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 Gracionapel 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. formous (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 Gracionapel, dentro de las margas de talud de Larrés. Esta información cromoestratigráfica 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. formous (Kamptner, 1963) Wise, 1973 así como diferentes especies de Reticulofenestra Hay et al., 1966, acompañadas 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).

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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 Ainsa 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 & Klimovitch, 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 turbidite systems 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 Burguí Marls Formation (Cámara & Klimovitch, 1985). These marls are also the distal equivalents of the shallow-marine carbonates of the Boltaña and Guara formations (Soler-Sampere & Puigdefàbregas, 1970; Puigdefábregas, 1975). To the east of the Boltaña anticline, the depositionally 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
E-W-continuum of turbidite elements in the Jaca Basin comprises channel-lobes transition, sheet-like lobe elements 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 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 Sabinánigo 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-lobes 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 mudtier, 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 Sabinánigo 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).
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 mm²). 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;
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 & Buckry (1980) have also been identified. In addition, a few additional biomarkers described by Perch-Nielsen (1985), Bown & Dunckey 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 LJSt, 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 LJSt, 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...
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 & Buckry, 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* (≥ 14 µm) 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 (*Dictyococcites bisectus-S. obtusus* CRZ) is defined by the T 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). 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.

On the basis of the bioevents T of *S. strigosus* and Bc of *S. furcatolithoides*, 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.

### 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     | *Sphenolithus predistentus* | Bown & Dunkley Jones (2006) |          |       |
| 2050     | B     | *Sphenolithus furcatolithoides* | Agnini et al. (2014) | 40.51    | C18r  |
| 2050     | T     | *Sphenolithus strigosus* | Bown & Dunkley Jones (2006) |          |       |
| 1450     | Bc    | *Cribrocentrum reticulatum* | Agnini et al. (2014) | 42.37    | C19r  |
| 1090     | Bc    | *Reticulofenestra umbilicus* | Agnini et al. (2014) | 43.06    | C20n  |
| 280      | T     | *Chiasmolithus gigas* | Agnini et al. (2014) | 43.96    | C20r  |
| 210      | B     | *Sphenolithus strigosus* | Bown & Dunkley Jones (2006) |          |       |
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) for 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 (Agini 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). 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). 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.

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 Larrès 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 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 (Rapitán 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.

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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 Cribrocentrum Perch-Nielsen, 1971
Cribrocentrum 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) Cribrocentrum reticulatum (sample 22). f) Chiasmolithus solitus (sample 6). g) Sphenolithus spiniger 0° (sample 2).
h) Sphenolithus spiniger 45° (simple 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 scrippsi Bukry & Percival, 1971.

Discoaster Tan, 1927
Helicosphaera Kamptner, 1954
Lanternithus Stradner, 1962
Lanternithus arcanus Bown, 2005
Lanternithus inversus Bown, 2005
Nannotetra 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