New Upper Carboniferous palynofloras from Southern Pyrenees (NE Spain): Implications for palynological zonation of Western Europe

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A B S T R A C T

In the western European basins, the paleoflora of late Pennsylvanian-early Permian transition is still a matter of discussion in terms of its age determination and biostratigraphic ranges. This study represents a review of the Upper Carboniferous and Permian stratigraphy of the Central and Eastern Pyrenees from continental successions with interbedded volcanic-volcaniclastic rocks, coupling new palynological data and known palynological assemblages to calibrate them with recent SHRIMP U-Pb zircon ages dates obtained in previous works. In this light, the first continental unit overlying the Variscan basement bears a Gzhelian palynological association, which fits perfectly with the isotopic SHRIMP U-Pb zircon dating of the associated pyroclastic rocks (304.6 ± 1.5 Ma and 300.4 ± 1.4 Ma).

In order to provide a solid base to characterize the Carboniferous-Permian microflora evolution in the western Tethys sub-basins, we have compared radiometrically dated palynological assemblages of the Euramerican Province such as Spain, southern France, the Alps and Sardinia (Italy). The new biostratigraphic and chronostratigraphic information presented here confirms the validity of the classical Carboniferous Palynological Zonation of Western Europe.

1. Introduction

The Late Pennsylvanian ($306.7\text{--}298.9 \pm 0.15$ Ma, [Ogg et al., 2016](#)) and Permian ($298.9 \pm 0.15\text{--}251.902 \pm 0.024$ Ma, [Lucas and Shen, 2018](#)) were characterized by the intense changes involved in the early tectonic post-assembly of the Pangea supercontinent and its breakup after the Variscan orogen climax ([Ziegler et al., 1979](#); [Simancas et al., 2005](#); [Isozaki, 2009](#)).

The first part of this period (Late Pennsylvanian-early Permian) is considered to be an interval of geological and climatic transition. Deposits of coal, laterite and bauxite, indicative of humid tropical paleoclimatic conditions, were replaced by signs of more aridity such as the presence of Vertisols and calcretes and aeolian and evaporite deposits ([Tabor and Poulsen, 2008](#)). Large variations in the concentration of atmospheric CO₂ and O₂ have also been registered for this period (e.g. [Beerling et al., 2002](#); [Bernier et al., 2007](#); [Montañez et al., 2007, 2016](#); [Royer, 2014](#)). All these changes occurred as a result of the trend toward global warming that followed the Permo-Carboniferous glacial retreat ([Fielding et al., 2008](#)).

The overall trend toward Carboniferous-Permian aridification in the Euramerican Biota Province has been described as a climatic transition from tropical everwet to sub-humid during early Cisuralian and to semi-arid during the last part of this period ([Roscher and Schneider, 2006](#); [Tabor and Poulsen, 2008](#); [Michel et al., 2015](#)). This progressive aridification reached its maximum around the Kungurian-Wordian age (late Cisuralian-early middle Guadalupian) and the climate continued as seasonal and dry during the late Guadalupian, across the Permo-Triassic Boundary and even in the Early Triassic ([Schneider et al., 2006](#); [Montañez et al., 2007](#); [Tabor and Poulsen, 2008](#); [Gulbranson et al., 2015](#); [Michel et al., 2015](#)).

The climatic change observed during the Late Pennsylvanian-Permian produced an increase in the extinction rates of land plants ([Cascales-Miñana and Cleal, 2014](#)). The influence of aridification during this time is directly reflected by the variations in the constitution and distribution of floral associations ([Ziegler, 1990](#); [Kerp, 1996](#); [DiMichele et al., 2001b](#); [Wagner, 2004a](#); [Schneider et al., 2006](#)). In fact, in the Euramerican Province, this period has been interpreted as the “collapse of the rainforests” ([DiMichele et al., 2009](#); [Cleal et al., 2010, 2011](#); [Sahney et al., 2010](#); [Gulbranson et al., 2015](#)). The replacement of hygrophytic (“Stephanian flora”) by mesophytic and meso-xerophytic floras (“Autunian flora”) that tolerated a seasonally dry climate has been documented. Conifers and other gymnosperms adapted to drier conditions and propagated progressively (e.g. [DiMichele et al., 2001a](#); [Looy et al., 2014](#)) to become a dominant element in the landscapes until the Mesozoic.

In the Euramerican Province, the continental vegetation during the Pennsylvanian was a hygrophilous flora comprising pteridosperms, marattialean ferns, lycopsids, *Calamites* and *Cordaites* trees ([DiMichele et al., 2006](#); [Thomas and Cleal, 2017](#)). In the Late Pennsylvanian-early Permian, “Carboniferous hygrophilous flora” proliferated in the wet depressions (lowlands). Mesophilic or even meso-xerophytic flora, whose most remarkable components were walchian conifers ([Lemoigne and Doubinger, 1984](#)) grew outside these areas (uplands), in dewatered habitats where the environmental conditions became less favourable for “Stephanian elements” ([Broutin et al., 1986](#)). This change in the flora was not isochronous across the Euramerican Province (e.g. [Bouroz and Doubinger, 1977](#); [Wagner, 1984](#); [Broutin et al., 1990a, 1990b](#); [Kerp, 1996](#); [Blake et al., 2002](#)). The early appearance of “Autunian flora” in Carboniferous rocks has been reported in outcrops from Western Europe (e.g. [Lemoigne and Doubinger, 1984](#); [Broutin and Gisbert, 1985](#); [Broutin et al., 1986](#); [Doubinger and Roy-Dias, 1985](#); [Broutin et al., 1990a, 1990b](#); [DiMichele and Aronson, 1992](#); [Kerp and Fichter, 1985](#); [Martín-Closas and Galtier, 2005](#); [Gand et al., 2013](#)). Conversely, taxa from a Carboniferous-type wetland biome, interpreted as stream- and lake-side elements ([DiMichele et al., 2006](#); [Gand et al., 2013](#)), reappear in early Permian landscapes dominated by conifers ([Broutin et al., 1990a](#); [Galtier and Broutin, 1995](#)).

Records of Permian “mixed flora”, including elements from more than one Palaeo-kingdom, may also appear in these above-cited environments (e.g. Broutin, 1986; Broutin et al., 1990b; Berthelin et al., 2003, 2006; Broutin and Berthelin, 2005; Sun, 2006; Cleal, 2016). This complex scenario was also affected by the phytogeographical provinciality that had a negative effect on the precise correlation between regional palynostratigraphic schemes (Stephenson, 2016).

Recently, two different lines of approach have emerged to shed some light on this problematic transition. The first is the isotopic SHRIMP U-Pb zircon dating (e.g. Pereira et al., 2014; Michel et al., 2015; Pellenard et al., 2017); the second is the new palynological data presented in this work. We combine the results of the two-pronged chronostratigraphic information to characterize the Carboniferous- Permian transition in the western Tethys sub-basins, reviewing the age of the rocks and comparing our results with the best known microfloral associations in the western Peri-Tethys region.

2. Background and geological setting

In the western European basins, the Late Pennsylvanian-early Permian transition is mainly represented by fluvio-lacustrine deposits with sequences of coal seams and bituminous shales frequently inter-bedded with volcanoclastic products (Cassinis et al., 2000, 2003; Bruguier et al., 2003; Schneider et al., 2006; Gand et al., 2013; Pereira et al., 2014; Michel et al., 2015; Luthardt et al., 2016; Opluštil et al., 2016a, 2016b, 2017; Pellenard et al., 2017). The radiometric dating of those volcanic and volcanoclastic rocks provides an important tool for correlating palynological associations with absolute ages. Correlating the age of microflora with other geochronological data (e.g. U-Pb dating, conodonts, macroflora, tetrapods footprints) would allow us to discern and validate the Palynological Zonation of Western Europe for the Late Carboniferous (Clayton et al., 1977). In order to precise the correlation of the Late Carboniferous-early Permian continental successions in the southwestern of Europe (eastern Equatorial Euramerica or western Tethys), it is essential to improve our knowledge of the

Fig. 1. Geographical and geological situational map of Iberia and the Late Carboniferous and Permian basins in the Pyrenees. A: Detailed geological map of Erill Castell Basin. The red line represents the site of the studied sections. B: Detailed geological map of Gramós Basin. The

red line represents the site of the studied sections. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

palynological associations of this period and to understand the significance of the unconformities and hiatuses present in the Post-Variscan deposits, which are important in the correlation of basins (Cassinis et al., 2012; Grotter et al., 2015).

The Pyrenean late Palaeozoic successions are located in the Axial zone of the Pyrenees and were the result of continental transtensive-extensive basins created during the initial phase of the Pangea breakup (Soula et al., 1979; Gisbert, 1981; Bixel and Lucas, 1983; Martí, 1986). These basins have been described as half-graben structures (Soriano et al., 1996; Saura and Teixell, 2006), which created a complex system of isolated or partly interconnected sub-basins (Gisbert, 1981, 1983; Grotter et al., 2015). Initially, the stratigraphic record was strongly affected by volcanism and widespread syn-sedimentary tectonic activity. Large andesite sheets and ignimbritic bodies are interbedded at various levels with the sedimentary infill (Martí, 1986; Mitjavilla and Molist, 1988; Grotter et al., 2015), and several faults defined the morphology of the basins (Fig. 1A, B; Soriano et al., 1996; Saura and Teixell, 2006). Until the absolute ages recently obtained by Pereira et al. (2014), the chronostratigraphic subdivision of these basins was palaeontologically assigned and subject to debate (Dalloni, 1930; Mey et al., 1968; Nagtegaal, 1969; Gisbert, 1981, 1983). The poor palaeontological content of the Permian red beds, mainly based on tetrapod footprints (Robles and Llompart, 1987; Mujal et al., 2016a, 2016b, 2017), has not been sufficient to establish a precise age for all the units.

Four lithostratigraphic units delimited by unconformities (Fig. 2) have been defined (Gisbert, 1981) for the latest Carboniferous-Permian time-interval. From base to top these are: a) Grey Unit (namely Aguiró Fm. and Erill Castell Fm. of Mey et al., 1968; Nagtegaal, 1969); b) Transition Unit (corresponding to the top of Erill Castell Fm. and Malpàs Fm. of Mey et al., 1968; Nagtegaal, 1969); c) Lower Red Unit, and d) Upper Red Unit (Peranera Fm. of Mey et al., 1968; Nagtegaal, 1969).

In the studied area, the succession starts with the Grey Unit, comprising basal breccias with thin interbedded coal seams (Aguiró Fm.). Going upward, it is mostly composed of volcanic and volcanoclastic rocks. The last part of the succession is composed by conglomerates, sandstones, siltstones and coal deposits. There are several remains of Pennsylvanian macroflora in these coal layers (Asturian-Stephanian C in age) in the Aguiró, Argestues, Malpàs, Surroca, Ogassa, and Coll de Sas localities (Table 1). The radiometric ages proposed by Pereira et al. (2014) from intrusive and extrusive lava sheets for the basal Grey Unit in Coll de Vanses andesite and Cadí ignimbrite (Fig. 1b) led to the assignment of the basal Grey Unit (Aguiró Fm.) to the Kasimovian (307.4 ± 1.4 Ma). Similarly, the upper portion of this unit (Erill Castell Fm.) has been assigned to an early Gzhelian age (304.6 ± 1.5 Ma and 300.4 ± 1.4 Ma; Pereira et al., 2014). It is noteworthy that the stratigraphic position of these absolute datings is located several meters below the aforementioned coal levels.

The Transition Unit ("Unidad de Tránsito" of Gisbert, 1981 and "Permien alternant" of Broutin et al., 1994) is characterized by volcanic levels (mainly andesites), intercalated volcanoclastics, conglomerate, sandstones and siltstone beds that include "late Stephanian-Autunian flora" (Table 1). The radiometric ages in the Estac ignimbrite of the basal part of this unit endorse an Asselian age (296.2 ± 3.1 Ma, 296.1 ± 4.0 Ma; Pereira et al., 2014).

The Lower and Upper Red units consist of red bed successions composed of reddish conglomerates, sandstones and siltstones. These

Fig. 2. Chronostratigraphy of the continental successions of the Southern Pyrenean basins. Modified from [Gretter et al. \(2015\)](#) and [Lloret et al. \(2018\)](#).

Table 1

Compilation of the palaeontological record of the Late Carboniferous-Permian basins in the Central-Eastern Southern Pyrenees.

Campodrón	Lower Red Unit	"Autunian" (Early Permian)	Broutin and Gisbert (1985)
Gotarta	Lower Red Unit	"Autunian" (Early Permian)	Broutin and Gisbert (1985)
Arcalis	Transition Unit	"Autunian" (Early Permian)	Talens and Wagner (1995)
		"Autunian" (Early Permian)	Schmidt (1931)
Baró	Transition Unit	Early Permian	Álvarez-Ramis (1985)
		"Autunian" (Early Permian)	Menéndez Amor (1952)
Coll de Jou	Transition Unit	"Middle-Upper Autunian" (late Gzhelian)	Wagner and Álvarez-Vázquez (2010)
		Stephanian B-C	Broutin and Gisbert (1985)
Coll de la Caritat	Transition Unit	Late Stephanian	Broutin and Gisbert (1985)
Malpás	Transition Unit (Malpás Fm)	Stephanian C	Wagner and Álvarez-Vázquez (2010)
		Late Stephanian C - "lower Autunian" (Early Permian)	Talens and Wagner (1995)
		Stephanian	Dalloni (1930); Nagtegaal (1969)
Estac	Uncertain	"Early Autunian" (Early Permian)	Álvarez-Ramis and Doubinger (1987)
Rio Pallarols/Gotarta	Grey Unit	Gzhelian	This Study
Coll de Sas	Grey Unit	Stephanian C	Mujal et al. (2018)
Surroca/Ogassa	Grey Unit	Stephanian C	Álvarez-Ramis et al. (1971); Doubinger et al. (1978); Doubinger and Álvarez-Ramis (1984); Martín-Closas and Martínez-Roig (2007); Wagner and Álvarez-Vázquez (2010)
		Late Stephanian	Dalloni (1930); Álvarez-Ramis et al. (1969); Álvarez-Ramis (1985)
		Middle Stephanian	Jongmans (1951)
		Stephanian (Surroca) – Late Stephanian (Ogassa)	Faura (1914)
		Upper Carboniferous	Faura (1913)
ErillCastell/Malpás	Grey Unit (Erill Castell Fm)	Cantabrian (Stephanian A)	Dalloni (1930); Talens and Wagner (1995)
Argestues	Grey Unit (Aguiró Fm)	Stephanian B	Broutin and Gisbert (1985)
Aguiró	Grey Unit (Aguiró Fm)	Asturian (Westphalian D)	Wagner and Álvarez-Vázquez (2010)
		Late Westphalian-Cantabrian (Stephanian A)	Talens and Wagner (1995)
		Westphalian D	Nagtegaal (1969)
		Middle-Upper Westphalian	Dalloni (1930)

Tetrapod's footprints and bones

Pla de St. Tirs/Noves de Segre	Upper Red Unit	"Late Permian"	Robles and Llopart (1987)
Noves/La Trava	Upper Red Unit	?Middle Permian (Wordian)	Mujal et al. (2016a)
Unit	"Late Permian"		Mujal et al. (2018)
La Mola d'Amunt	Lower Red Unit	Middle-Late early Permian	
(Artinskian)			Mujal et al. (2016b)

two red units are separated by an angular unconformity ([Gisbert, 1983](#); [Gretter et al., 2015](#)). The age of these units is still a subject of debate. Nevertheless, tetrapod footprints from the Lower Red Unit would suggest an Artinskian age ([Mujal et al., 2016a, 2016b](#)), and the radiometric dating in the Castellar de N'Hug area obtained by [Pereira et al. \(2014\)](#) indicates 283.4 ± 1.9 Ma age. The finding of a caseid vertebra (synapsids group) from the uppermost part of the Upper Red Unit by [Mujal et al. \(2016a, 2017\)](#) did not yield any chronostratigraphic constraints, but a middle Permian age can be considered for this unit, based on regional correlation and facies comparison ([Gretter et al., 2015](#)).

The Late Pennsylvanian-early Permian palaeontological data from the Catalan Pyrenees has been described by previous authors in two main areas ([Fig. 1](#)). The central Pyrenees include the areas of Erill Castell, Malpás, Baró, Arcalis, Coll de Sas, Gotarta and Estac ([Dalloni, 1930](#);

Schmidt, 1931; Menéndez Amor, 1952; Nagtegaal, 1969; Álvarez-Ramis, 1985; Talens and Wagner, 1995; Wagner and Álvarez-Vázquez, 2010; Mujal et al., 2018). The main sections in the eastern Pyrenees are Ogassa, Surroca, Coll de Jou, Coll de la Caritat and Camprodón (Faura, 1913, 1914; Dalloni, 1930; Jongmans, 1951; Álvarez-Ramis et al., 1969, 1971; Doubinger et al., 1978; Doubinger and Álvarez-Ramis, 1984; Broutin and Gisbert, 1985; Wagner, 2004b; Gómez-Alba, 2007; Martín-Closas and Martínez-Roig, 2007; Wagner and Álvarez-Vázquez, 2010). In both areas, the precise characterization of the Permo-Carboniferous transition is a challenge, due to the poor preservation of palynological remains and because some studies were preliminary in its palynological and stratigraphic interpretations (Broutin and Gisbert, 1985), or the location of the palynological samples was uncertain (Álvarez-Ramis and Doubinger, 1987).

3. Materials and methods

This work involves a palynological and stratigraphic review of the Late Carboniferous and Permian successions of the Central and Eastern Pyrenees. On the basis of the established stratigraphic division (Gisbert, 1981), we logged and sampled the Grey Unit in six different locations of the Erill Castell (Fig. 1A) and Gramós (Fig. 1B) basins. The stratigraphic loggings were made using standard physical parameters such as lithology, sedimentary structures and thicknesses (Figs. 3, 4). Only Rio Pallarols and Gotarta sections provided positive palynological samples: Pall-1, PL-02 and PL-06 (Rio Pallarols) and GT-2 (Gotarta).

The Grey Unit palynological assemblage was obtained from PL-02 and Pall-1 samples from the Argestes locality (Rio Pallarols, Fig. 3). The PL-06 sample association was discarded due to its poor preservation and low taxonomic diversity. Similarly, the organic matter from the GT-02 sample was highly altered even though the same taxa are observed. Preservation and taphonomy constraints prevented a quantitative study of samples. Therefore, we studied all the samples as the same “assemblage”, which provided the first palynological

Fig. 3. Stratigraphic log of Rio Pallarols section placed in Gramós Basin (Fig. 1B). A: Basal conglomerate with rounded basement clasts corresponding to Palaeozoic. B: Plants remain. C: Materials where was collected the sample PL-5. D: Trunk fossil.

characterization for the Grey Unit.

The samples were processed in the laboratory of the Geosciences Department at the University

of Vigo, using maceration procedures (HCl-HF-HCl techniques) followed those outlined by [Erdtman \(1943\)](#), [Wood et al. \(1996\)](#) and [Traverse \(2007\)](#). The samples were processed by first adding HCl and HF to remove carbonate and silicate minerals. No oxidising treatment was used, due to the fragility of the palynomorphs. A dispersing agent was subsequently added to facilitate filtering and sieving at 10 µm. The palynological slides were analyzed in the Mi- croscopy Labs at the University of Vigo with a Leica DM 2000 LED and the photos were taken with a Leica ICC50 W camera magnified x1000.

4. Results

4.1. Stratigraphy and sedimentology

Two stratigraphic sections were studied in detail: the Argestes section and the Gotarta section.

In the Argestes section (Fig. 3) the four lithostratigraphic units of the latest Carboniferous and Permian defined by Gisbert (1981) are well exposed. The first deposits comprised polygenic breccia with Devonian carbonates and Silurian schists clasts (Fig. 3A). The clasts are 10–15 cm in size and are often imbricated with poor vertical gradation. Moving upward, the breccias yield to channelised conglomerate bodies with erosive basal surfaces constituting fining-upward sequences 2–5 m thick with thin coal horizons and 2–5 cm thick greyish claystone levels at the top. The PL-2 sample was collected from a dark, thick claystone levels where several plant fragments with a variable grade of conservation were found (Fig. 3B). The general thinning and fining-upward trend of this first part of the Grey Unit has been interpreted as distal alluvial fans in the base, evolving to more developed fluvial systems in its topmost parts (Gisbert, 1981, 1983). Moving upward, the section consists of beds 10–30 cm thick and up to 10 m wide, constituted by medium- coarse greyish sandstones with low angle trough cross-bedding inter- bedded with thin beds of greyish siltstones with horizontal laminations and 20–30 cm thick coal levels at the topmost part. The sample Pall-1 was collected in the finest upper part of these deposits.

The middle-upper part of the Argestes section is composed of finer grey sediments corresponding to alluvial-fluvial deposits associated with low-gradient fluvial systems with widespread overbank deposits (Fig. 3C). The uppermost part of the Grey Unit in the Argestes section was highly influenced by volcanic activity and contains reworked ochre tuffs and middle-size sandstone levels with cross-laminations. One important characteristic of this interval was the presence of life-position petrified trunks, up to 20–30 cm in diameter (Fig. 3D), with annual-growth-rings still preserved. Volcanic bombs larger than 20 cm and lapilli deposits were interbedded at the top, with alternating levels of greyish sandstones and siltstones with 5–10 cm thick coal beds. The sample PL-6 was collected in the grey siltstones placed near the boundary with the Transition Unit.

The Gotarta section (Fig. 4) is represented by the Grey, Transition and Lower Red units. The stratigraphic record begins with the basal breccias of the Grey Unit composed of sub-rounded clasts of Silurian and Devonian rocks. Above it, there are outcrops of volcanoclastic deposits with tuffs and bombs of up to 30 cm in size (Fig. 4A). These deposits pass up gradually to reworked sandstones with cross-bedding stratification, and plant remains that are overlaid by tabular carbonate beds of less than 10 cm thick (Fig. 4).

The upper part of the Grey Unit in the Gotarta section is represented by medium-coarse grained volcanoclastic deposits with a fining-upward general trend followed by sandstones and siltstones of ephemeral fluvial systems (Gisbert, 1981; Gretter et al., 2015). The GT-2 sample was collected at thin-dark levels intercalated in the finer upper deposits (Fig. 4B, C). The topmost part consisted of intercalated laminated fine sandstones, and red claystones of fluvio-lacustrine origin and lacustrine deposits (Gisbert, 1981, 1983) with badly preserved plant remains.

4.2. Palynology

A palynological assemblage has extracted from the Grey Unit (Figs. 5 and 6):

Acanthotriletes echinatus (Knox) Potonié and Kremp 1955.

Acanthotriletes tenuispinosus Naumova 1953. *Angulisporites splendidus* Bharadwaj 1954.

Apiculatisporis microacanthus Andreyeva 1956. *Apiculatisporis parvispinosus* (Leschik)

Schulz 1962. *Calamospora breviradiata* Kosanke 1950.
Calamospora microrugosa (Ibrahim) Schopf, Wilson and Bentall 1944.
Calamospora pedata Kosanke 1950.
Cirratiradites rarus (Ibrahim) Schopf, Wilson and Bentall 1944.
Cyclogranisporites microgranus Bharadwaj 1957. *Deltoidospora adnata* (Kosanke) McLean 1993. *Deltoidospora priddyi* (Berry) McGregor 1973. *Deltoidospora sphaerotriangula* (Loose) Ravn 1986. *Florinites junior* Potonié and Kremp 1956.
Florinites mediapudens (Loose) Potonié and Kremp 1955.
Granulatisporites granulatus Ibrahim 1933. *Granulatisporites minutus* Potonié and Kremp 1955. *Granulatisporites microgranifer* Ibrahim 1933.
Laevigatosporites perminutus Alpern 1958. *Laevigatosporites vulgaris* (Ibrahim) Ibrahim 1933. *Latensina trileta* Alpern, 1958.
Lophotriletes microsaetosus (Loose) Potonié and Kremp 1955.
Lundbladispora gigantea (Alpern) Doubinger 1968.
Potonieisporites novicus Bhardwaj 1964. *Potonieisporites simplex* Wilson 1962.
Punctatosporites minutus Ibrahim 1933. *Punctatosporites punctatus* Ibrahim 1933.
Savitrissporites camptotus (Alpern) Doubinger 1968.
Vesicaspora wilsonii (Schemel) Wilson and Venkatachala 1963. *Vestispora* cf. *cancellata* (Dybová and Jachowicz) Wilson and Venkatachala 1963.
Chromotriletes sp. *Dictyotriletes* sp. *Endosporites* sp. *Guthoerlisporites* sp.
Lundbladispora sp. *Maculatasporites* sp. *Nuskoisporites* sp.
Plicatipollenites sp. *Potonieisporites* sp. *Spinisporites* sp.
Wilsonites sp. Unidentified disaccites.

5. Discussion

To date, only two palynological studies have been performed in the Late Carboniferous-lower Permian succession of the Central-Eastern Pyrenees (Broutin and Gisbert, 1985; Álvarez-Ramis and Doubinger, 1987). In the first of these (Broutin and Gisbert, 1985), a “Stephanian- Autunian flora” from Argestes, Coll de Jou, Coll de la Caritat, Vehinat de Fogonella and Gotarta (Lleida, Spain) was reported. In the Vehinat de Fogonella Outcrop (Campodrón locality), a preliminary palynological assemblage was obtained between two volcanic levels in the basal section of the Lower Red Unit: *Costapollenites ellipticus*, *Potonieisporites bhardwaj*, *Potonieisporites novicus*, *Vittatina fasciolata*, *Cordaitina* sp., *Gardenasporites* sp. and *Florinites* sp. This assemblage presents “Autunian characteristics” due to the presence of monosaccate pollen together with striated taxa, which indicates a younger age than the Grey Unit assemblage described in this study. Therefore, the association described by Broutin and Gisbert (1985) is consistent with the Artinskian age of the Lower Red Unit (283.4 ± 1.9 Ma) provided by Pereira et al. (2014) in the Southern Pyrenees.

In the second study (Álvarez-Ramis and Doubinger, 1987), from an uncertain outcrop of fossiliferous shales a microflora obtained from fossiliferous shales was described with the following taxa: *Florinites mediapudens*, *Granulatisporites* cf. *parvus*, *Guthoerlisporites magnificus*, *Laevigatosporites vulgaris*, *Leiotriletes adnatus* (= *Deltoidospora adnata*), *Lundbladispora* cf. *gigantea*, *Potonieisporites novicus*, *Potonieisporites* cf. *bhardwaj*, *Polymorphisporites laevigatus*, *Spinisporites spinosus*, *Calamospora* sp., *Cheileidonites* sp., *Cordaitina* sp., *Punctatosporites* sp.,

Fig. 4. Stratigraphic log of Gotarta section placed in Erill Castell Basin (Fig. 1A). A: Volcanic bombs are corresponding to the basal volcanoclastic deposits. B: Lacustrine deposits where GT-2 was collected. C: A general overview of the lacustrine-fluvial deposits with dark colouration. D: Topmost deposits of Gotarta section with intercalation of carbonate deposits and dark-fine deposits corresponding to lacustrine deposits.

Schopfipollenites sp. and indeterminate baccates. These authors proposed a “lower Autunian age” based on its comparison with other studies in Western Europe ([Remy and Remy, 1968](#); [Doubinger, 1971, 1974](#); [Bouroz and Doubinger, 1974](#); [Coquel et al., 1976](#); [Doubinger and Elsass, 1979](#)). This association is very similar to the results described in

this study for the Grey Unit assemblage because of the presence of the genera *Calamospora*, *Deltoidospora*, *Puntatosporites*, *Granulatisporites*, *Lundbladispota* and the monosaccate pollen.

The samples from the Grey Unit described in the present work show spores and pollen that are frequent in “Stephanian” associations

Fig. 5. GU palynological assemblage. A: *Deltoidospora priddyi*. B: *Deltoidospora adnata*. C: *Deltoidospora sphaerotriangula*. D: *Granulatisporites minutus*. E: *Granulatisporites granulatus*. F: *Granulatisporites micrograniifer*. G: *Lophotriletes microsaetosus*. H: *Acanthotriletes tenuispinosus*. I: *Acanthotriletes echinatus*. J: *Cyclogranisporites microgranus*. K: *Apiculatisporis parvispinosus*. L: *Apiculatisporis microacanthus*. M: *Maculatasporites* sp. N: *Punctatosporites punctatus*. O: *Spinisporites* sp. P: *Punctatosporites minutus*. Q: *Chromotriletes* sp. R: *Laevigatosporites perminutus*. S: *Laevigatosporites vulgaris*.

("hygrophytic microflora" and pollen of cordaites), such as *Acanthotriletes echinatus*, *Acanthotriletes*

tenuispinosus, *Angulisporites splendidus*, *Apiculatisporis microacanthus*, *Apiculatisporis parvispinosus*, *Cirratiradites rarus*, *Cyclogranisporites microgranus*, *Deltoidospora adnata*, *Deltoidospora priddyi*, *Deltoidospora sphaerotriangula*, *Granulatisporites granulatus*, *Granulatisporites microgranifer*, *Granulatisporites minutus*, *Laevigatosporites perminutus*, *Laevigatosporites vulgaris*, *Latensina trileta*,

Lophotriletes microsaetosus, *Lundbladispora gigantea*, *Punctatosporites minutus*, *Punctatosporites punctatus*, *Florinites junior*, *Florinites mediapudens* and *Savitrissporites camptotus*. The presence of “Autunian microflora” (represented in the Grey Unit by monosaccate pollen) such as *Guthoerlisporites* sp., *Nuskoisporites* sp., *Plicatipollenites* sp., *Potonieisporites simplex* and, particularly, *Potonieisporites novicus* would indicate a younger age for these materials.

Fig. 6. GU palynological assemblage. A: *Calamospora breviradiata*. B: *Calamospora microrugosa*. C: *Calamospora pedata*. D: *Lundbladispora gigantea*. E: *Lundbladispora* sp. F: *Latensina trileta*. G: *Dictyotriletes* sp. H: *Savitrissporites camptotus*. I: *Angulisporites splendidus*. J: *Cirratriadites rarus*. K: *Endosporites* sp. L: *Potonieisporites simplex*. M: *Potonieisporites* sp. N: *Potonieisporites novicus*. O: *Plicatipollenites* sp. P: *Guthoerlisporites* sp. Q: *Nuskoisporites* sp. R: *Wilsonites* sp. S: *Vestispora* cf. *cancellata*. T: *Vesicaspora wilsonii*. U: *Florinites junior*. V: *Florinites mediapudens*. W-X: Unidentified Disaccites.

Although the presence of mixed microflora has been reported even in the Permian, the appearance of *Angulisporites splendidus*, *Latensina trileta*, *Lundbladispora gigantea*, *Savitrisporites camptotus*, *Vestispora* cf. *cancellata* and *Dictyotriletes* sp. would indicate an older age (pre- Asselian age). *Laevitagosporites* spp. is also more common in the Carboniferous age ([Clayton et al., 1977](#)).

5.1. *The beginning of the “mixed flora” in Upper Carboniferous sediments*

To understand the “mixed flora” concept and its attendant problems, we need to observe the first appearance of the taxa that will become dominant during the Permian. Therefore, the presence and diversification of monosaccate pollen (e.g. genus *Potonieisporites*) is

western Paleotethys with the location of the reviewed palynological assemblages.

fundamental to analyse Upper Carboniferous-early Permian rocks.

The first appearance of the genus *Potonieisporites* (typical “Autunian taxa”) in the Late Carboniferous sediments was reported for the upper Westphalian (upper Moscovian) - Barruelian (lower Kasimovian) interval ([Clayton et al., 1977](#)).

In Western Europe, it has been reported in the Cantabrian Zone (North of Spain; Fig. 7A) from the Picos de Europa and Puentellés (Las Llacierias) Formations. The palynological study was carried out in this region by Coquel and Rodriguez (1994) indicates a stratigraphic interval corresponding to the upper part of Asturian to Barruelian. A comparison with the data of Clayton et al. (1977) is difficult because the palynomorphs were found in a marine section. However, the microfossil assemblages point to the *Thymospora obscura*-*Thymospora thiessenii* Zone (Asturian - Barruelian) due to the presence of the genera *Microreticulatisporites*, *Polymorphisporites* and *Raistrickia* and the taxa *Cirratiradites saturni*, *Crassispora kosankei*, *Radiizonates tenuis*, *Savitrissporites camptotus* and *Westphalensisporites irregularis*, together with the appearance of *Thymospora* spp., *Potonieisporites* spp. and *Angulispores splendidus* (Fig. 8). The Upper Carboniferous hygrophytic microfossil flora is also present. This temporal attribution is consistent with the age provided by conodonts (Blanco-Ferrera et al., 2004; Mendez, 2006; Buggisch et al., 2008) that located the upper Moscovian-Kasimovian succession in the Las Llacierias Section (García-López and Sanz-López, 2002a, 2002b; Buggisch et al., 2008).

Fig. 8. Palynological Biozones of Late Carboniferous-early Permian taxa observed in this study (modified from Clayton et al., 1977. Adjusted to the latest research results). The microflora is separated by its “Westphalian”, “Stephanian” and “Autunian” affinity. The “Zone Supérieure” and “Zone Inférieure” are located in Guadalcanal, Spain.

In slightly younger materials, a proliferation of this typical “Autunian” monosaccate pollen has been observed. Pittau et al. (2008b) reported miospore assemblages in Bèdero (west part of the Southern Alps, North of Italy. Fig. 7A). These authors suggest a *Thymospora ob- scura-Thymospora thiessenii* Zone of Western Europe for these deposits due to the presence of a large amount of *Potoneisporites* (with diverse species) and a group of taxa representative of the Westphalian paly- noflora of Western Europe, such as the genera *Raistrickia*, *Spelaeotrilites*, *Stenozonotrilites*, *Endosporites* and the “Stephanian” taxa *Crassispore kosankei*, *Savitrissporites campitotus* and *Thymospora thiessenii* (Clayton et al., 1977)(Fig. 8). Furthermore, Pittau et al. (2008b) compare the Bèdero assemblage with the one from the Saar Lorrain Basin, a locality typical of the Asturian strata (Alpern, 1963; Alpern and Liabeuf, 1966; Alpern et al., 1969), with the miospore assemblages of the San Giorgio basin (Southwest of Sardinia, Italy. Fig. 7A, recently dated by macro- flora as late Asturian age, late Moscovian by Cleal et al., 2017) and the Late Carboniferous and early Permian microflora from Southwest of Sardinia (Pittau and Del Rio, 2002, 2004; Pittau et al., 2002, 2008b).

These latest Carboniferous assemblages from Southwest Sardinia are related to the San Giorgio Basin and the Tuppa Niedda section (Southwest of Sardinia, Italy. Fig. 7A) and their chronostratigraphic assignation probably encompasses the Bolsovian to the Barruelian (“*Pteridophytic, pre-Striatiti*” Palynological Phase. Del Rio and Pittau, 2004; Pittau and Del Rio, 2004). This hypothesis is based on the broad palynological similarities between these assemblages and those of many other European sections (Clayton et al., 1977). These palynofloras are considered to be characteristic of the late Westphalian-early Stephanian ages because they contain a diversity of pteridophytic, sphenophytic, lycophytic and pteridospermaphytic spores and cordaite pollen. In the San Giorgio Basin (Pittau et al., 2008a), the presence of the genera *Spelaeotrilites* and *Kraeuselisporites*, with possible *Kraeuselisporites or- natus*, previously recorded from the Namurian-Westphalian interval in

Western Europe and extending up to the Westphalian-Stephanian(?) in Saudi Arabia (Owens and Turner, 1995) is coherent with their suggestion (Fig. 8). In the Tuppa Niedda assemblage (Pittau et al., 2008a), gymnosperm pollen are mainly represented by *Florinites* species, whereas *Potonieisporites* is very rare. The assemblage includes a large component of representative Late Carboniferous genera, such as *Leio-triletes* (= *Deltoidospora*), *Cyclogranisporites*, *Cadiospora*, *Lophotriletes*, *Convolutispora*, *Microreticulatisporites*, *Reticulatisporites* and *Triquitrites*, which would show a “Stephanian B affinity” for this section (Fig. 8).

It is during the Stephanian age that hygrophilous flora became dominant. The typical Upper Carboniferous ferns of the tedeleacean, zygopteridaceae, gleicheniaceae and boctryopteridaceae groups (such as *Deltoidospora*, *Lophotriletes*, *Punctatisporites*, *Spinosisporites*, *Triquitrites* and *Verrucosisporites*), the marattialean ferns (such as *Thymospora* or *Punctatosporites*) and lycopsids (as *Lycospora*, *Lundbladispota* and *Crassispora*) are present here. The diversification of cordate pollen (such as *Florinites* and *Latensina*) is also characteristic of this period (Fig. 8). The presence of *Potonieisporites* is rare, even though it frequently occurs during such period of time. This proposition is coherent with the microflora found recently in the Saberian stratotype

(Quemadas Formation. Juncal et al., work in progress) located in the Sabero Coalfield (León, Spain). The Saberian microflora corresponds to the *Angulisporites splendidus*-*Latensina trileta* (ST) Zone (Clayton et al., 1977), due to the abundance of *Lycospora pusilla*, *Densosporites* spp., *Laevigatosporites* spp., *Thymospora* sp., *Florinites* spp., and the presence of more or less constant numbers of *Disaccites non striatiti*, *Angulisporites splendidus*, *Latensina trileta*, *Spinoporites spinosus*, *Candidispora* sp. and *Lundbladispota* sp. Furthermore, the Barruelian–Stephanian B boundary was recognised in the Sabero Coalfield (NW Spain) in correlation with the putative Stephanian A (Barruelian)–B boundary identified in the Carmaux Coalfield (south-central of France. Knight and Wagner, 2014). The preliminary age determinations indicate that the lower part of the Saberian corresponds to an age of 302.25 ± 0.28 Ma and 302.13 ± 0.23 Ma (Knight and Wagner, 2014).

5.2. The problematic issue of “Stephanian-Autunian mixed flora”

The diversification of the “Autunian microflora” has not been observed until the latest Carboniferous. A great variety of monosaccate pollen of the genera *Cordaitina*, *Guthoerlisporites*, *Nuskoisporites*, *Plicatipollenites* and *Potonieisporites* have been observed, together with the “Stephanian microflora”. Broutin (1986) distinguishes two palynological zones for these levels.

- 1) The “Zone inférieure” in which the trilete spores are the most abundant. In Guadalcanal (Southwest of Spain, Broutin, 1986), it is characterized by the dominance of *Crassispota plicata* and the absence of the genera *Thymospora* and *Lycospora* (that were presented as relics in some of the studied levels). Also, the absence of the genera *Punctatosporites* and *Densosporites*, linked to the Upper Carboniferous, was observed (Fig. 8). For these reasons, Broutin (1986) suggests a “terminal” Stephanian age for these associations. We also compared the “Zone inférieure” with the classic baseline study of Doubinger (1974), which described the palynological studies of the “Autunian flora” of the French Basins of Autun, Blanzay, l'Aumance, Brive and Lodève (Fig. 7A). Doubinger (1974) distinguishes three associations (A1 to A3). The “Zone A1” is the one that fits best with the Guadalcanal assemblages. The “mixed flora” of “Zone A1” (“lower Autunian age”) is characterized by a decrease in the genera *Thymospora* and *Punctatosporites*, which are replaced by smooth monolet spores of the genus *Laevigatosporites*. the Moskovian palynomorphs reported in the Cantabrian Zone, Bédéro and San Giorgio (such as *Crassispota kosankei*, *Cirratritadites saturni*, *Radiizonates tenuis*, *Savitrissporites camptotus*, *Kraeuselisporites* spp., *Spe-laetotriteles* spp. and *Stoenozonotriteles* spp.) are no longer present, being replaced by monosaccate pollen of the genera *Florinites*, *Potonieisporites*, *Guthoerlisporites*, *Candidispora* and *Wilsonites*. This microflora is characteristic of Assise d'Igornay (Doubinger, 1974), recently dated as late Gzhelian (299.91 ± 0.38 Ma) by Pellenard et al. (2017).
- 2) The “Zone Supérieure” of Broutin (1986) is typically characterized by the very strong dominance of monosaccate pollen. Using a quantitative method and considering the local variation of the composition, this association is quite comparable with “Zone A2” of Doubinger (1974). The “Autunian microflora” of “Zone A2” displays a very scarce presence of “Stephanian elements” (such as the genera *Lundbladispota*, *Triquitites* and *Verrucosisporites*, while the genus *Thymospora* is relict). The genus *Potonieisporites* displaces the *Florinites* and *Wilsonites* genera, and the striated disaccites, monocolpate pollen and striated forms from the genus *Vittatina* are always present. This microflora is characteristic of Assise de Muse (Doubinger, 1974), recently dated as Asselian age (298.57 ± 0.38 – 298.05 ± 0.39 Ma) by Pellenard et al. (2017), and the Tuilière and Usclas, Saint-Privat, from the Lodève Basin (Doubinger, 1974), dated as Sakmarian age (Tuilière -Loiras Fm., 293.85 ± 0.10 Ma. Michel et al., 2015).

The differentiation between the Upper Carboniferous and lower Permian deposits is not obvious when interspersed levels of coal layers (or levels with a higher concentration of organic matter) in Permian deposits appear with a palynological assemblage similar to that of “Stephanian microflora” (e.g. Broutin, 1986; Paquette et al., 1980).

Focusing on this problem, Broutin (1986) proposed a systematic examination that analyzed and compared the microflora of these strata with genuine “Stephanian assemblages”. When “Autunian flora” appears between Stephanian materials (e.g. Doubinger et al., 1979), the immediately subsequent “Stephanian assemblage” occurs without any impoverishment in its composition. In contrast, when “Stephanian flora” appears within lower Permian sediments (e.g. Guadalcanal section, Southwest of Spain, described by Broutin, 1986), the genera *Thymospora*, *Punctatosporites* or *Densosporites* are never observed, probably because they could not survive the first manifestations of climate change, instability and gradual evolution to drier conditions (Broutin, 1986).

Finally, in clearly early Permian sediments, the assemblages contain mainly *Potonieisporites*, striated taxa and other walcchian conifer pollen. Following the recommendations of Broutin (1986), we study the assemblages of Pittau et al. (2002, 2008b) from Guardia Pisano basin (southwest of Sardinia, Fig. 7A) in which *Potonieisporites* spp. is dominant (35–57%), the taeniate and ataeniate disaccate pollen correspond to the 20–25% of the assemblage and the spores are generally very rare (2%) (Pittau et al., 2008b). It is observed the presence of Late Carboniferous microflora as *Densosporites* sp., *Granulatisporites* sp., *Knoxisporites glomus*, *Lavigatosporites vulgaris*, *Lophotriletes* sp., *Lycospora pusilla*, *Punctatosporites minutus*, *Raistrickia* sp., *Spelaeotriletes* sp., *Thymospora* sp. and *Triquitrites* spp., together with Permian taxa *Costapollenites ellipticus*, *Hamiapollenites bullaeformis*, *Limitisporites* sp., *Vittatina* sp. and an atypical presence of genera *Crucisaccites* and *Lueckisporites* (Pittau et al., 2002). The description of these assemblages is comparable with the “Zone inferieure” of Broutin (1986) with dominant taxa (*Potonieisporites* spp.) and some spores presented as relics (*Densosporites*, *Puntatosporites* and *Thymospora*). The assignation of these assemblages to the late Gzhelian is consistent with the absolute dating age obtained in the interlayered volcanic rocks, breccia and lava flow at the base of Guardia Pisano basin (297 ± 5 Ma, Pittau et al., 2002). Also, in the Seui Seulo lacustrine deposits equivalent to the Guardia Pisano Fm. (Seui Seulo Fm., central-eastern Sardinia, Fig. 7A) was assigned to the “*Potonieisporites* Phase”, of early Asselian age by Pittau et al. (2008b). At the top of Seui-Seulo Basin, Gaggero et al. (2017) obtained in rhyolitic ignimbrites a 294 ± 3.0 Ma and 296 ± 4.3 Ma ages. A similar age (295 ± 3.5 Ma, Gaggero et al., 2017) is registered in the dacites capping the Rio su Luda Fm. (Perdasdefogu Basin, central-eastern Sardinia). The macroflora remains obtained in this formation was compared by Broutin et al. (1999) with the Assise de Millery (“Upper Autunian”, Autun Basin, France, Fig. 7A). In Punta Lu Caparoni (Nurra Basin, north of Sardinia, Fig. 7A), a palynological assemblage is reported in Broutin et al. (1999). The assemblage contains a dominance of *Potonieisporites novicus* and *Potonieisporites bhardwajii* (50% of the assemblage) and the taxa *Costapollenites* sp., *Florinites* spp., *Hamiapollenites* cf. *bullaeformis*, *Illinites* spp., *Laevigatosporites* spp., *Limitisporites* spp., *Lundbladispota* cf. *gigantea*, *Nuskoisporites* cf. *dulhuntyi*, *Playfordiaspora crenulata*, *Protophloxypinus samoilovichii*, *Striatoabieites* sp., *Vittatina ovalis* and *Vittatina* sp. The macroflora of Punta Lu Caparoni is also attributed to “Upper Autunian” age by comparison with the Assise de Millery (Broutin et al., 1999) although recent zircon dating indicates 297 ± 1.8 Ma to the Punta Lu Caparoni ignimbrite (Gaggero et al., 2017).

5.3. The age of Grey Unit microflora

In the “Stephanian microflora” the appearance of distinctive elements is key to characterize the Late Carboniferous assemblages. The presence of some Westphalian elements (e.g. *Cirratriradites*,

Kraeuselisporites, *Radiizonates* and *Spelaeotriletes*) would indicate that the sediments are older than strata of other areas with typical Stephanian taxa, such as *Angulisporites splendidus*, *Latensina trileta*, *Lundbladispora gigantea* and *Savitrissporites camptotus*. The proliferation of monosaccate pollen (genera *Florinites*, *Potonieisporites*, *Guthoerlisporites*, *Candidispora* and *Wilsonites*) suggests a “terminal” Carboniferous age. On the other hand, the presence of striated taxa (such as *Vittatina*, *Hamiapollenites* and *Protohaploxypinus*) and bisaccate palynomorphs (e.g. *Jugasporites* and *Gardenasporites*) would indicate a Permian age (Fig. 8).

The Grey Unit shows the presence of “Stephanian microflora” and the diversification of monosaccate pollen such as *Guthoerlisporites* sp., *Nuskoisporites* sp., *Plicatipollenites* sp., *Potonieisporites simplex* and *Potonieisporites novicus*. The presence of Upper Carboniferous elements, such as *Angulisporites splendidus*, *Latensina trileta*, *Lundbladispora gigantea*, *Savitrissporites camptotus* and *Dictyotriletes* sp. (with Stephanian affinity, Fig. 8), in the studied samples, suggests a Gzhelian age. Moreover, the Grey Unit microfloral assemblage is comparable with the “Zone inférieure” of Broutin (1986), which is equivalent to the microflora of Assise d'Igornay (Doubinger, 1974) dated as late Gzhelian (299.91 ± 0.38 Ma, Pellenard et al., 2017).

This age also fits very well with the absolute radiometric ages provided by Pereira et al. (2014), obtained from volcanic rocks interbedded in the Grey Unit deposits in the two neighbouring areas of Coll de Vanses (304.6 ± 1.5 Ma, Fig. 1B) and the Cadí Ignimbrite (300.4 ± 1.4 Ma, Fig. 1B).

Once the age of the Grey Unit is established, a palynological comparison with the Western Europe palynological Zonation of Clayton et al. (1977) is necessary. The *Potonieisporites novicus-bhardwaji* – *Cheiledonites major* (NBM) Zone corresponds to the Assise d'Avaize, the Loire Basin and the Assise d'Igornay (Autun Basin), and is equivalent to the Stephanian C-D (Clayton et al., 1977).

The NBM Zone is characterized by the frequency of *Cheiledonites* spp., *Potonieisporites* spp., *Spinisporites spinosus* and the “top of the epibole” of *Densosporites* spp., and *Savitrissporites camptotus*. Also, in the NBM Zone there is an abundance of the genera *Lycospora*, *Laevigatosporites*, *Punctatosporites*, *Thymospora*, *Spinisporites* and *Florinites*, but also contains Autunian palynomorphs as *Vittatina* spp. and the disaccites striatiti (Clayton et al., 1977).

The presence of *Angulisporites splendidus*, *Florinites* spp., *Laevigatosporites* spp., *Latensina trileta*, *Lundbladispora gigantea*, *Potonieisporites* spp., *Punctatosporites* spp., *Spinisporites spinosus*, and the “disaccites non striatiti” are common on both assemblages.

Although both assemblages have similar age, the Grey Unit assemblage has a hygrophytic affinity due to the presence of *Acanthotriletes*, *Apiculatisporis*, *Deltoidospora*, *Granulatisporites*, *Lophotriletes* and *Punctatosporites*. The outcrops used to define the NBM Zone are characterized by a drier environment with conditions more favourable for the appearance of xerophytic elements such as *Vittatina* and disaccites striatiti.

For the first time in the studied area, it is possible to calibrate a palynological assemblage with absolute ages (Fig. 7A) and thus correlate the beginning of the Post-Variscan continental succession in the western Palaeotethys domain (Fig. 7B). These new palynological data indicate that the Southern Pyrenean basins started their development during the Kasimovian, as in the case of the Lodève basin (Fig. 7A), and continued during the Gzhelian. The Autun basin contains a Gzhelian palynomorph assemblage, but Gzhelian deposits have not been reported in the Lodève basin. This finding indicates significant sedimentary disconnections between neighbouring basins. The Italian basins seem to have begun their deposition before the French and Pyrenean ones, even though the most Upper Carboniferous was not recorded in the easternmost basins (Fig. 7B).

This disconnection between neighbouring basins could be responsible for the differences between the Grey Unit assemblage and the NBM Zone of Clayton et al. (1977). The isolated basins of the Pyrenees acted as a refuge with more favourable conditions for the Carboniferous hygrophilous flora, delaying the appearance of the meso-xerophytic floras.

6. Conclusions

We present the first palynological characterization of the Grey Unit in the Central-Eastern Pyrenees, Northeast Spain. Our palynological data were obtained from levels of the Gzhelian Grey Unit, radio-metrically dated as 304.6 ± 1.5 – 300.4 ± 1.4 Ma. The palynological assemblage obtained from the Grey Unit can be compared with the Assise d'Igornay one, which shows a zircon age of 299.91 ± 0.38 Ma. For the first time, a palynological assemblage has been correlated with absolute ages in the Southern Pyrenees area, providing key information on the chronostratigraphy of the Permo-Carboniferous transition in southern Europe. Based on these results, it is possible to verify the validity of the classical Carboniferous Palynological Zonation of Western Europe and the palynological studies of the “Autunian flora” of the French Basins of Autun, Blanzay, l'Aumance, Brive and Lodève presented in [Doubinger \(1974\)](#). Based on the comparison of our results with previous works, the microflora evolution in the Upper Carboniferous has been described at the low latitudes of the Euramerican Province. Furthermore, a comparison between these assemblages with different dating methods is presented to provide a solid base for stabilizing relationships between flora assemblages and palynostratigraphic schemes in the Euroamerica province and other areas across Pangea.

The Grey Unit Assemblage is Gzhelian in age, as determined by U-Pb dating. This fact is also important for correlating the Post-Variscan continental basins in the Southwestern Palaeotethys, as well as their palaeogeography. The results presented in this study are indicative of a complex and diachronous evolution of these basins during the Late Carboniferous-early Permian. However, the sedimentary filling of the Southern Pyrenean basins and the French Autun basin started probably during the Gzhelian.

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