



## Middle Eocene calcareous nannofossils in the Jaca transect (South-central Pyrenees Eocene Basin, Aragón river valley, Huesca)

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### ABSTRACT

The calcareous nanoplankton is studied from the base of the turbidite systems of the Upper Hecho Group (Jaca Basin, middle Eocene of the South-central Pyrenean Basin) up to the Gracionepel instabilities, within the Larrés slope Marls. This new chronostratigraphic contribution is of crucial importance for the improvement of the detailed temporal and spatial correlation framework of the genetically related depositional systems at basin scale.

The calcareous nanofossil assemblage is largely dominated by *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930, *C. formosus* (Kamptner, 1963) Wise, 1973 as well as different species of *Reticulofenestra* Hay *et al.*, 1966, accompanied by occasional specimens of several species of *Sphenolithus* Deflandre in Grassé, 1952 and *Chiasmolithus* Hay *et al.*, 1966. The results obtained, based on the detailed biostratigraphic study of a composite succession 2,500 m thick, allow us to characterize the main biohorizons of the middle Eocene on the basis of global biostratigraphic standards. The studied succession was deposited during the CNE11-CNE15 or NP15-

### RESUMEN

Se estudia el contenido de nanoplancton calcáreo desde la base de los sistemas turbidíticos del Grupo Hecho superior (Cuenca de Jaca, Eoceno medio de la Cuenca Surpirenaica Central) hasta las inestabilidades de Gracionepel, dentro de las margas de talud de Larrés. Esta información cronostratigráfica es de capital importancia para mejorar el marco de correlación temporal y espacial detallado de los sistemas de depósito genéticamente asociados a escala de la cuenca.

La asociación de nanofósiles calcáreos identificada se encuentra ampliamente dominada por *Coccolithus pelagicus* (Wallich, 1877) Schiller, 1930, *C. formosus* (Kamptner, 1963) Wise, 1973 así como diferentes especies de *Reticulofenestra* Hay *et al.*, 1966, acompañados de especímenes ocasionales de varias especies de *Sphenolithus* Deflandre en Grassé, 1952 y *Chiasmolithus* Hay *et al.*, 1966. Los resultados obtenidos, basados en el estudio bioestratigráfico detallado de una sucesión sintética de 2.500 m, permiten caracterizar los principales biohorizontes del Eoceno medio acorde a los estándares bioestratigráficos globales. El depósito de la

NP16 biozones, within a time span of ~3.45 Myr, between 43.96 and 40.51 Ma (Lutetian/Bartonian). This age range is compatible with the existing scheme for the South-central Pyrenean Basin.

The Upper Hecho Group, between the Roncal-Fiscal megaturbidite (MT-5) and the instability facies of Gracionepel, starts in the uppermost part of Zone NP15 continues into Zone NP16.

The proposed biozonation provides new data for a correlation between stratigraphic events of other regional sections and facilitates the understanding of the lateral and temporal evolution of the studied systems, as well as the improvement of the general palaeogeographic framework of the basin.

**Keywords:** Calcareous nannofossils, middle Eocene, biostratigraphy, Jaca transect, Pyrenees (Spain).

sucesión tuvo lugar durante las biozonas CNE11-CNE15 o NP15-NP16, con una representación estratigráfica que abarca un rango temporal de ~3,45 Myr comprendido entre los 43,96 y 40,51 Ma (Luteciense/Bartoniense). Este modelo de edad completa el existente para la Cuenca Surpirenaica Central.

La propuesta de biozonación proporciona nuevos datos para una correlación más precisa entre eventos estratigráficos de otras secciones regionales, y facilita la comprensión de la evolución lateral y temporal de los sistemas estudiados, así como la mejora del marco paleogeográfico general de la cuenca.

El Grupo Hecho superior, entre la megaturbidita de Roncal-Fiscal (MT-5) y las facies de inestabilidades de Gracionepel, se inicia en la parte terminal de la zona NP15 y se extiende dentro de la NP16.

**Palabras clave:** Nanofósiles calcáreos, Eoceno medio, bioestratigrafía, transecto de Jaca, Pirineos (España).

## 1. INTRODUCTION

The Hecho Group (defined by Mutti *et al.*, 1972) is a worldwide reference model for deep-marine clastic sedimentation. Biostratigraphically, our research places the Upper Hecho Group in the depositional systems of the Jaca Basin, outcropping along the Aragón river valley (Fig. 1). The studied transect (Fig. 2) is characterised by the replacement up-section of basin floor turbidites by the slope-fan system of the lower Larrés Marls. In the study area, the lack of accurate age dating hampers the correlation of stratigraphic units between the proximal Aínsa and the Jaca Basin systems, as physical correlation is interrupted by erosion in the hinge zone of the Boltaña anticline and internal splitting by the Oturia thrust.

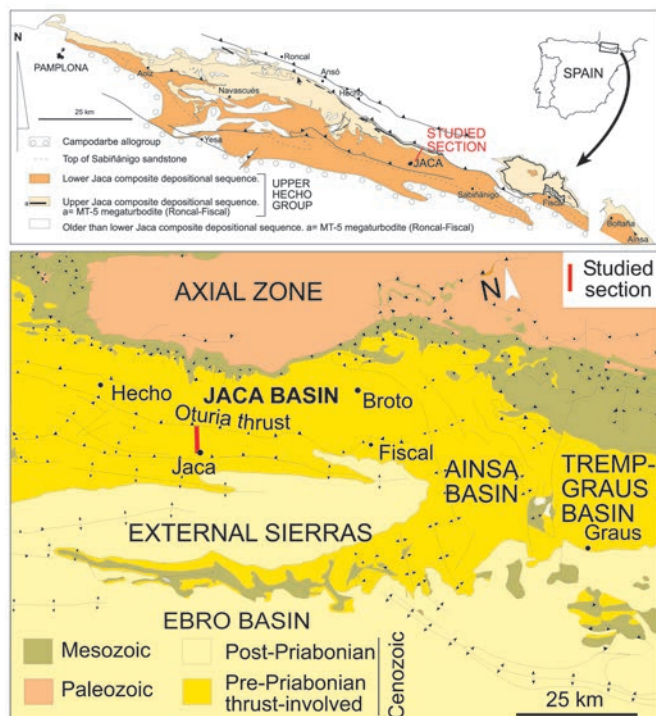
The available chronological data from the Hecho Group is rather limited, restricted to only a few general publications. The upper part of the group has been biostratigraphically studied in the Roncal Valley and partially located as late Lutetian (NP15 zone) by Labaume *et al.* (1985). Canudo & Molina (1988) locate the Upper Hecho Group and the younger deltaic succession of the eastern Jaca Basin to between late Lutetian and early Priabonian, i.e. from P.12 to the lower P.16 zones. Oms *et al.* (2003) carried-out a palaeomagnetic study in the Upper Hecho Group with samples obtained along the Aragón river valley. As a result, the Upper Hecho Group turbidite systems in the Aragón valley were deposited during the time span ranging from the upper C20r to the mid C18r (middle Lutetian to early Bartonian times; Fig. 2).

Previous regional correlations in the Jaca Basin (Labaume *et al.*, 1985; Remacha & Fernández, 2003) are challenged by Oms *et al.* (2003) and also by magnetostratigraphic and calcareous nannofossil studies

from the Aínsa Basin by Mochales *et al.* (2012) and Scotchman *et al.* (2015), respectively. Our study provides new data with the aim of resolving the controversial dating of the Jaca Basin and clarifying the general chronostratigraphic framework at basin scale.

## 2. GEOLOGICAL SETTING AND STRATIGRAPHY

The outcrop belt of the Paleogene Jaca Basin (South-central Pyrenees foreland basin system), forms an ESE-WNW elongated asymmetrical syncline developed west of the Boltaña anticline (Fig. 1). Its thicker northern limb consists of forward breaking thrust systems involving cover rocks (Mesozoic to upper Eocene), overlying a basement-involved duplex mostly comprising Paleozoic rocks (Cámara & Klimowith, 1985; Labaume *et al.*, 1985, 2016; Teixell, 1990, 1996; Cámara & Flinch, 2017) (Fig. 1). In the cover systems and overlying lower Eocene carbonates, the Hecho Group turbidites form a thick deep-marine clastic succession reaching up to 4,500 m in thickness. On the southern, passive margin of the basin, this group wedges-out by lateral onlap and horizontal facies change into the Burgui Marls Formation (Cámara & Klimowith, 1985). These marls are also the distal equivalents of the shallow-marine carbonates of the Boltaña and Guara formations (Soler-Sampere & Puigdefàbregas, 1970; Puigdefàbregas, 1975). To the east of the Boltaña anticline, the depositinally equivalent systems of the Jaca Basin are found in the Aínsa Basin. This last basin contains most of the architectural elements such as submarine canyons, turbidite channels and slope-fan systems. The general



**Figure 1.** Geological setting of the studied section. Top: location on a sketch map of the Upper Hecho Group. Bottom: location in the central part of the South-central Pyrenees.

E-W-continuum of turbidite elements in the Jaca Basin comprises channel-lobe transition, sheet-like lobes and finally basin plain. Exceptions to the general distribution of architectural elements within the Hecho Group have been found in the uppermost part of the section in the Jaca Basin (Remacha *et al.*, 1987, 1995; Remacha & Picart, 1991), culminating in the northly-derived Rapitán turbidite system, the last turbidite system in the basin.

The studied section is ca. 2,500 m thick and is located north of Jaca, along the Aragón river valley. It is summarised in graphic form in Figure 2, together with the associated bio- and chronostratigraphic framework. The following section is a simplified review of the key depositional elements comprising the study transect.

At the base of the section and the starting point of the lower Jaca turbidite system (abbreviated hereinafter as LJSt), the Roncal-Fiscal megaturbidite (Mt-5) is found, bounded to the north by the Oturia thrust. The top of the section is marked by the Gracionepel instabilities (Gracionepel facies of Puigdefàbregas, 1975), within the Larrés Marls. These marls are interpreted as a slope fan, developing above the Rapitán turbidite channel of the upper Jaca turbidite system (abbreviated hereinafter as UJSt), and are genetically related to the Sabiñánigo Sandstone delta complex sealing the Eocene deep-marine clastic sediments in the South-central Pyrenees.

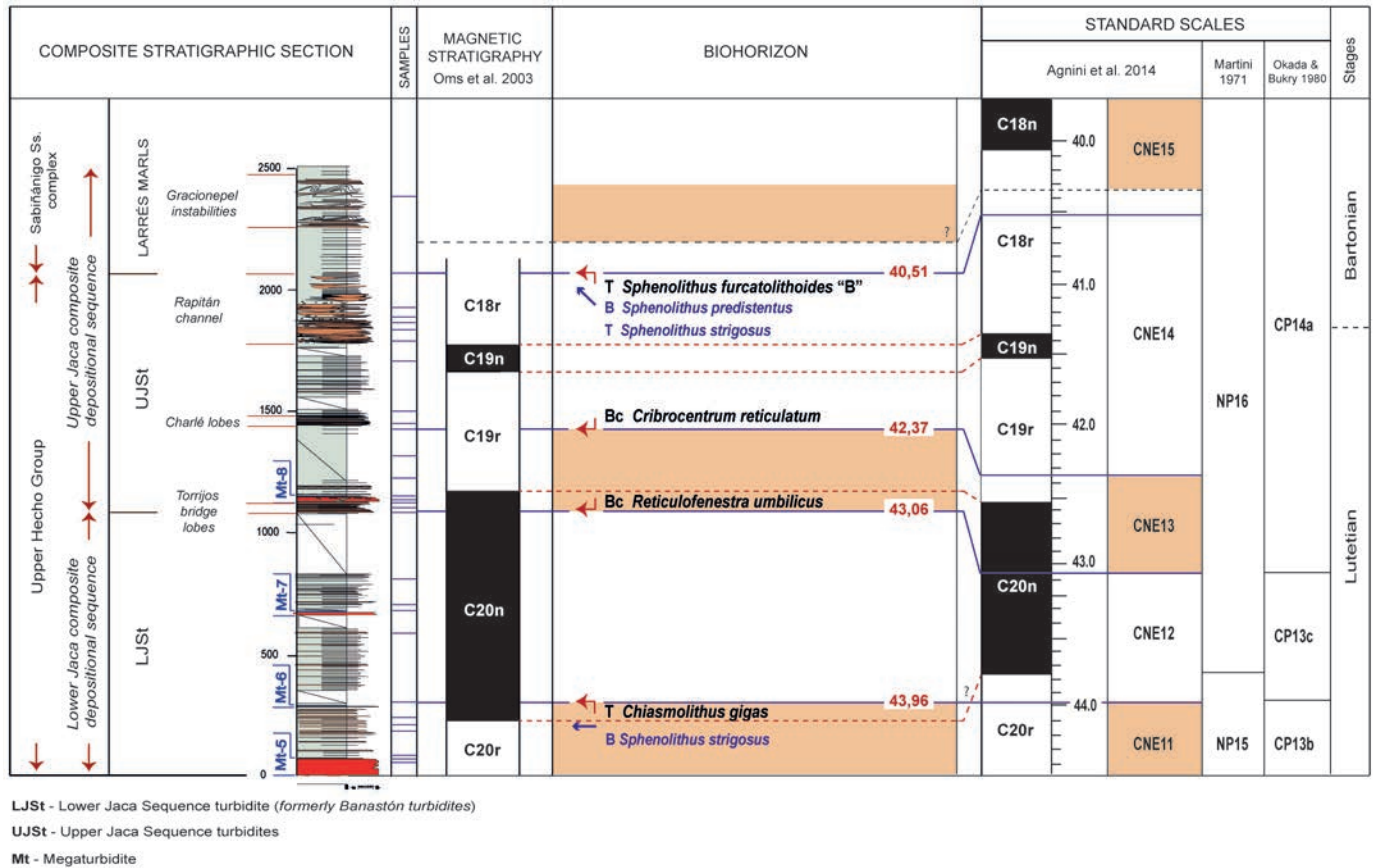
The basal ca. 1,100 m of the composite section (LJSt, see Fig. 2) contains the unit formerly known as the Banastón turbidites, represented in the Aragón valley by sheet-like lobe elements (Remacha & Fernández, 2003; Remacha *et al.*, 2005). LJSt contains three megaturbidites: Mt-5 (Roncal Fiscal), Mt-6 and Mt-7. In the Aragón section, the LJSt is sharply overlain by thick-bedded and very sand-rich facies forming the Torrijos Bridge lobes, comprising channel-lobe transition elements overlain by the Mt-8 megaturbidite.

The stratigraphic succession subsequently comprises a ca. 70 m thin-bedded package containing several distinctive, medium-scale cross-bedded sandstone beds. The following 50 m occurs in restricted outcrops, which are also thin-bedded with local sheet-like sandy intervals. The ensuing Charlé lobes are ca. 60 m thick and locally derived from the north. These lobes are relatively thick-bedded, sand-rich and sheet-like. The Charlé lobes are themselves overlain by 300 m of muddier, sheet-like lobes characterised by fewer thick beds and a net-to-gross of around 50%. The top of this unit is defined by a remarkable submarine erosional feature linked to the development of the Rapitán channel (Remacha *et al.*, 1987, 1995), the last turbidite system of the Hecho Group. In the studied section, the channel fill contains minor, thick-bedded, lenticular channel sand bodies separated by muddy debrites.

The upper part of the Rapitán channel evolves upward to the thin-bedded, lower Larrés Marls, which have a thickness of ca. 200 m. The latter are capped by the instabilities with abundant dolomite concretions of the Gracionepel facies, forming the slope and base-of-slope environments of the lower Sabiñánigo deltas (Remacha & Picart, 1991)

The Hecho Group has been placed within a framework of tectonosedimentary units (TSUs) by Remacha & Fernández (2003). These units are considered as second-order basinal divisions, each containing a number of third-order composite depositional sequences. Within the second-order framework, the upper Hecho Group comprises TSU-4 and TSU-5 (Remacha *et al.*, 1987; Remacha & Picart, 1991; Remacha & Fernández, 2003). The turbidites of TSU-4 and TSU-5 belong, respectively, to LJSt and UJSt.

A distinctive feature of the Upper Hecho Group in the Jaca Basin is the occurrence of the four, previously described, thick carbonate megaturbidites (Fig. 2). These megaturbidites, with a significant lateral extension, may be regarded as extremely useful time-line marker-beds. They provide first-order physical correlation and segregation of strictly time-equivalent stratal packages extending for significant distances within the Upper Hecho Group of the Jaca Basin (Labaume *et al.*, 1985; Remacha & Fernández, 2003; Remacha *et al.*, 2005).



**Figure 2.** Integrated magneto-biostratigraphic data from the Aragón valley section. Lithostratigraphic section to the left contains: LJSt = Lower Jaca Sequence Turbidites (formerly Banastón turbidites); UJSt = Upper Jaca Sequence Turbidites; Mt = Megaturbidites. Calcareous nannofossil sampling levels and magnetostratigraphic record by Oms *et al.* (2003). Center: biostratigraphic results, with red arrows indicating significant bioevents (Agnini *et al.*, 2014) and blue arrows indicating other biomarkers (Perch-Nielsen, 1985; Bown & Dunkey Jones, 2006; Martini, 1971; Okada & Bukry, 1980). Right: Standard biozonation and magnetostratigraphic assignment for middle Eocene according to Agnini *et al.* (2014). Correspondence with standard scales of Martini (1971) and Okada & Bukry (1980). Eocene stages.

### 3. METHODS

A total of 29 samples were prepared following the Flores & Sierro (1997) settling technique, allowing for the generation of homogeneous and comparable data. For observation, a *Nikon eclipse 80i* polarized microscope was used at 1,000x magnification. The abundance of calcareous nannofossils was analyzed by systematic counting of the total content of non-reworked nannofossils in a pre-established area of 50 fields per sample (equivalent to 1 mm<sup>2</sup>). The quantitative pattern of selected biomarker taxa is expressed in percentages calculated in relation to the total number of nannofossils in each sample (Fig. 3).

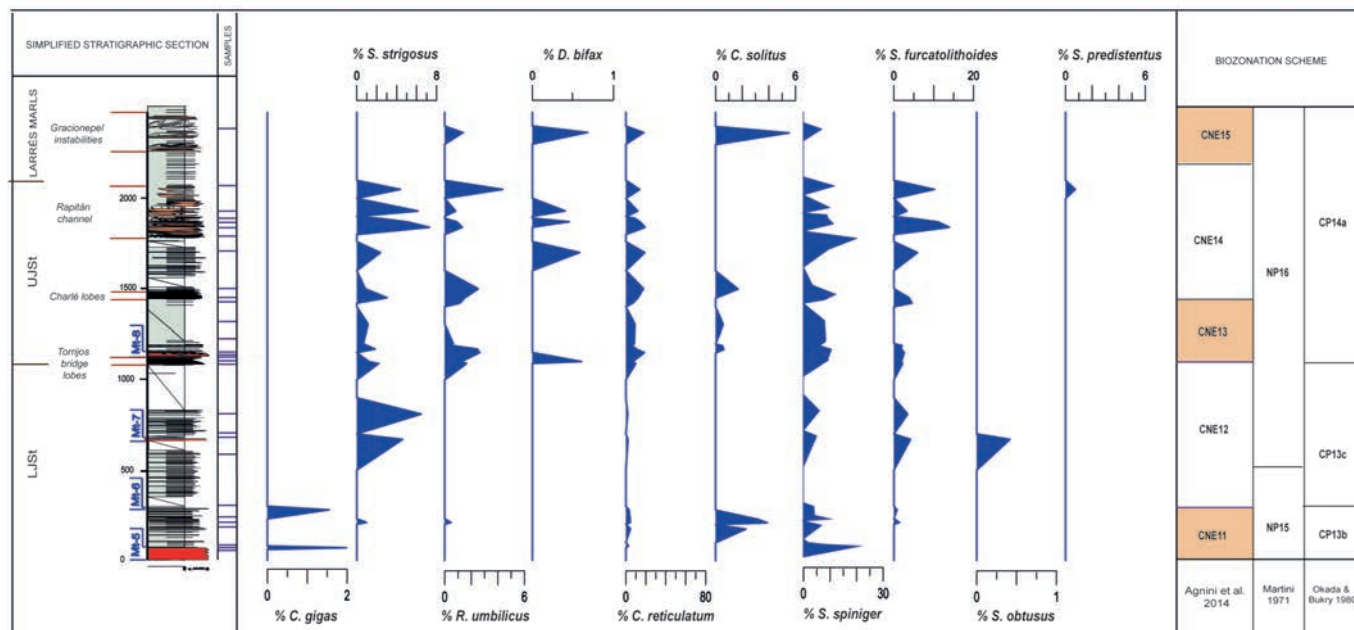
Calcareous nannofossils were identified using the taxonomic concepts of Perch-Nielsen (1985), Bown (1998), Young *et al.* (1997, 2003, 2017). A total of 74 different species have been identified (Appendixes I and II).

### 4. CALCAREOUS NANNOFOSSIL ASSEMBLAGE

The calcareous nannofossil content in the studied samples is generally rich, although we have observed variations in nannofossil concentrations between sedimentary units. Despite this, a high diversity of species is constant throughout the Jaca section.

The preservation of coccoliths was good to moderate, with occasional low dissolution and partial breaking of large specimens, such as *Discoaster* Tan, 1927 and *Reticulofenestra* spp. For *Chiasmolithus* spp. only complete specimens with the central cross were identified.

The assemblages are dominated by *Reticulofenestra* spp., *Dictyococcites* Black, 1967, *Cribrocentrum reticulatum* (Perch-Nielsen, 1985), *Coccolithus pelagicus*, and *Coccolithus formosus*. For *Reticulofenestra umbilicus* (Levin, 1965) Martini & Ritzkowski, 1968 we have only considered specimens larger than 14 μm (Backman, 1986;



**Figure 3.** Percentage of abundance of biostratigraphically significant calcareous nannofossils and its position in relation to the simplified composite stratigraphic section (see more details in Fig. 2).

Backman & Hermelin, 1986; Wei & Wise, 1989; Fornaciari *et al.*, 2010; Norris *et al.*, 2014).

*Sphenolithus moriformis* (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967, *Sphenolithus spiniger* Bukry, 1971, *Sphenolithus furcatolithoides* Locker, 1967, *Sphenolithus strigosus* Bown & Dunkley Jones, 2006, and *Sphenolithus predistentus* Bramlette & Wilcoxon, 1967 are also abundant. *Pemma* Klumpp, 1953, *Zygrhablithus bijugatus* (Deflandre in Deflandre and Fert, 1954) Deflandre, 1959, *Blackites* Hay & Towe, 1962, and *Lanternithus* Stradner, 1962 have a significant level of abundance. *Discoaster* spp. and *Chiasmolithus* spp., *Helicosphaera* Kamptner, 1954 and *Pontosphaera* Lohmann, 1902 are occasionally recorded. Cretaceous reworked nannofossils are consistently present but in low abundance.

Appendixes I and II show a summary of the identified calcareous nannofossil taxa.

## 5. BIOSTRATIGRAPHY

For this study we used the calcareous nannofossil biozonation and calibrated bioevents of Agnini *et al.* (2014), following the nomenclature of B (Base), Bc (Base common), T (Top) and Tc (Top common) for the lowest occurrence, first common record, last occurrence and highest common record in the studied section, respectively.

Some bioevents of the standard zonation of Martini (1971) and Okada & Bukry (1980) have also been identified. In addition, a few additional biomarkers

described by Perch-Nielsen (1985), Bown & Dunkley Jones (2006), and Fornaciari *et al.* (2010) have been identified, supporting the correlation between the standard schemes.

Table 1 is a summary of the identified chronographically calibrated events.

## 6. RESULTS AND DISCUSSION

Our results from the Upper Hecho Group, in the Aragón river valley are derived from the same section and outcrops studied for magnetostratigraphic purposes by Oms *et al.* (2003); i.e., in the succession formed by LJSSt, containing Mt-5, Mt-6 and Mt-7 megaturbidites, overlain by UJSt (between the Torrijos Bridge lobes to the top of the Rapitán channel system). Therefore, the magnetostratigraphic units, defined by Oms *et al.* (2003) in the Aragón valley, can be combined with the calcareous nannoplankton zones proposed here.

The presence of *Sphenolithus cuniculus* Bown, 2005 together with *Chiasmolithus gigas* (Bramlette & Sullivan, 1961) Radomski, 1968, from the lowest part of LJSSt, permits identification of zone CNE11 (*Sphenolithus cuniculus/Chiasmolithus gigas* Concurrent Range Zone), included in the Lutetian. Agnini *et al.* (2014) dated the Bc of *S. cuniculus* at 44.64 Ma. Consequently, the age of the materials studied here is younger (Fig. 2).

Zone CNE11 corresponds to the upper part of zone NP15 (Martini, 1971) and to upper part of Subzone CP13b (Okada & Bukry, 1980), also identified in the Jaca section

**Table 1.** List of calcareous nannofossil events: height (m), event, species, age (Ma) and magnetic chron. B = base; Bc = base common; T = Top; Tc = Top common. Additional information (reference work and time scale reference) is also provided.

High (m)	Event	Species	Ref.	Age (Ma)	Chron
2050	<b>B</b>	<i>Sphenolithus predistentus</i>	Bown & Dunkley Jones (2006)		
2050	<b>B</b>	<i>Sphenolithus furcatolithoides</i> (B)	Agnini <i>et al.</i> (2014)	40.51	C18r
2050	<b>T</b>	<i>Sphenolithus strigosus</i>	Bown & Dunkley Jones (2006)		
1450	<b>Bc</b>	<i>Cribo centrum reticulatum</i>	Agnini <i>et al.</i> (2014)	42.37	C19r
1090	<b>Bc</b>	<i>Reticulofenestra umbilicus</i>	Agnini <i>et al.</i> (2014)	43.06	C20n
280	<b>T</b>	<i>Chiasmolithus gigas</i>	Agnini <i>et al.</i> (2014)	43.96	C20r
210	<b>B</b>	<i>Sphenolithus strigosus</i>	Bown & Dunkley Jones (2006)		

based on the presence of *Blackites gladius* (Locker, 1967) Varol 1989, *Blackites inversus* (Bukry & Bramlette, 1969) Bown & Newsam, 2017, *Lanternithus arcanus* Bown, 2005, *Sphenolithus spiniger*, *Sphenolithus furcatolithoides*, and *Nannotetrina* Achuthan & Stradner, 1969 (Fig. 2).

The T of *C. gigas* marks the base of zone CNE12 (*Nannotetrina* spp. PRZ), dated at 43.96 Ma in chron C20r (Agnini *et al.*, 2014). This biohorizon is identified above the Mt-6 of the LJSt (Fig. 2).

The T of *B. gladius* marks the zone NP15-NP16 boundary (Martini, 1971), traditionally considered as correlative with the T of *C. gigas* (Okada & Bukry, 1980; Perch-Nielsen, 1985; Martini & Müller, 1986). In the Jaca section, *B. gladius* is still observed, although very scarce, within the LJSt unit, up to Mt-6 (CNE12). We cannot discard the possibility of some reworking or a certain degree of diachronism for this event, located by some authors within zone NP16 (Wei & Wise, 1989; Berggren & Aubry, 1984) and also at zone NP17 (Berggren & Aubry, 1984). Despite ambiguity surrounding the establishment of the zone NP15-NP16 boundary, we have elected here to follow the correlation of Agnini *et al.* (2014), which would place it within zone CNE12.

A high abundance of *S. strigosus* has also been observed within zone CNE12 in the Jaca section (Fig. 3). The B of this species is placed within zone NP16 (Bown & Dunkley Jones, 2006), supporting the correspondence of zones CNE12 and NP16 in this part of the section, above Mt-6 (Fig. 2). The observation of a few specimens in zone CNE11, corresponding to zone NP15 (Lutetian), is also described by Lupi & Wise (2006) and Fioroni *et al.* (2015).

The Bc of *R. umbilicus* ( $\geq 14 \mu\text{m}$ ) marks the base of zone CNE13 (*Reticulofenestra umbilicus* Base Zone) dated at 43.06 Ma in chron C20n (Agnini *et al.*, 2014). This biohorizon was identified in the Torrijos Bridge lobes, beneath Mt-8 of the lower UJSt unit (Fig. 2).

On the basis of the bioevents T of *C. gigas* and Bc of *R. umbilicus*, the LJSt unit should be chronostratigraphically defined as ranging from C20r to C20n (Fig. 2), which is in agreement with the proposal of Oms *et al.* (2003). In detail, the C20r-C20n polarity reversal, in this paper, is defined at stratigraphic levels below our placement of the T of *C. gigas* (Fig. 2). We should accordingly consider a possible diachronism associated with this event. In addition, we cannot discard reworking. Although the number of samples analysed for magnetostratigraphy, across this interval were indeed interpreted as a polarity reversal, a significant scattering of the declination and inclination values was also observed, so that, some slight modification of the exact position of the reversal event cannot be completely ruled out. A high-resolution revision is required here of both biostratigraphy and magnetostratigraphy in order to calibrate age assignments.

The Bc of *C. reticulatum* is used to define the base of zone CNE14 (*C. reticulatum* BZ) included in the Lutetian and dated at 42.37 Ma in chron C19r (Agnini *et al.*, 2014). This event was identified at the Charlé lobes stratigraphic level of UJSt (Fig. 2). Agnini *et al.* (2014) documented, nonetheless, a sporadic occurrence in zone CNE13. In the LJSt unit, specimens of *C. reticulatum* (with unclear central net) were sporadically observed.

The boundary between zones CNE14-CNE15 (*D. bisectus*-*S. obtusus* CRZ) is defined by the B of *Dictyococcites bisectus* (Hay *et al.*, 1966) Bukry & Percival, 1971 in the Bartonian and dated at 40.34 Ma in chron C18r (Agnini *et al.*, 2014). The scarce record of these specimens precludes a precise placement of the event, which, however, is identified within the LJSt unit. Other authors have considered this event as diachronic (Mita, 2001; Larrasoana *et al.*, 2008).

The T of *S. furcatolithoides* morphotype B (Agnini *et al.*, 2014) is constrained to the upper part of zone CNE14,

included in the Bartonian and dated at 40.51 Ma in chron C18r (Agnini *et al.*, 2014). This biohorizon was identified in the Rapitan channel system, in the upper part of UJSt unit (Fig. 2).

The UJSt unit is bounded by the Bc of *R. umbilicus* and the T of *S. furcatolithoides* (B) corresponding respectively to C20n and C18r (Fig. 2). This identification in the Jaca section is consistent with chron assignments by Oms *et al.* (2003), who defines the same polarity pattern for this part of the section. The intermediate location of C19r, according to Oms *et al.* (2003), is here also supported by the identification of Bc of *C. reticulatum* (Fig. 2).

The B of *S. predistentus* (Perch-Nielsen, 1985; Fornaciari *et al.*, 2010; Toffanin *et al.*, 2013) has been correlated by Agnini *et al.* (2014) with the lower part of zone CNE15, in the Bartonian. In the Jaca section, the T of *S. furcatolithoides* morphotype B was observed at the same stratigraphic level (Fig. 2). We used these two events to approximate the location of the CNE14-CNE15 boundary in the Rapitan channel system (Fig. 2).

The T of *C. solitus* has a range, which extends throughout the middle part of zone CNE15 (Agnini *et al.*, 2014), at the bottom of zone NP17 (Martini, 1971) and CP14b (Okada & Bukry, 1980). A scarce record of these specimens has been observed until the Gracionepel instabilities, in agreement with the base of zone CNE15 in the Bartonian (Fig. 2).

The B of *Sphenolithus obtusus* Bukry, 1971 and the Tc of *S. spiniger* (Fornaciari *et al.*, 2010) are correlated with the upper part of zone CNE15 (Agnini *et al.*, 2014). The abundance of *S. spiniger*, up to the top of the section is far from the prominent decrease described in Fornaciari *et al.* (2010) before the Tc (Fig. 3). The B of *S. obtusus* was dated at 39.64 Ma in chron C18n.2n (Fornaciari *et al.*, 2010). The absence of this taxon in the samples permits us to interpret this section as older than this date, in agreement with Oms *et al.* (2003) (Fig. 2).

The biostratigraphic results presented here validate the magnetostratigraphic data and correlation by Oms *et al.* (2003), reinforcing the methods of this paper in the sense that it is a rare example of magnetostratigraphic techniques applied to expanded deep-marine clastic systems.

The general correlation between sedimentary units of the Aínsa and Jaca Basins should be reconsidered, comparing our results with the proposal of Mochales *et al.* (2012) and Scotchman *et al.* (2015). First, the timing of the LJSt would correspond with the Guaso turbidite systems of the Aínsa Basin. Second, the overlying lowermost part of the UJSt would be the time equivalent of the Sobrarbe delta. Finally, the last turbidite system of the Hecho Group (Rapitan channel, established in the Jaca Basin) would be the deep-marine time equivalent of the continental sediments of the lower Escanilla formation in the Aínsa Basin. Although additional work is required, the above correlation should be taken as a guideline for any revised

palaeogeographic reconstruction involving the Aínsa and Jaca Basins.

## 7. CONCLUSIONS

Four age-calibrated calcareous nannofossil bioevents have been identified in the Jaca transect, establishing a biostratigraphic framework for the sedimentary units of the Upper Hecho Group and Larrés Marls. These results reinforce the magnetostratigraphic scheme and correlation established by Oms *et al.* (2003).

Sedimentation took place during the middle Eocene, including part of Lutetian and Bartonian stages, during biozones CNE11-CNE15 or NP15-NP16, covering a time-interval of at least ~3.45 Myr between 43.96 Ma (T of *C. gigas*) and 40.51 Ma (T of *S. furcatolithoides* morphotype B).

The correlation between the Aínsa and Jaca Basins should be revisited when integrating data by Mochales *et al.* (2012) and Scotchman *et al.* (2015). As an outline framework, the Upper Hecho Group, in the Jaca Basin, should correlate with the time span between the Guaso turbidite systems and the lower part of the already continental Escanilla Formation, with a slight overlap of the lower UJSt with the Sobrarbe Delta Formation.

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## APPENDIX I: CALCAREOUS NANNOFOSSIL SYSTEMATICS

### Calcareous nannofossil biomarker genus and species

Order ISOCHRYSIDALES Pascher, 1910.

Family **Noelaerhabdaceae** Jerkovic, 1970 emend. Young & Bown, 1997.

Genus *Reticulofenestra* Hay, Mohler & Wade, 1966.

*Reticulofenestra umbilicus* (Levin, 1965) Martini & Ritzkowski, 1968.

(Fig. 4d)

Genus *Cribocentrum* Perch-Nielsen, 1971

*Cribocentrum reticulatum* (Perch-Nielsen, 1985)

(Fig. 4e)

Genus *Dictyococcites* (Hay, Mohler & Wade, 1966) Bukry & Percival, 1971.

*Dictyococcites bisectus* (Hay, Mohler & Wade, 1966) Bukry & Percival, 1971.

Order COCCOLITHALES Schwarz, 1932.

Family **Coccolithaceae** Poche, 1913 emend. Young & Bown, 1997.

Genus *Coccolithus* Schwarz, 1894

*Coccolithus gigas* (Bramlette & Sullivan, 1961) Radomski, 1968.

(Fig. 4a)

Genus *Chiasmolithus* Hay *et al.*, 1966.

*Chiasmolithus solitus* (Bramlette & Sullivan, 1961) Locker, 1968.

(Fig. 4f)

Order DISCOASTERALES Hay, 1977

Family **Sphenolithaceae** Deflandre, 1952

Genus *Sphenolithus* Deflandre in Grassé, 1952

*Sphenolithus furcatolithoides* Group sensu Bown & Dunkley Jones, 2012

*Sphenolithus furcatolithoides* Locker, 1967; morphotype "B" Perch-Nielsen, 1985

(Figs 4i, 4j)

*Sphenolithus strigosus* Bown & Dunkley Jones, 2006

(Figs 4b, 4c)

*Sphenolithus radians* Group sensu Bown & Dunkley Jones, 2012

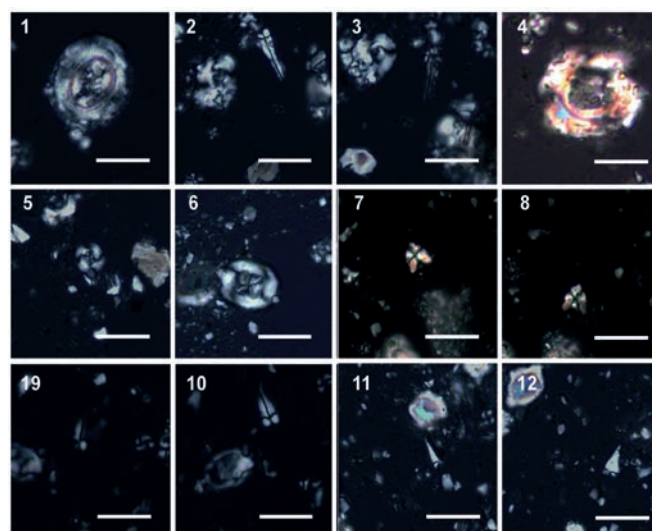
*Sphenolithus spiniger* Bukry, 1971

(Figs 4g, 4h)

*Sphenolithus predistentus* Group sensu Bown & Dunkley Jones, 2012

*Sphenolithus predistentus* Bramlette & Wilcoxon, 1967

(Figs 4k, 4l)



**Figure 4.** Microphotographs of Eocene calcareous nannofossil index species from the Jaca section. **a)** *Chiasmolithus gigas* (sample 6). **b)** *Sphenolithus strigosus* 0° (sample 7). **c)** *Sphenolithus strigosus* 45° (sample 11). **d)** *Reticulofenestra umbilicus* >10 μm (sample 20). **e)** *Cribocentrum reticulatum* (sample 22). **f)** *Chiasmolithus solitus* (sample 6). **g)** *Sphenolithus spiniger* 0° (sample 2). **h)** *Sphenolithus spiniger* 45° (sample 2). **i)** *Sphenolithus furcatolithoides* "B" 20° (sample 23). **j)** *Sphenolithus furcatolithoides* "B" 0° (sample 23). **k)** *Sphenolithus predistentus* 0° (sample 28). **l)** *Sphenolithus predistentus* 45° (sample 28). Scale bars 10 μm.

## APPENDIX II. OTHER TAXA CITED IN TEXT

- Blackites* Hay & Towe, 1962  
*Blackites gladius* (Locker, 1967) Varol, 1989  
*Blackites inversus* (Bukry & Bramlette, 1969) Bown & Newsam, 2017  
*Coccolithus* Schwartz, 1894  
*Coccolithus pelagicus* (Wallich 1877) Schiller, 1930  
*Coccolithus formosus* (Kamptner, 1963) Wise, 1973  
*Dictyococcites* Black, 1967  
*Dictyococcites bisectus* (Hay *et al.*, 1966) Bukry & Percival, 1971  
*Dictyococcites scrippsae* Bukry & Percival, 1971.
- Discoaster* Tan, 1927  
*Helicosphaera* Kamptner, 1954  
*Lanternithus* Stradner, 1962  
*Lanternithus arcanus* Bown, 2005  
*Lanternithus inversus* Bown, 2005  
*Nannotetrina* Achuthan & Stradner, 1969  
*Pemma* Klumpp, 1953  
*Pontosphaera* Lohmann, 1902  
*Sphenolithus* Deflandre in Grassé, 1952  
*Sphenolithus cuniculus* Bown, 2005  
*Sphenolithus moriformis* (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967  
*Zygrhablithus* Deflandre, 1959  
*Zygrhablithus bijugatus* (Deflandre in Deflandre & Fert, 1954) Deflandre, 1959