26.9"N, 02°10'12"E). The Serrat Rodó section is located 500m SE of the previous locality (base coordinates 42°02'49.7"N, 02°10'18.4"E, top coordinates 42°02'47.3"N, 02°10'26.1"E). These sections cut the marine sandstones from the Sant Martí Xic Fm., the intermediate transitional deposits which are the subject of this study, and the overlying non-marine materials from the Artés Fm. The Sobremunt road section (base coordinates 42°02'18.62"N and 2°10'21.76"E, top coordinates 42°02'16.41"N and 2°10'19.33"E) is located close to km 1 of the BV-4607 road, 2km SE of the El Perers section and cuts about 10m of marine and transitional deposits. Cal Carreter section, (base coordinates 41°56'55.04"N and 2°09'34.15"E, top coordinates 41°57'01.40"N and 2°09'09.57"E) is located between km 8 and km 9 from the C-154 road, close to Sant Bartomeu del Grau village and cuts the Terminal Complex and the overlying transitional and continental deposits. The Santa Maria d'Oló and Oristà sections are stratigraphically located at the top of the continental Artés Fm. The first section follows the BV-4315 road at the entrance to the village of Santa Maria d'Oló (base coordinates 41°52'42.3"N and 02°02'3.3"E, top coordinates 41°52'35.6"N and 02°02'5.1"E) and shows a largely siliciclastic succession passing upwards to lacustrine limestones. The Oristà section is located near the B-433 road, close to the Can Julià farm (base coordinates

41°56'2.3"N and 02°03'56"E, top coordinates 41°56'7.4"N and 02°04'1.4"). This section is dominated by fluvial red beds with subordinated lacustrine marls containing abundant charophyte gyrogonites and ostracods.

Rock samples were disaggregated in water, oxygen peroxide and Na₂CO₃ solution and later sieved with sieves with mesh apertures of 1.0, 0.5 and 0.2mm. Gyrogonites were picked out under a light microscope and measured at 40x magnification. One hundred gyrogonites were selected and measured for each species. Selected gyrogonites were studied and photographed with a scanning electronic microscope Quanta 200 at the Serveis Científico-Tècnics (Universitat de Barcelona). The material is housed at the Departament d'Estratigrafia, Paleontologia i Geociències marines, Universitat de Barcelona.

RESULTS

Abundant and diverse fossil charophyte floras were found in transitional and non-marine deposits in the Lluçanès area. With the aim of characterizing these deposits, which are covering the last fully marine unit

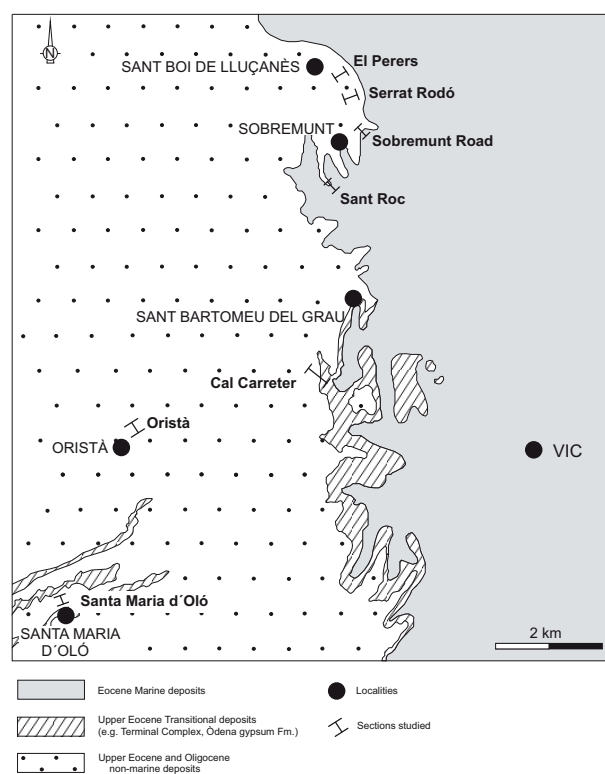


FIGURE 3 | Geological sketch of the northeastern margin of the Ebro Basin showing the location of the studied sections (after Institut Cartogràfic de Catalunya, 2006).

in the north-eastern Ebro Basin, a lithostratigraphic and biostratigraphic study was carried out.

Lithostratigraphy

Sant Boi Formation

Under the name Sant Boi Sandstone, Lignite and Marl Formation we propose a new unit cropping out along 15km on the north-eastern margin of the Ebro Basin, in the Lluçanès area, to the west of the town of Vic. Until now, this unit has been considered to represent the lowest part of the Artés Fm. in this area (Ramírez del Pozo et al., 1975; Barnolas et al., 1983; Barnolas et al., 1994; Mató et al., 1994) but lithological and biostratigraphic differences have allowed us to characterize it as a new formation. The change of facies has already been reported by Farrés and Staid-Saadt (1964), who described a number of brackish gastropods and inferred brackish conditions for these facies.

The Sant Boi Fm. is generally composed of an alternation of up to 15m of grey to yellowish fine rippled sandstone with yellow to brown lutite to the base, passing upwards to a characteristic interval of up to 5m of grey to yellowish marls, frequently with thin lignite horizons. The base of the unit is defined by a change in facies from the thick, coarse and massive marine sandstones of the Sant Martí Xic Fm. The upper boundary is sharply defined by a sudden change to red arkosic sandstone bodies alternated with red lutite of the Artés Fm. This boundary is proposed here as the base of the continental Artés Fm. (Fig. 4).

The stratotype proposed for the new formation is the so-called Serrat Rodó section, which represents the most complete and well exposed section of the Sant Boi Fm. A supplementary section called El Perers is proposed as another reference section (Figs. 4, 5) in order to characterize the facies variation better. Both sections are located east of the village of Sant Boi de Lluçanès. The Sant Boi Fm. displays marked lateral change in thickness and facies. Sections located to the north, near the type locality (Sant Boi de Lluçanès), cut up to 15m of transitional and lacustrine facies, whilst southwards, from Sobremunt to Sant Bartomeu del Grau, the new formation is only a few meters thick and shows reduced freshwater influence.

In the type locality, the Sant Boi Fm. overlies coarse metric sandstone bodies intercalated with thin lutite horizons of the marine Sant Martí Xic Fm. Decimetric yellow, plastic clays drape some of these sandstone bodies and contain abundant miliolid foraminifera and rare charophytes. The base is composed of 1-2m thick lenticular bodies of fine grained sandstone with ripple marks and heavily bioturbated tops passing laterally to

yellow or brown lutite. This succession is attributed to the infilling of low sinuosity channels and their corresponding floodplain deposits. Five meter thick grey marl overlies the previous interval (Fig. 5). At the base it is intercalated with two thin layers of lignite, showing rootlet marks, and banks of oysters. This marl is rich in euryhaline gastropods (e.g. Potamidae) and represents deposition in a brackish marsh. The upper part of the marly interval is rich in charophytes

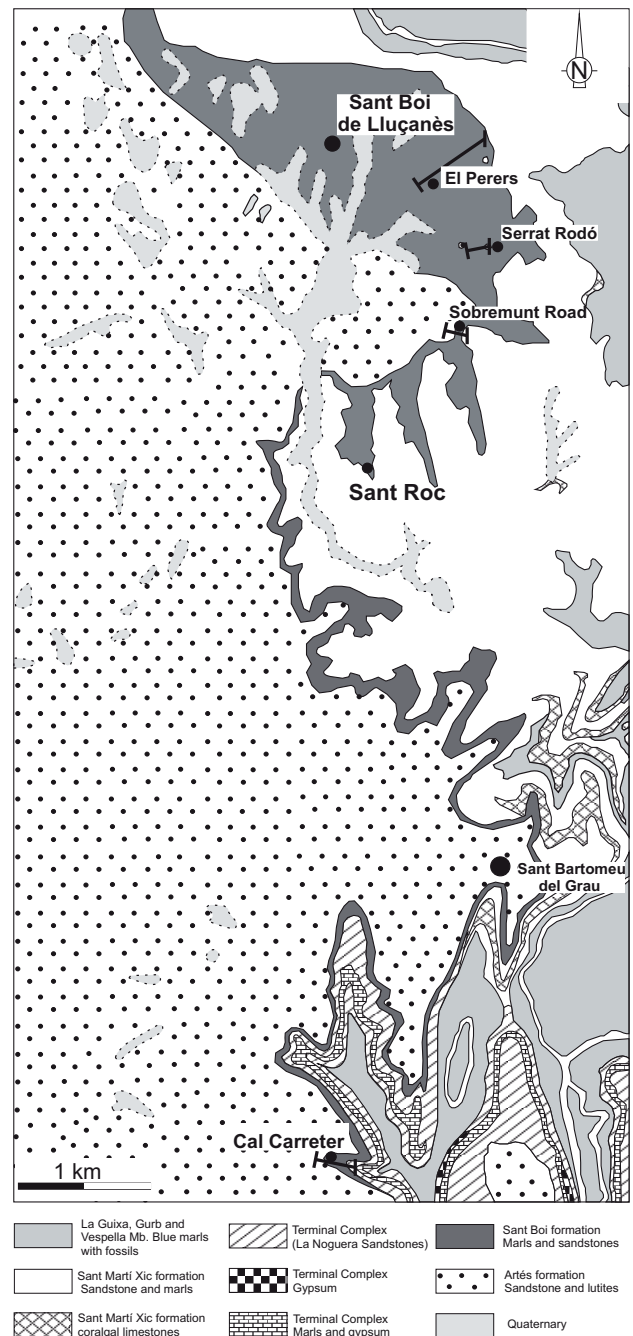


FIGURE 4 | Geological map of the Sant Boi Formation. Studied sections are El Perers, Serrat Rodó, Sobremunt road, and Cal Carreter.

and non-ornamented ostracods, and devoid of brackish fauna which suggest freshwater lacustrine facies.

About 2km southeast of the type locality, near Sobremunt, the Sant Boi Fm. shows a sudden reduction in thickness (Figs. 4, 5). In this locality, the top of the Sant Martí Xic Fm. shows blue marls with abundant marine fossils, such as corals (*Stylophora contorta*, *Stylophora herzegowiensis*, *Goniopora elegans*, *Siderastrea moreti* and *Placosmiliopsis bilobatus*, Álvarez, 2009), marine gastropods (*Velates* sp.), oysters and bioturbations. The overlying Sant Boi Fm. is formed by 6m of yellowish marls with oyster banks (*Saccostrea* sp.) passing upwards to marls with abundant charophytes and topped by a

centimetric lignite horizon. This shallowing-upward succession indicates a progressive shift from marine to brackish conditions.

About 9km southwards, near Sant Bartomeu del Grau (Figs. 4, 5), the Sant Boi Fm. is represented at the Cal Carreter section by a 5m thick succession of thin fining-upward, cross-bedded sandstone bodies with bioturbated tops overlain by 3m thick grey marls containing abundant charophytes. Arkosic red sandstones alternated with red mudstones and thin gypsum veins from the Artés Fm. sharply cover the grey siltstones and marls of the Sant Boi Fm. In this locality, the Sant Boi Fm. covers the marine sandstones of the La Noguera Fm. and underlying anoxic

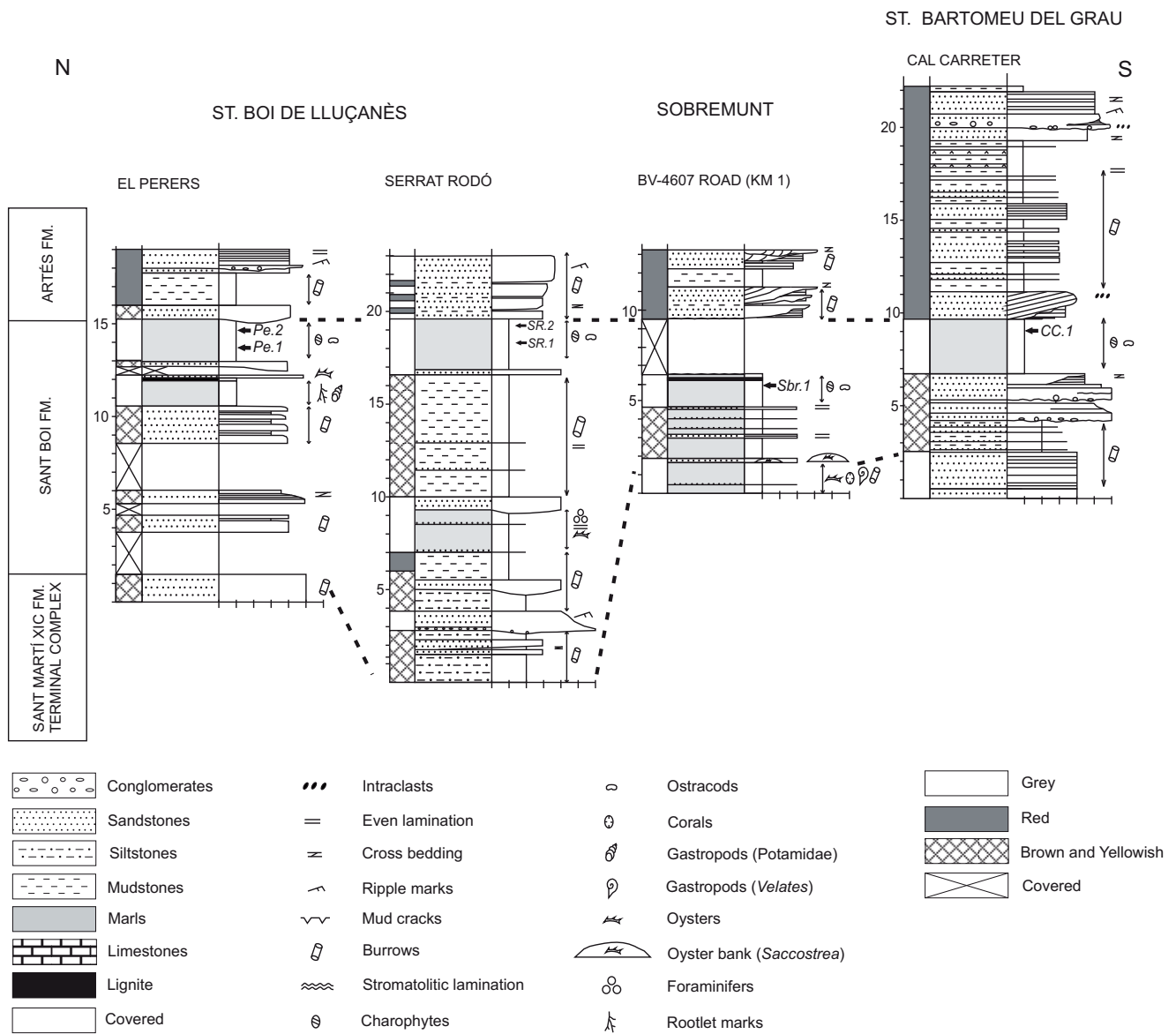


FIGURE 5 | Stratigraphic logs of the Sant Boi Formation.

marls. Both lithologies represent the last marine facies from the Terminal Complex showing an overall upward shallowing. The absence of sedimentary interruption between the marine facies of the Terminal Complex and the transitional Sant Boi Fm. suggests continuous deposition. Therefore, the Sant Boi Fm. is considered to represent a vertical and lateral equivalent of the marine part of the Terminal Complex.

Artés Formation

Facies and age of the Artés Fm. were characterized in two sections, Oristà and Santa Maria d'Oló, representing relatively different facies of the same unit (Figs. 3, 6), the former corresponding to the more proximal facies. The Oristà section is dominated by red beds. The base is composed of red laminated siltstone and clays alternating with minor lacustrine marlstone with abundant charophytes and ostracodes. Overlying materials include thin lenticular layers of lacustrine limestones with stromatolithic lamination. These facies are related to floodplain deposits including temporary lakes. At the top of the section, coarse to medium grained sandstone bodies with erosive base, cross-bedding and large-scale lenticular morphology are related to low energy palaeochannel sequences.

The Santa Maria d'Oló section corresponds to the distal facies of the Artés Fm. (Fig. 6). Thick marls with ferruginous hardgrounds are located at the base of the section. Overlying materials include fine alternating layers of marl, siltstone and sandstone. Lacustrine limestone levels characterize the top of section. Both the lithology

and the abundance of charophytes and ostracod remains indicate freshwater lacustrine conditions in a distal alluvial fan context. These lacustrine deposits would mostly correspond to temporary lakes; however, the limestone at the top of the section indicates more perennial lacustrine conditions.

Systematic Palaeobotany (charophytes of biostratigraphic interest)

Division: Charophyta MIGULA, 1897

Class: Charophyceae SMITH, 1938

Order: Charales LINDLEY, 1836

Family: Characeae RICHARD ex C. AGARDH, 1824

Subfamily: Charoideae AL. BRAUN in MIGULA, 1897

GENUS *Harrisichara* GRAMBAST, 1957

Harrisichara lineata GRAMBAST, 1957

Fig. 7A-7C

Material. About one hundred gyrogonites per kg of sediment from samples Pe-1 and Pe-2 from El Perers section and tens of gyrogonites from St.Roc-1 sample from the Sant Roc outcrop.

Description. Gyrogonite large in size, 960µm (mean 753µm) high and 520-853µm (mean 659µm) with an isopolarity index of 83-133 (average 115), ellipsoidal or oval in shape. Apical area flat to rounded and frequently ornamented with comma-shaped tubercles. Spiral cells are not modified at the apex. Eight to eleven (frequently 9) convolutions are visible laterally. The base is elongated in a small column. The ornamentation is formed by a regular mid-cellular crest along the central line of spiral cells.

Harrisichara vasiformis-tuberculata FEIST-CASTEL, 1977

Fig. 7D-7F

Material. About hundreds of gyrogonites per kg of sediment from sample Sbr-1 from the Sobremunt road section, 50 gyrogonites from samples SR-1 and SR-2 from the Serrat Rodó section and 300 specimens from sample CC-1 from the Cal Carreter section.

Description. Gyrogonites medium to large in size, 594-756µm (mean 655µm) high and 567-675µm (mean 619µm) wide with an isopolarity index of 96-116 (average 106) ovoidal or sub-ovoidal in shape with a flat or rounded apex, without any periapical modification of the spiral cells. The apex is frequently ornamented with tubercles. Nine to eleven (frequently ten) convolutions are visible laterally. The base is rounded or conical and in some cases

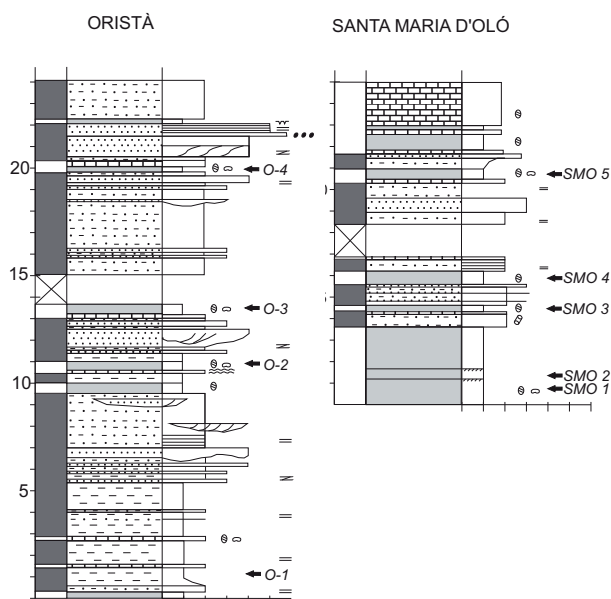


FIGURE 6 | Stratigraphic logs of the Artés Formation. Legend as in Figure 5.

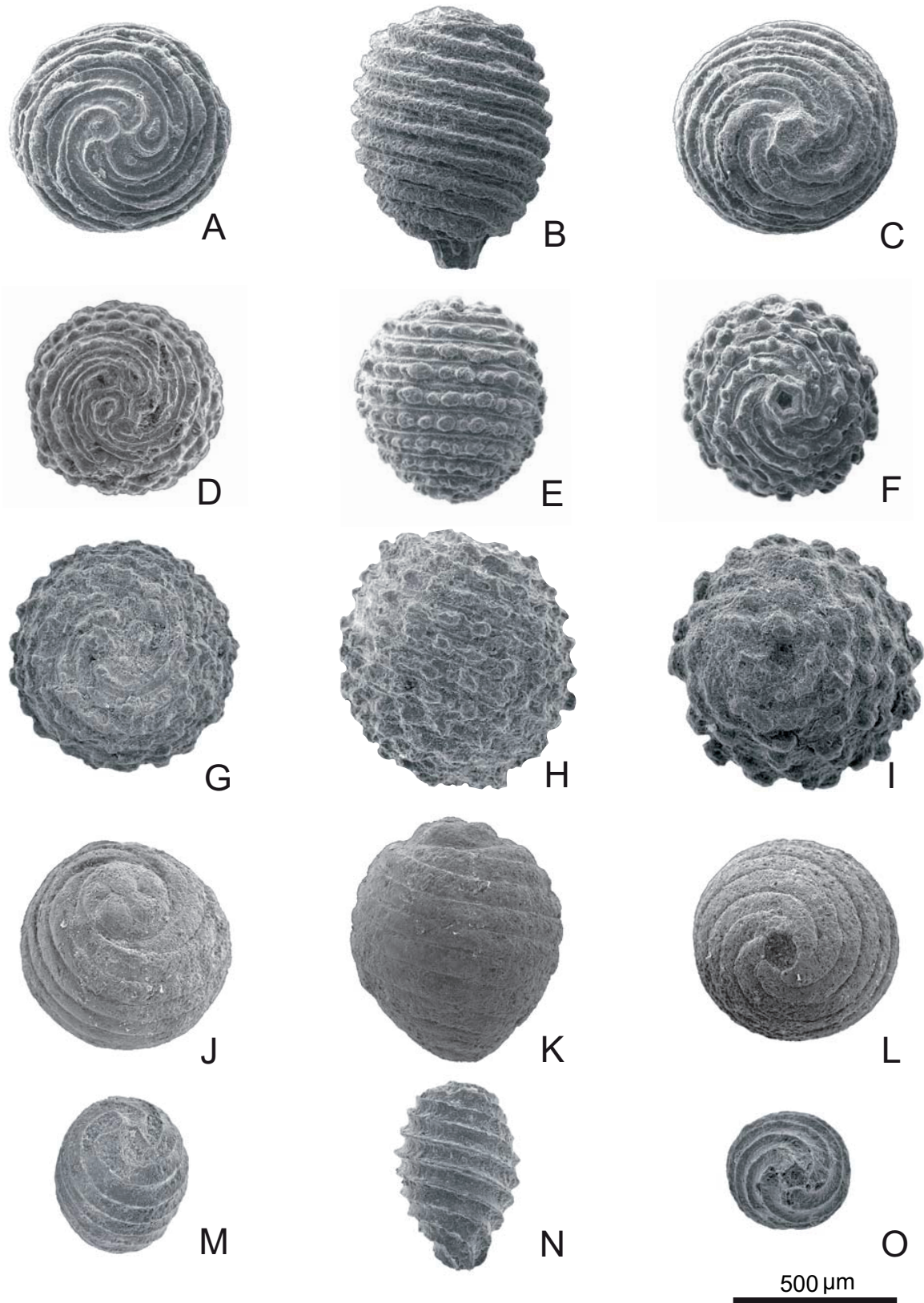


FIGURE 7 | Gyrogonites of biostratigraphic interest from the Upper Eocene of the Northeastern Ebro Basin. A to C *Harrisichara lineata*, El Perers section; A) apex, B) lateral view, C) base. D to F *Harrisichara vasiformis-tuberculata*, Sobremunt and Serrat Rodó sections; D) apex, E) lateral view, F) base. G to I *Harrisichara tuberculata*, Oristà and Santa Maria d'Oló sections; G) apex, H) lateral view, I) base. J to L *Nodosochara jorbae*, Sobremunt road, Serrat Rodó, Oristà and Santa Maria d'Oló section; J) apex, H) lateral view, L) base. M to O *Lychnothamnus longus*, Oristà and Santa Maria d'Oló section; M) apex, N) lateral view, O) base.

elongated in a small column. The ornamentation is formed by a succession of regularly spaced tubercules, which are arranged along the central line of the spiral cells and may form an irregular crest.

Harrisichara vasiformis-tuberculata represents an informal taxon created to show the transition between *H. vasiformis* (Reid and Groves, 1921) Grambast, 1957 and *H. tuberculata* (Lyell, 1826) Grambast, 1957. This gradual change was modeled with the Eigenshape method by Sille et al. (2004).

Harrisichara tuberculata (LYELL, 1826) GRAMBAST, 1957

Fig. 7G-7I

Material. A few gyrogonites of *Harrisichara tuberculata* were found in samples O-4 from Oristà section and in SMO-1 and SMO-2 in Santa Maria d'Oló section.

Description. Gyrogonites large in size, high and wide average 862 and 800µm an isopolarity index average 105, spherical in shape, with a flat or slightly convex and ornamented apex. The base is rounded or slightly pointed. Ten to eleven convolutions are visible laterally. The ornamentation is typically formed by large regularly spaced tubercules.

GENUS *Nodosochara* MÄDLER, 1955

Nodosochara jorbae CHOI, 1989

Fig. 7J-7L

Material. Hundreds of gyrogonites per kg of sediment from samples Sbr-1 in Sobremunt road and SR-2 in Serrat Rodó sections and in sample O-1, O-3, O-4 from Oristà and SMO-2, SMO-3 from the Santa Maria d'Oló section.

Description. Gyrogonite large, 660-912µm high (mean 758µm) and 540-860µm wide (mean 680µm) with an isopolarity index 90-140 (mean 112), normally pear-shaped but sometimes sub-spherical or ellipsoidal in shape with convex spiral cells, devoid of ornamentation. A characteristic nitellopsidoid apex, i.e. shortening and narrowing of the spiral cells in the periapical zone, along with a small pentagonal basal pore identifies this genus. Periapical depression is well-marked and apical nodules occur in many specimens. Seven to ten convolutions (often 9) are visible in lateral view. The base is rounded or conical.

GENUS *Lychnothamnus* (RUPRECHT, 1845) LEONHARDI, 1863 emend. A. BRAUN in BRAUN et al. 1882

Lychnothamnus longus CHOI, 1989

Fig. 7M-7O

Material. *Lychnothamnus longus* is represented by hundreds of gyrogonites per kg sieved in samples O-3 and O-4 from Oristà section. In contrast, it is represented by dozens of gyrogonites per kg in samples from the Santa Maria d'Oló section.

Description. Gyrogonites are medium in size, 450-724µm (mean 618µm) high and 380-580µm (mean 464µm) with an isopolarity index of 104-180 (average 130), ellipsoidal to ovoidal in shape. The apex is psilocharoid, rounded to truncate, in some cases pointed in the centre. It displays a remarkable apical thinning. The base shows a variable morphology, in some cases elongated to form a broad column, and the basal pore shows a small star-shaped funnel. The spiral cells, flat to concave, are devoid of ornamentation and separated by prominent sutures which are bicarinate in some specimens. Seven to ten (frequently 8) convolutions are visible laterally.

Biostratigraphy

This biostratigraphic study focused on the dating of the new Sant Boi Fm. and its chronostratigraphic distinction from the overlying Artés Fm. Taxonomic composition of the samples and relative abundance of gyrogonites is represented in Table 1.

Sant Boi Formation

The charophyte assemblage from the new formation at the El Perers section and at Sant Roc outcrop is composed of *Harrisichara lineata* and *Chara* sp. According to Riveline (1986), *H. lineata* is widely distributed in the Middle Bartonian to Middle Priabonian of Europe. It has been reported in the biozones *Chara friteli*, *Raskyella vadaszi*, *Psilochara repanda*, *Gyrogona tuberosa*, *Harrisichara vasiformis-tuberculata* and the basal part of biozone *Stephanochara vectensis* of Riveline et al. (1996) and Riveline in Hardenbol et al. (1998). *H. lineata* is also present in Biozones 1 (undefined) and 2 (*Sphaerochara labellata*) of the Ebro Basin biozonation proposed by Feist et al. (1994).

In Sobremunt road and in Serrat Rodó sections, south of the type locality, the charophyte assemblage from the Sant Boi Fm. is composed of *Harrisichara vasiformis-tuberculata*, *Nodosochara jorbae*, *Gyrogona* sp. and *Chara* sp. The two first species are biostratigraphically significant. In the Cal Carreter section the charophyte assemblage is also represented by *H. vasiformis-tuberculata* and *Lamprothamnium* sp. According to Riveline (1986), *H. vasiformis-tuberculata* is found in the middle part of

TABLE 1 | Charophyte assemblages of non-marine Palaeogene samples from the Lluçanès area. Legend: X) rare, XX) abundant, XXX) very abundant

Lithostratigraphy		Sant Boi Fm.						Artés Fm.									
Locality		El Perers		Serrat Rodó		Sobremunt road	St. Roc	Cal Carreter	Oristà			Sta. Maria d'Oló					
Species	Samples	Pe.1	Pe.2	SR.1	SR.2	Sbr.1	St.Roc.1	CC.1	O.1	O.2	O.3	O.4	SMO.1	SMO.2	SMO.3	SMO.4	SMO.5
<i>Harrisichara lineata</i>		XXX	XX				XX										
<i>H. vasiformis-tuberculata</i>				X	XXX	XX		XXX									
<i>H. tuberculata</i>												X	X	X			
<i>Nodosochara jorbae</i>					XX	XXX			XXX		XX	XX	X	XX	XXX	X	XX
<i>Lychnothamnus longus</i>											XX	XXX		X	X	XX	X
<i>Lamprothamnium</i> sp.								X									
<i>Gyrogonia</i> sp.						X											
<i>Chara</i> sp.		XX				XX		XX	XX	X	XX	XX		X	X	X	XX

the Priabonian of Europe. Indeed, it represents the index species of the homonymous charophyte biozone, which has been correlated with biozones NP 19-20 of the marine domain (Riveline et al., 1996; Riveline, 1998). The other biostratigraphically significant species, *Nodosochara jorbae*, has only been found, up to now, in the Upper Priabonian beds of the Eastern Ebro Basin in the Igualada area. This species was included in the *Stephanochara vectensis* local biozone proposed by Choi (1989) and Feist et al. (1994). Our results indicate that the range of *N. jorbae* must be enlarged at its base to include the middle part of the Priabonian since it occurs in association with *Harrisichara vasiformis-tuberculata*, i.e. in the *Harrisichara vasiformis-tuberculata* European biozone of Riveline et al. (1996) and Riveline (1998). Summarizing, the Sant Boi Fm. is attributed to the middle part of the Priabonian (*H. vasiformis-tuberculata* biozone).

Artés Formation

Charophyte assemblages from the Artés Fm., studied in Oristà and Santa Maria d'Oló, are homogeneously formed by *Nodosochara jorbae*, *Lychnothamnus longus*, *Harrisichara tuberculata* and *Chara* sp. The association of the three first species is biostratigraphically significant. The biostratigraphic range of *Nodosochara jorbae*, discussed before, suggests that the deposition of the Artés Fm. took place from the middle part of Priabonian to the Eocene-Oligocene boundary. However, this range can be restricted by another chronostratigraphically significant species, common in the Oristà and Santa Maria d'Oló sections, *Lychnothamnus longus*. The total range of *L. longus* extends from the late Priabonian to the middle Rupelian. The first appearance of the species marks the base of the local biozone 3 (*Stephanochara vectensis*) defined by Feist et al. (1994), which corresponds to the upper part of the *Stephanochara vectensis* biozone of the European biozonation proposed by Riveline et al. (1996) and Riveline (1998). Finally, *Harrisichara tuberculata*

defines a superbiozone that extends from the middle part of the Priabonian to the middle of the Rupelian and includes the two charophyte biozones *Stephanochara vectensis* and *Stephanochara pinguis* of Riveline et al. (1996) and Riveline (1998).

In sum, the charophyte assemblages from the Artés Fm. studied in the Lluçanès area can be related to the European superbiozone *Harrisichara tuberculata* or to the local biozone 3 (*Stephanochara vectensis*) from Feist et al. (1994). The latter biozone represents the Uppermost Priabonian.

DISCUSSION

The beginning of continentalization in the northeasternmost part of the Ebro Basin has been a matter of controversy. Disagreement exists about the age of the youngest marine sedimentation and the beginning of continentalization. New magnetostratigraphic data from the youngest marine rocks located in the central part of the eastern margin of the Ebro Basin (Igualada area) indicate that continentalization of the basin began in chron 16 (Costa et al., 2010). Moreover, recent studies on calcareous nannofossils of the marine facies of the Terminal Complex and the underlying Milany sequence, document the base of the NP19-20 Zone, Lower Priabonian, in the Vic area (Casella and Dinarès-Turell, 2009).

The marine-continental boundary has been poorly studied up to now in the Lluçanès area northwest of the town of Vic, where the sedimentary succession shows an intermediate transitional unit, traditionally considered to belong to the continental Artés Fm. This study aimed to show that this unit, defined here as the Sant Boi Fm., covers the underlying marine Milany Depositional Sequence and is a lateral and vertical equivalent, to the south, of the Terminal Complex (Fig. 2). Thus, it represents the last

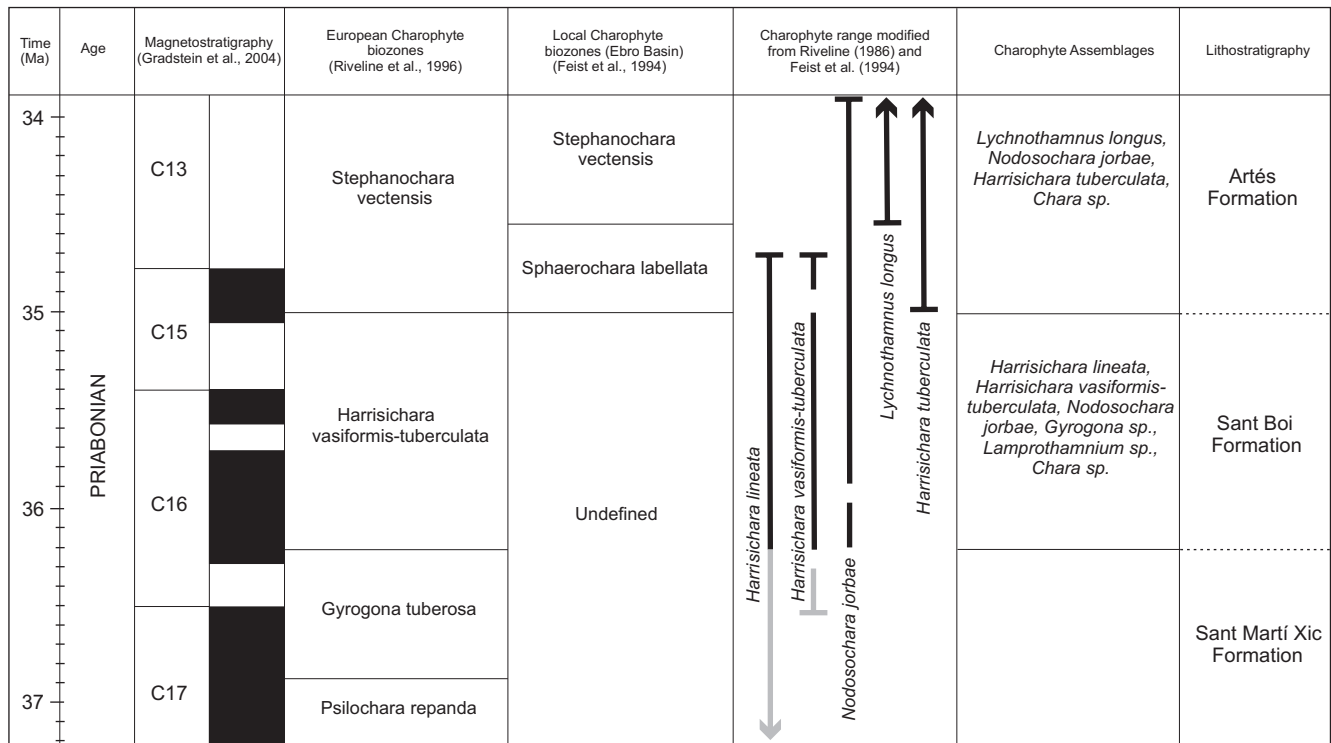


FIGURE 8 | Late Eocene magneto-bio-cronostratigraphy. Geochronological time-scale according to Gradstein et al. (2004), European charophyte biozonations are after Riveline et al. (1996) and Riveline in Hardenbol et al. (1998); local charophyte biozonation (Ebro Basin) after Feist et al. (1994).

marine-linked deposits in this northeasternmost sector of the basin rather than the first terrestrial deposits after continentalization, as previously thought.

Five different charophyte species are reported from Sant Boi Fm. The assemblage is formed by *Harrisichara lineata* Grambast, 1957, *H. vasiformis-tuberculata* Feist-Castel, 1977, *Nodosochara jorbae* Choi, 1989, *Gyrogona* sp., *Lamprothamnium* sp. and *Chara* sp. and belongs to the *Harrisichara vasiformis-tuberculata* European biozone, which represents the middle part of the Priabonian according to correlations with zone NP 19-20 in the English Basin (Riveline et al., 1996). The overlying Artés Fm. has yielded *H. tuberculata* (Lyell, 1826) Grambast, 1957, *Nodosochara jorbae* Choi, 1989, *Lychnothamnus longus* Choi 1989 and *Chara* sp. from the *Harrisichara tuberculata* superbiozone of Riveline et al. (1996) and the local biozone 3 (*Stephanochara vectensis*) from Feist et al. (1994). The latter is Late Priabonian in age (Fig. 8). These results appear to indicate that a small gap exists between the assemblages from the Sant Boi Fm. and those from the overlying Artés Fm., equivalent to the local biozone 2 (*Sphaerochara labellata* zone) from Feist et al. (1994). This gap would represent part of the Upper Priabonian. Given that the charophyte samples studied from the Artés Fm. are closer to the top of the unit than to the base, this gap could correspond to the non-sampled part of the Artés Fm.

In conclusion, the latest marine-linked deposits of the North-easternmost Ebro Basin (Lluçanès area, near Vic) are transitional and lacustrine siltstones, marls and lignites of the Sant Boi Fm., which cover and are laterally equivalent to the Terminal Complex of Travé et al. (1996). They belong to the mid-part of the Priabonian (*Harrisichara vasiformis-tuberculata* biozone) and are probably within chron C16 according to the hypothesis of Costa et al. (2010). These data, along with the biostratigraphic data gathered from other parts of the basin by Ramírez et al. (1991) and Canudo et al. (1988) support the conclusion that the continentalization of the Ebro Basin was a rapid and synchronic event throughout the basin.

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