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Review of the Ediacaran-Lower Ordovician (pre-Sardic) stratigraphic framework of the Eastern Pyrenees, southwestern Europe

M. PADEL[1] S. CLAUSEN[2*] J.J. ÁLVARO[3] J.M. CASAS[4*]

[1]Bureau de Recherches Géologiques et Minières (BRGM)
Z3 Avenue Claude Guillemin, 45100 Orléans, France. E-mail: m.padel@brgm.fr

[2]Unité Mixte de Recherche (UMR), Université de Lille
8198 EEPCNRS, Université de Lille 1, Bâtiment SN5, Avenue Paul Langevin, 59655 Villeneuve d'Ascq Cedex, France.
E-mail: sebastien.clausen@univ-lille1.fr

[3]Instituto de Geociencias (CSIC-Universidad Complutense de Madrid)
Dr. Severo Ochoa 7, 28040 Madrid, Spain. E-mail: jj.alvaro@csic.es

[4]Departament de Dinàmica de la Terra i de l'Oceà - Institut de Recerca Geomodels, Universitat de Barcelona
Martí i Franquès s/n, 08028 Barcelona, Spain. E-mail: casas@ub.eduj

*Corresponding author

ABSTRACT

The Ediacaran-Lower Ordovician successions exposed in the Eastern Pyrenees are updated and revised based on recent U-Pb zircon radiometric ages, intertonguing relationships of carbonate-dominated strata, and onlapping patterns marking the top of volcano-sedimentary complexes. A stratigraphic comparison with neighbouring pre-Variscan outcrops from the Montagne Noire (southern French Massif Central) and Sardinia is related to i) the absence of Cadomian deformation close to the Ediacaran-Cambrian boundary interval; ii) the presence of an episodic, Cadomian-related, acidic-dominant volcanism related to carbonate production punctuating the Ediacaran-Cambrian transition, similar to that recorded in the northern Montagne Noire; and iii) the lack of Guzhangian (Cambrian Epoch 3) regressive shoal complexes present in the Montagne Noire and probably in Sardinia.

KEYWORDS | **Lithostratigraphy. Chronostratigraphy. Palaeogeography. Cambrian. NW Gondwana.**

INTRODUCTION

The Pyrenees is an Alpine intracontinental fold and thrust belt that resulted from the convergence between the Iberian and European plates from Late Cretaceous to Oligocene times (Roest and Srivastava, 1991; Muñoz, 1992). In the Pyrenees, rocks ranging in age from Late Neoproterozoic to Mississipian form an elongated strip in the backbone of the chain, unconformably overlain by Mesozoic and Cenozoic rocks (Fig. 1). This pre-

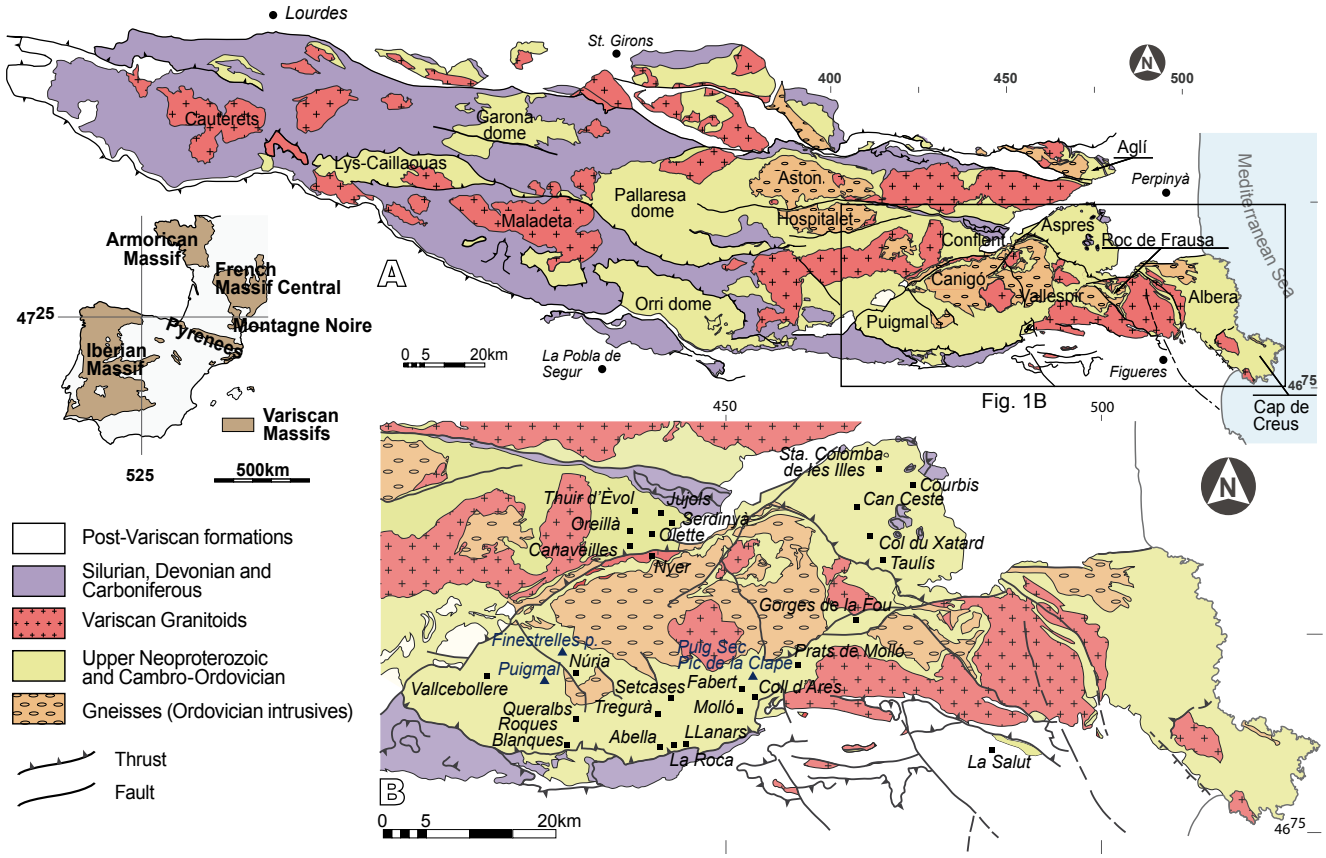

FIGURE 1. A) Simplified geological map of the Pyrenees. B) Geological map of the eastern Pyrenees with localities referred to in the text.

Variscan basement lies geographically disconnected from neighbouring outcrops that also belong to the eastern branch of the Ibero-Armorican Arc, such as the Catalan Coastal Range to the South, the Mouthoumet and Montagne Noire (southern French Massif Central) to the North, and Sardinia to the East.

The lower part of this pre-Variscan succession is made up by a pre-Upper Ordovician succession, more than 3000m-thick, which crops out extensively in the Central and Eastern Pyrenees (Fig. 1). The succession records three different magmatic events (Cadomian, Ordovician and Variscan) and three deformational episodes (related to Sardic, Variscan and Alpine tectonics) together with a Variscan regional metamorphism. As a result, the study area constitutes a key element to reconstruct the geodynamic evolution of Northwest Gondwana form Late Neoproterozoic to Variscan times. However, this is hampered by several factors, such as the monotonous character of an important part of the succession, the lack of a well-preserved fossiliferous record, the complex macrostructure and the absence of a well-established stratigraphic framework. As a result, some palaeogeographic reconstructions and stratigraphic correlations with other basins of NW Gondwana are very hypothetical and the Pyrenees are often absent from most of the palaeogeographic reconstructions of this margin.

The aim of this paper is to propose an updated revision of the Ediacaran-Lower Ordovician (pre-Sardic) stratigraphic framework in the Eastern Pyrenees, based on recent geochronologic data coupled with detailed field work. Previous, emended and new stratigraphic units are formally introduced and subsequently correlated, at the stage level, with neighbouring platforms of the eastern branch of the Variscan Ibero-Armorican Arc. This may allow a comparison with neighbouring pre-Variscan massifs and a better understanding of the initial (pre-Variscan) position of this margin of Gondwana.

GEOLOGICAL SETTING

The study area comprises the Albera/Albères, Cap de Creus, Aspres, Canigó/Canigou (including the Puigmal, Conflent and Vallespir areas) and the Roc de Frausa/Roc de France massifs, and the La Salut Alpine thrust sheet in the eastern Pyrenees (Fig. 1). The pioneer studies on the pre-Variscan exposures of these areas considered the existence of a Precambrian basement, *i.e.* the orthogneissic dome

of the Canigó, Roc de Frausa or Albera massifs, covered by a Cambro-Ordovician succession that, in turn, started with a characteristic marble bed (Autran *et al.*, 1966; Autran and Guitard, 1969; Guitard, 1970; Vitrac-Michard and Allègre, 1975). Roussel (1893, 1904) was the first to attribute a Precambrian-Cambrian age to these marbles bordering the Canigó orthogneiss ("marbre de base" *sensu* Guitard, 1970; Laumonier and Guitard, 1986; Laumonier *et al.*, 1996; Barbey *et al.*, 2001). The geochronological reappraisal of the pre-Variscan magmatic rocks, including the Canigó, Aston-Hospitalet, Albera and Roc de Frausa gneiss, as Ordovician intrusives, drastically changed previous stratigraphic interpretations (see *e.g.* Deloule *et al.*, 2002; Cocherie *et al.*, 2005; Castiñeiras *et al.*, 2008; Denèle *et al.*, 2009; Casas *et al.*, 2010; Liesa *et al.*, 2011; Martínez *et al.*, 2011; Mezger and Gerdes, 2016). Current macrostructural models describe a complete Ediacarian-Lower Ordovician succession, later intruded by uppermost Lower-Middle Ordovician and Upper Ordovician plutons. Moreover, recent geochronologic data provide evidence of an Ediacaran magmatic event lasting 30Ma that gave rise to the protoliths of felsic metavolcanic rocks, metabasites and small bodies of orthognessic bodies (*e.g.* Mas Blanc and Port gneiss in the Roc de Frausa and Cap de Creus massifs, respectively: Cocherie *et al.*, 2005; Castiñeiras *et al.*, 2008; Casas *et al.*, 2015; Padel *et al.*, 2018). Up to now, no tectono-metamorphic event related to this Ediacaran magmatism has been described in the Pyrenees.

In the Canigó Massif, Cavet (1957) defined the two principal pre-Sardic stratigraphic units of the Eastern Pyrenees, the Canaveilles and Jujols Schists Series, later assigned to groups (Laumonier and Guitard, 1986; Laumonier, 1988; Laumonier *et al.*, 1996, 2004, 2015a, b) (Fig. 2). Both the geologic mapping at a scale of 1:50,000 made in the Eastern Pyrenees by the Spanish and Catalan Geological Surveys (Instituto Geológico y Minero de España (IGME) and Institut Carogràfic i Geològic de Catalunya (ICGC)), respectively; Carreras *et al.*, 1994; Cirés *et al.*, 1994a,b, 1995; Muñoz *et al.*, 1994) and the French Geological Survey (Bureau de Recherches Géologiques et Minières (BRGM)) (Llac *et al.*, 1988; Guitard *et al.*, 1998; Autran *et al.*, 2004; Donzeau *et al.*, 2010; Calvet *et al.*, 2012; Laumonier *et al.*, 2015a, b) have been trying to correlate and homogenise the pre-Sardic lithostratigraphic units throughout the Central and Eastern Pyrenees. However, a formal definition of formations and members (including stratotype designation, selection of contacts and intertonguing relationships) are commonly absent. The modification of lithological content and lithostratigraphic boundaries in homonymous units has led to nomenclatural confusion. In addition, the correlation throughout numerous massifs remains contentious. The scarcity of biostratigraphic data in the Ediacaran-Lower Ordovician succession (Abad, 1988; Perejón *et al.*, 1994; Casas and Palacios, 2012) has been partly compensated by reporting of geochronologic U/Pb dating of zircon of interbedded metavolcanic rocks (Cocherie *et al.*, 2005; Castiñeiras *et al.*, 2008; Casas *et al.*, 2015; Padel, 2016; Padel *et al.*, 2018).

As other neighbouring Palaeozoic massifs, such as Sardinia and the Montagne Noire, the Pyrenean succession contains a Middle Ordovician gap and unconformity that may be related to a Mid-Ordovician uplift and denudation, the so-called Sardic Phase (Santanach, 1972; Casas and Fernández, 2007; Álvaro *et al.*, 2016).

STRATIGRAPHIC FRAMEWORK

As stated above, the lithostratigraphic framework of the Pyrenees has been in a permanent nomenclatural flux

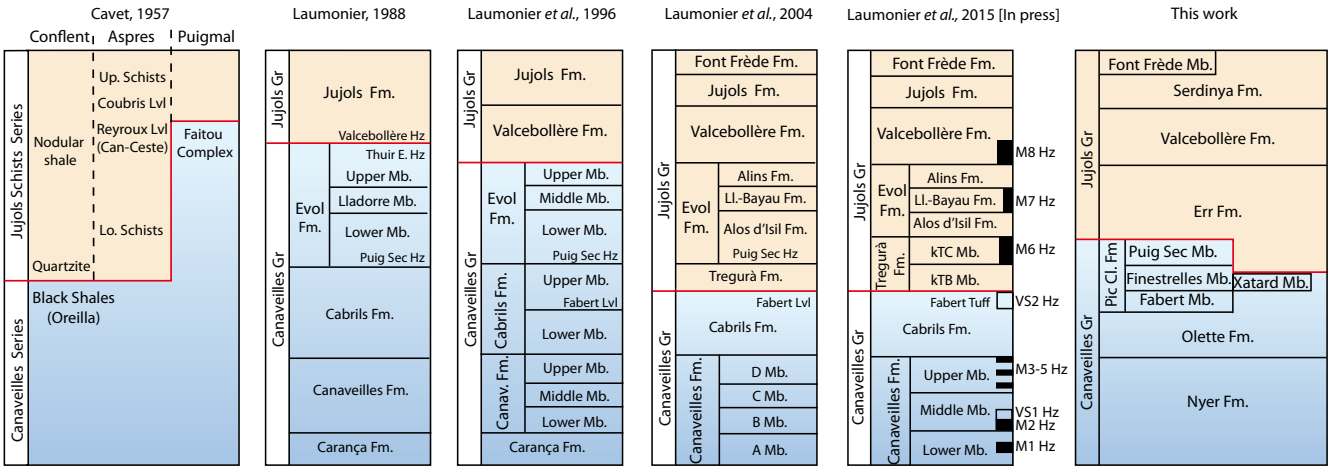

FIGURE 2. Evolution of the Ediacaran-Lower Ordovician lithostratigraphic nomenclature in the Eastern Pyrenees (Fm.: Formation; Gr: Group; Hz: Horizon; Lvl: Level; Lo: Lower; M: Marble; Mb.: Member; VS: Volcanosedimentary; Up: Upper). A correlation between the subunits of the Jujols Schists Series was not introduced by Cavet (1957) and is, therefore, tentative.

throughout successive Spanish and French geological maps (Fig. 2), which needed revision. Consequently, an updated revision of the Ediacaran-Lower Ordovician stratigraphic framework in the Eastern Pyrenees is proposed below based on recent U-Pb radiometric ages, intertonguing relationships of carbonate-dominated strata and onlapping relationships capping volcano-sedimentary complexes (Fig. 3). Previous nomenclatures have been maintained if their lithologies and original bases and tops have suffered no changes; otherwise, a new nomenclature is proposed to avoid ambiguities among lithostratigraphic units that have been used to represent different lithologies and contacts in successive geological maps. Exception is made with the Canaveilles and Jujols groups: although their contact has been continually modified, their nomenclature is maintained due to traditional use.

Canaveilles Group (emended)

The Canaveilles Series was broadly defined by Cavet (1957) to encompass the lowermost carbonate-bearing levels interbedded in a monotonous schist-dominant succession. Then, this heterolithic succession was interpreted as directly onlapping a Precambrian gneissic dome, the so-called Canigó Massif. According to Cavet (1957), the base of the Canaveilles Series was located at the contact between the Cadomian orthogneisses and the micaschist cap, whereas its top was placed between some black shales cropping out across Oreilla and Olette villages (Conflent area in the northern slope of the Canigó Massif; Fig. 1B) and some quartzitic levels that were attributed to the Jujols Schists Series (Fig. 2). The resulting Canaveilles Series extended throughout the Albera, Aspres, Cap de Creus, Canigó and Roc de Frausa massifs (Fig. 1). Subsequently, Laumonier and Guitard (1986), Laumonier (1988) and Laumonier *et al.* (1996) successively redefined the Canaveilles Series as a group subdivisable into the Canaveilles, Cabrils and Evol formations (fms.) (Fig. 2). Recently, Laumonier *et al.* (2004, 2015a) excluded the Evol Formation (Fm.) from the Canaveilles Group and included it into the overlying Jujols Group. The Canaveilles Group, as reviewed herein, contains scattered volcanogenic levels (the so-called "gneiss granulés" of Guitard and Lafitte, 1956), and is covered, in the southern slope of the Canigó Massif, mainly in the Puigmal and Vallespir areas, by a thick volcanosedimentary complex. A part of the latter has been mapped and reported in previous works as the so-called Tregurà conglomerates (Cirés *et al.*, 1995) or Tregurà Fm. (Laumonier *et al.*, 2004), which mark the top of a succession characterized by the episodic presence of volcanic products that have not yet been reported in the overlying Jujols Group. Despite the everlasting nomenclatural modifications proposed for the Canaveilles Group, this lithostratigraphic unit is worldwide known and the toponymy is maintained herein. The thickness of the group, as revised below in the Eastern Pyrenees, was estimated between 2 and 3km by Laumonier *et al.* (2004).

The basal formation of the Canaveilles Group (Canaveilles Fm. *sensu* Laumonier *et al.*, 2015a) is renamed here Nyer Fm. to remove potential ambiguity between a group and its homonymous formation (see Owen, 2009) (Fig. 3). The Olette Fm. is restricted herein to the upper carbonate-free, shale-dominated package of the Cabrils Fm. *sensu* Laumonier *et al.* (2015a). The uppermost rhyolitic tuffs, volcano-sedimentary complexes and carbonate interbeds recognized in the Puigmal area (a part of Tregurà and Evol fms. *sensu* Laumonier *et al.*, 2004; Fabert level or VS2 *sensu* Laumonier *et al.*, 2015a; kTB Member (Mb.) *sensu* Laumonier *et al.*, 2015b) are grouped below in the Pic de la Clape Fm. (Fig. 3, section 3).

Nyer Formation (new)

The Canaveilles Fm. *sensu* Laumonier *et al.* (2004, 2015a) is renamed here Nyer Fm. after the homonymous village, near of Canaveilles village situated in the Conflent area (northern slope of the Canigó Massif) (Fig. 1). It is the basal unit of the Canaveilles Group and is restricted to the Eastern Pyrenees, where it is broadly crosscut by Variscan and Sardic intrusions. The stratotype is located along the road D28 around the Canaveilles village (42º31'58.80"N-02º15'6.54"E). Two parastratotypes are proposed: i) along the neighbouring road N116 (base at 42º31'59.62"N-02º15'11.36"E) and ii) between Queralbs and the Núria sanctuary, close to the Freser dome that represents the southern prolongation of the Canigó Massif (base at 42º22'2.59"N-02º9'28.36"E).

The Nyer Fm. (Figs. 3; 4A, B), about 2000m-thick, is a heterolitic succession dominated by micaschists and subsidiary marbles, metasandstones, metabasites and, at least, one metaryodacite layer (Guitard and Laffite, 1956; Guitard, 1970; Ayora and Casas, 1986; Casas *et al.*, 1986; VS1 of Laumonier *et al.*, 2015a). The latter, 10 to 200m-thick, is exclusively recognized to the South of the Canigó Massif.

Laumonier *et al.* (2015a) differentiated at least 5 marble marker-beds (M1 to M3-5; Fig. 3), up to 300m-thick, and selected the top of the fifth one as the base of the overlying Cabrils Fm. However, the number of marble interbeds varies throughout the tectonostratigraphic units due to both intertonguing and tectonic truncations, and the marble interbeds lack any chronostratigraphic control. A single radiometric constraint is yielded by the volcanic level VS1 that, according to Laumonier *et al.* (2015a), overlies M2 to the South of the Canigó Massif. However, the age of VS1 (580±10Ma; Cocherie *et al.*, 2005), obtained by U-Pb

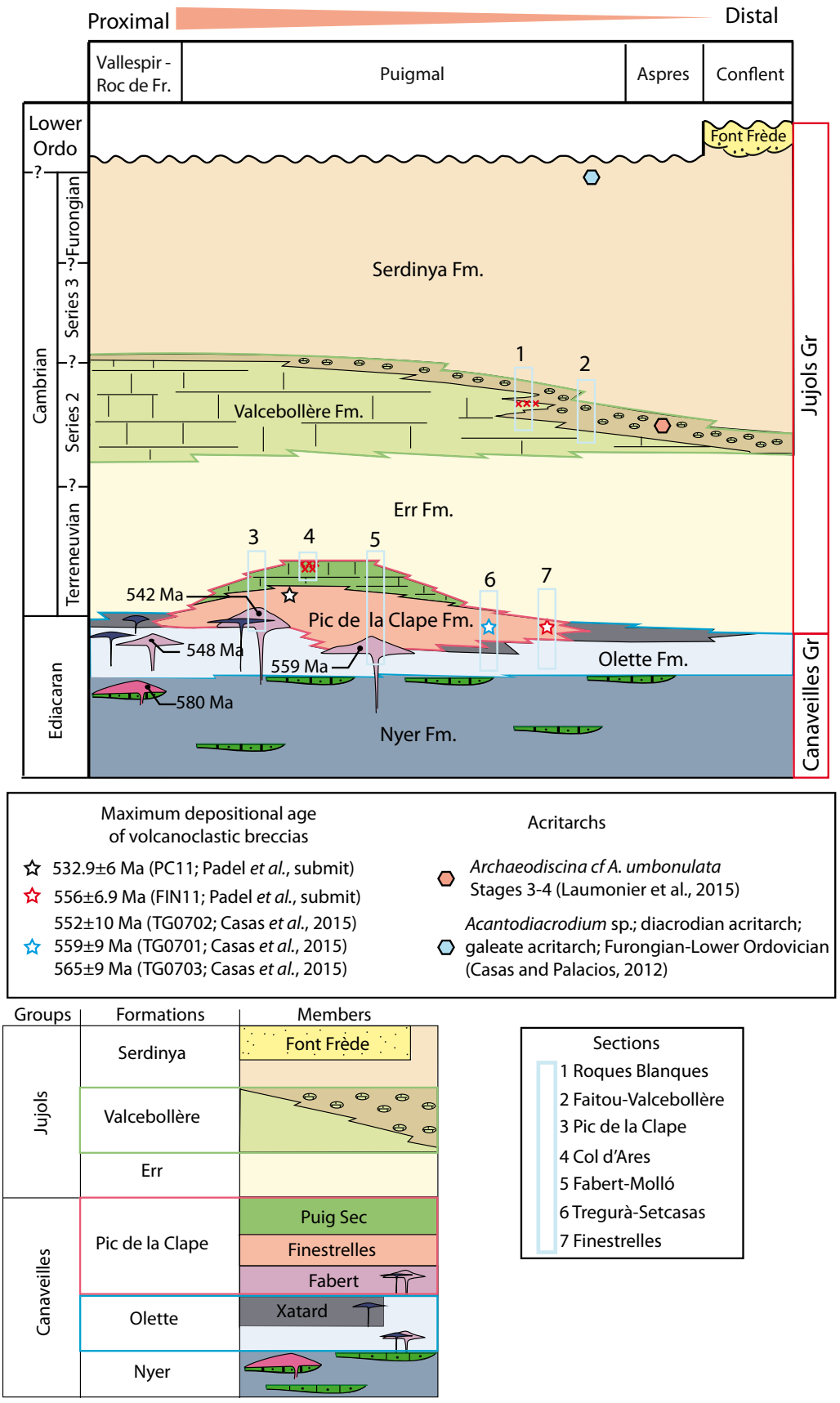

FIGURE 3. New stratigraphic framework proposed for the Ediacaran-Lower Ordovician of the Eastern Pyrenees; not at scale.

dating on zircon, should be re-evaluated due to the selected method (see discussion in Padel, 2016 and Padel *et al.*, 2018). At present, the lateral correlation of the M1-M5 marble beds included in the Nyer Fm. may be considered as tentative. M3-M5 marbles are unknown in some areas, such as the northeast of Núria sanctuary in the Freser dome, near Taulis village at the northeast of the Canigó Massif, and to the southeast of Prats de Molló-la Presta village in the Vallespir area, as a result of which, the Nyer/Olette contact is not distinct to the North of the Canigó dome (Donzeau *et al.*, 2010; Laumonier *et al.*, 2015b).

The maximum thickness of the Nyer Fm. was estimated by Laumonier *et al.* (2015a) in the Queralbs area. However, this estimate includes a North dipping thrust that situates the Nyer marble interbeds over the Cambrian Valcebollère marble package. As a result, the maximum thickness of the Nyer Fm. should be re-evaluated.

Olette Formation and Xatard Member (new)

The Olette Fm. (uppermost Canaveilles Series in the Conflent area by Cavet, 1957) represents the marble-free and shale-dominant part of the Cabrils Fm. *sensu* Laumonier *et al.* (1996, 2004, 2015a) (see Fig. 3). The upper volcanic level (Fabert level *sensu* Laumonier *et al.*, 1996), overlain by a volcano-sedimentary complex locally rich in carbonate clasts, was described as the upper member of the Cabrils Fm. to the South of the Canigó Massif (Laumonier *et al.*, 1996). Laumonier *et al.* (2004) informally defined the Tregurà Fm. to include these conglomerates and considered it as the lowermost part of the Jujols Group. By contrast, the underlying Fabert metarhyolitic level was selected to mark the top of the Canaveilles Group. As both volcanogenic episodes are genetically related (Padel, 2016; Padel *et al.*, 2018), and the resulting volcanosedimentary complex is episodically punctuated with carbonate interbeds, the Fabert volcanic level, the overlying volcano-sedimentary "conglomerates" (or breccias) and the Puig Sec Horizon *sensu* Laumonier (1988) that cap the whole volcanic episode are included below as members of the Pic de la Clape Fm.

The Olette Fm. (Fig. 3) conformably overlies the Nyer Fm. and is overlain by either the Pic de la Clape Fm. or the Err Fm. The Olette Fm., 400–500m-thick, consists of greenish and black shales, schists, greywackes and arkoses. The uppermost black shales of the formation, commonly named "graphite schists", "ampelites" or "schistes carburés" by previous authors (Casas *et al.*, 1986; Guitard *et al.*, 1998; Laumonier *et al.*, 2015a), are included here in the Xatard Mb.

The stratotype of the Olette Fm. is selected along the Cabrils river (42º33'49.18"N-02º15'24.42"E), in the Conflent area, and the stratotype of the Xatard Mb. along the road D13, near the Col du Xatard (42º33'12.36"N-02º37'0.66"E) in the Aspres Massif. A parastratotype of the Xatard Mb., located in the Conflent area, broadly coincides with the Oreilla Schists of Guitard *et al.* (1998), recognized between Oreilla and Olette villages, along the D4 road and to the South of the Pic Lluomet. These black shales are well exposed in the Puigmal area, between Catllar valley and Setcases village, along the road GIV 5264. In its stratotype, the base of the Xatard Mb. is visible, but its top is faulted (Laumonier *et al.*, 2015a). The top is distinct on the right cliffy bank of the Ter river at the Tregurà section (42º21'30.68"N-02º17'34.44"E), where it is marked by the occurrence of the tuffaceous sandstones and volcanoclastic breccias that belong to the overlying Pic de la Clape Fm. The latter is absent in the Aspres massif and in the Conflent area, where the Err Fm. conformably overlies the Xatard Mb.. The latter pinches out laterally, grading northward into the greenish shales of the Err Fm.

Pic de la Clape Formation (new)

The Pic de la Clape Fm. (Figs. 3; 4C, D) includes a succession of genetically related volcanic pulsations linked to episodes of carbonate production. The formation is subdivided, from bottom to top, into i) the Fabert level *sensu* Laumonier *et al.* (1996) and VS2 *sensu* Laumonier *et al.* (2004, 2015a), named Fabert Mb. herein; ii) the Finestrelles Mb., corresponding to the Tregurà conglomerates (Cirés *et al.*, 1995) and a part of the Tregurà Fm. *sensu* Laumonier *et al.* (2004) and the basal volcano-sedimentary member of the Tregurà Fm. (kTB) *sensu* Laumonier *et al.* (2015b); and iii) the Puig Sec Mb. (Puig Sec Horizon *sensu* Laumonier, 1988; kTC or M6 *sensu* Laumonier *et al.*, 2015a). These three members are genetically linked and are representative of a major tectono-magmatic pulsation recording episodes of carbonate production (Padel, 2016; Padel *et al.*, 2018).

The Pic de la Clape Fm. crops out to the South of the Canigó massif in the Vallespir and Puigmal areas and in the Roc de Frausa Massif, around the Tregurà and Fabert villages, and at the Pic de Finestrelles and Pic de la Clape summits. Its type section is defined at the summit of Pic de la Clape (42º23'47.64"N-02º26'40.99"E). The age of the Pic de la Clape Fm. is late Ediacaran to Terreneuvian based on new and revised U-Pb dating (Padel, 2016; Padel *et al.*, 2018).

The Fabert Mb. (Fig. 3), up to 50m-thick, crops out discontinuously from the Puigmal to the Vallespir areas and Roc de Frausa Massif. Its stratotype is located along the Fabert Torrent, 200m East of its homonymous village. Guitard and Lafitte (1956) referred this unit to as "gneiss granulés" and interpreted them as metamorphized volcanic or volcano-sedimentary protoliths. The Fabert

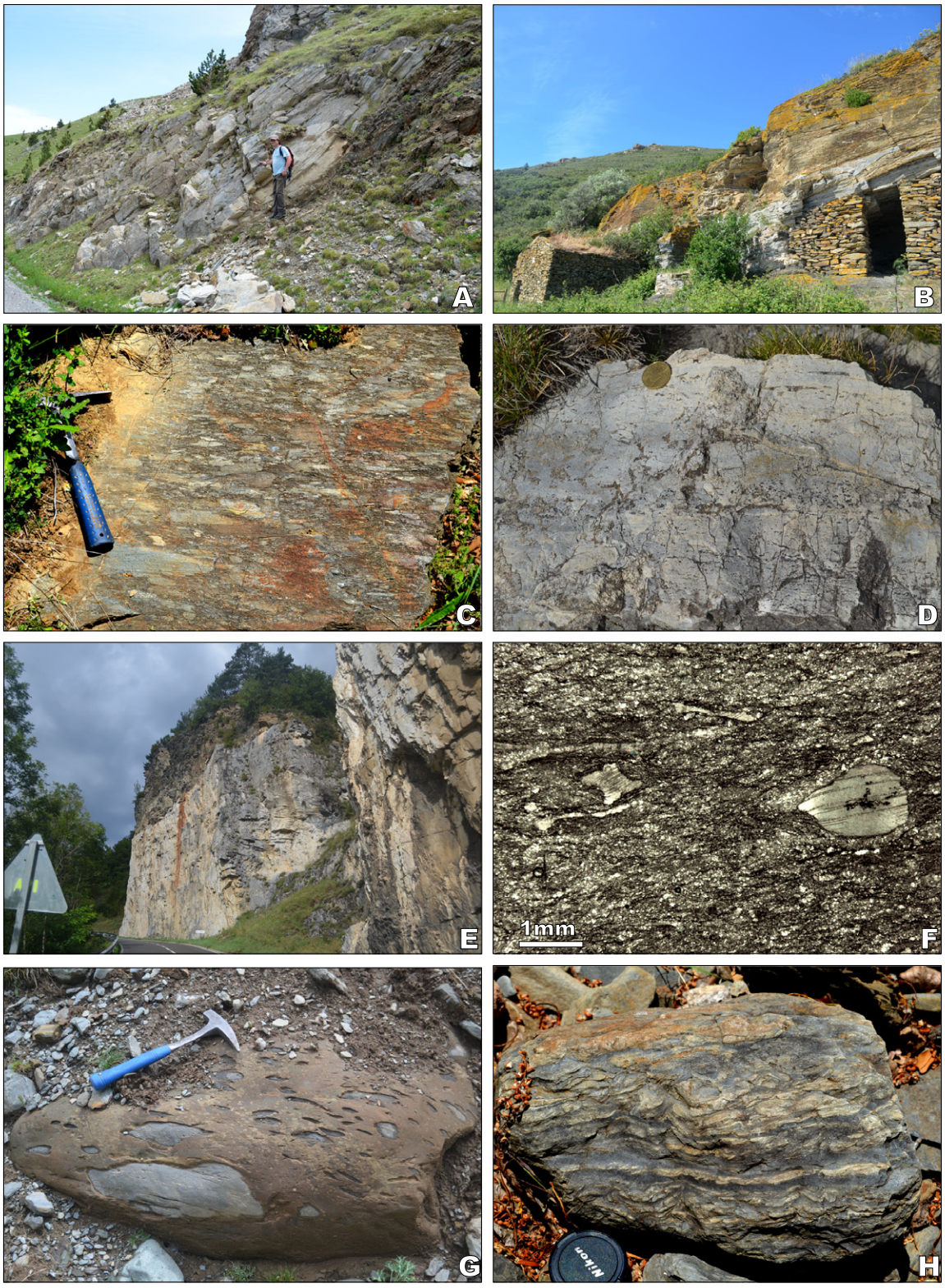

FIGURE 4. A) Decametre package of marble strata from the Nyer Fm. in Espinelves; B) Decametre package of marble and dolostone strata from the Nyer Fm. close to Cap Norfeu; C) Volcanosedimentary breccia marking the basal part of the Finestrelles Member (Pic de la Clape Fm.) close to Tregurà village; D) Fenestral and microbial limestones of the Puig Sec Member (Pic de la Clape Fm.) at the Coll d'Ares pass; E) Valcebollère/Serdinya contact close to Roques Blanques; F) Thin-section photomicrograph of the Valcebollère limestones from the "crête frontière", in the vicinity of the homonymous village, showing disarticulated echinoderm ossicles; G) Massive shales bearing centimetric-to-decimetric marble nodules marking the topmost of the Valcebollère Fm. and mimicking the Iberian "facies rizada" or French "schistes troués" at Queralbs valley; H) Typical aspect of the Serdinya Fm., characterized by contorted and finely laminated clayey/silty alternations at Ravierou creek.

level *sensu* Laumonier *et al.* (1996) or VS2 of Laumonier *et al.* (2015a) is considered herein as a metarhyolithe (Padel, 2016; Padel *et al.*, 2018), which exhibits lenticular shapes and conformably overlies fine- to medium-grained quartzo-feldspatic greywackes (Olette Fm.). At the Pic de la Clape, a basic lava flow is interbedded in the member. In the Puigmal area, two divergent radiometric ages were estimated for the Fabert metarhyolites: 559.1+1.75/-1.35Ma near Fabert village, and 542.9+5/-1.30Ma at the Pic de la Clape (Padel, 2016; Padel *et al.*, 2018), suggesting this unit does not record a single volcanic event but successive pulsations. In the Roc de Frausa Massif, an acidic tuff lying in the Olette Fm. was dated at 548±8Ma (Concordia Age, n=7) by Castiñeiras *et al.* (2008). These ages and the stratigraphic position of sampled rocks confirm that the upper part of the Olette Fm. was contemporaneous with the Fabert Mb. (Fig. 3).

The Finestrelles Mb. (Figs. 3; 4C) is a heterolithic unit, up to 500m-thick, composed of tuffaceous sandstones, volcanoclastic breccias and subsidiary shale and pristine-to-volcaniclastic limestone interbeds showing sharp intertonguing relationships and common scouring discontinuities. The matrix of the volcanoclastic breccia and tuffaceous sandstone is variously carbonate cemented. Locally (*e.g.* in the uppermost Tregurà-Setcases section, 42º20'36.04"N-02º17'52.95"E), massive volcanoclastic breccias include carbonate boulders up to 2m across. The stratotype of the Finestrelles Mb. is selected at the summit of its homonymous hill (42º24'30.54"N-02º7'29.76"E; section 7 in Fig. 3), to the NW of the Núria sanctuary, where it consists of about 150m of volcanoclastic breccia, tuffaceous limestone sandstone and shale preserved in inverse position. There, U-Pb dating of zircon of a tuffaceous sandstone has yielded a maximum depositional age of 556±6.9Ma (Padel, 2016; Padel *et al.*, 2018). The volcanoclastic deposits of the Finestrelles Mb. conformably overlie both the Olette Fm. in the Finestrelles and Setcases-Tregurà sections, and the Fabert Mb. in the Molló-Fabert and Pic de la Clape sections. The member is overlain by both the Puig Sec Mb., in the Molló-Fabert and Pic de la Clape sections, and onlapped by the Err Fm., in the Finestrelles and Setcases-Tregurà transects (Fig. 3). The Finestrelles Mb. was previously dated by Casas *et al.* (2015) on three samples collected near the Tregurà village, and obtained ages of 569.7±4.8Ma, 567.8±5.8Ma and 575.1±3.6Ma. Padel *et al.* (2018) suggest recalculating these ages as a maximum (re)depositional age and propose new ages of 559±9Ma, 552±10Ma and 565±9Ma respectively, based on the three youngest, concordant and equivalent dates within error.

A parastratotype of the Finestrelles Mb. lies at the summit of the Puig Sec Mb.. There, the fine- to medium-grained matrix of the greywacke interbeds is depleted of carbonate cement; limestone clasts and boulders are also absent. U-Pb dating of zircon of breccias from this parastratotype has yielded a maximum depositional age of 532.9±6Ma (Padel, 2016; Padel *et al.*, 2018). Rejuvenation of the maximum depositional age *versus* age of the underlying metarhyolithe, attest that the breccias deposited during cogenetic volcanic activity (Padel, 2016; Padel *et al.*, 2018).

The Puig Sec Mb. (Puig Sec Horizon *sensu* Laumonier, 1988; M6 and kTC *sensu* Laumonier *et al.*, 2015b; Figs. 3; 4D), up to 180m-thick, consists of the bedded and massive limestone, dolostone and marble strata that cap the Finestrelles Mb. The base of the member is well exposed in the Fabert-Molló transect (42º21' 3.10"N-02º24'26.06"E; section 5 in Fig. 3), and its top with the Err Fm. at the parastratotype of Col d'Ares (42º22'2.80"N-02º27'17.00"E; section 4 in Fig. 3) and the summit of Pic de la Clape (42º23'20.49"N-02º25'55.29"E; section 3 in Fig. 3). The stratotype is located at the Puig Sec Mb. (42º23'40.00"N-02º25'56.36"E).

Jujols Group (emended)

The Jujols Group (Figs. 3 and 4E–G) was firstly described as the Jujols Schists Series by Cavet (1957) and comprised a monotonous succession of shale/sandstone alternations. However, Cavet (1957) included in the "Series" what is now considered a succession of Upper Ordovician conglomerates and volcanic deposits. The latter are distinctly post-Sardic, underlain by a significant unconformity and, therefore, must be excluded from the Jujols Group (Laumonier, 1988). According to Cavet (1957), the base of the Jujols Schists was characterized by the presence of gray shales with carbonate nodules and quartzite interbeds. Laumonier (1988) elevated the Jujols Schists Series *sensu* Cavet (1957) and Jujols Series of Laumonier and Guitard (1986) as an invalid group including a single, eponymous formation. Subsequently, Laumonier *et al.* (1996) included in the Jujols Group the so-called Valcebollère Fm. (previously described as a horizon), which consisted of bedded and massive limestones/marbles and shales with carbonate nodules (see Cavet, 1957; Laumonier *et al.*, 2004, 2015a), and extended the Jujols Group to include the Tregurà, Evol, Valcebollère, Jujols and Font Frède fms. Consequently, three carbonate levels, interstratified within the mostly siliciclastic Jujols Group, were recognized in the Eastern Pyrenees by Laumonier *et al.* (2015a) (Fig. 3): the Puig Sec Horizon or M6 (uppermost part of the Tregurà Fm.), the Lleret Bayau Fm. or M7 (including the Can Ceste and Reyroux levels of Cavet, 1957, invalidly incorporated into the Evol Fm.), and the Valcebollère Fm. (M8, including the Courbis level of Cavet, 1957). The lowermost marble level, called Puig Sec Horizon by Laumonier (1988) and Laumonier *et al.*

(1996), corresponds to the new Puig Sec Mb. that should not be separated from the Pic de la Clape Fm. because similar lithologies and facies occur interbedded in its Finestrelles Mb.. The two uppermost levels (Lleret-Bayau and Valcebollère fms.) never co-occur in a same continuous section, whatever the tectonostratigraphic unit. In addition, only the Coubris (~Valcebollère Fm.) level of Cavet (1957), from the Aspres Massif, has been biostratigraphically constrained (acritarch record mentioned in Laumonier *et al.*, 2015a). Therefore, in the absence of indisputable lithologic markers and until better age constraints are available, we consider herein that these two carbonate levels cannot be stratigraphically differentiated in the Eastern Pyrenees. Thus, the Valcebollère Fm. is the only considered carbonate level herein as we consider that the Lleret-Bayau limestones should be part of the Valcebollère Fm.

As a result, the base of the Jujols Group coincides with the base of the Err Fm. (Fig. 3), which onlaps the palaeorelief formed by the Pic de la Clape Fm. to the South of the Canigó Massif. Where the Pic de la Clape Fm. is absent, the Err Fm. conformably overlies the Olette Fm. The top of the Jujols Group is highlighted by the Middle-Upper (pars) Ordovician hiatus associated with the Sardic Phase (Dégardin *et al.*, 1996; Casas and Fernández, 2007; Laumonier *et al.*, 1996, 2004, 2015a; García-Sansegundo *et al.*, 2004; Casas and Palacios, 2012). The thickness of the group can be estimated at about 3 to 4km.

Err Formation (new)

As mentioned above, the limits and content of the Evol Fm. *sensu* Laumonier *et al.* (1996, 2004, 2015a) has often changed through time (Fig. 3). In addition, the invalid inclusion of the Lleret-Bayau Fm. is not recognized herein in the Eastern Pyrenees. Therefore, the new Err Fm. is defined as a siliciclastic-dominant succession, either depleted or containing some scattered carbonate interbeds.

The Err Fm. is considered as a relatively monotonous shale-dominant, up to about 2000m-thick unit (Figs. 3; 4). It consists of gray to brownish and greenish shale and centimetre-to-decimetre thick, fine-grained sandstone interbeds, locally punctuated by gravelly sandstone ("microconglomérat" *sensu* Laumonier *et al.*, 1996, 2004, 2015a). These sandstones never exceed 10m of thickness and can be observed: i) in the Puigmal area, near the summit of the Puigmal (42º22'28.54"N-02º7'5.85"E) and ii) at the Pic de la Clape Fm. (42º23'31.60"N-02º26'26.91"E) where they overlie the Puig Sec Mb. These sandstones are also well developed in the Aspres Massif and the Conflent area. The base of the Err Fm. is well exposed at the Pic de Finestrelles, where it conformably overlies the Finestrelles Mb., and its top to the South of the Pic de Duraneu, where it is conformably overlain by the Valcebollère Fm. (42º22'43.01"N-02º4'32.54"E). Its stratotype is located near the summit of the Puigmal (42º22'29.04"N-02º7'18.90"E).

Valcebollère Formation (emended)

The Valcebollère Fm. consists of a lower massive-to-bedded limestone-to-marble package (up to 300m-thick), overlain and grading westward to a 15 to 200m-thick, shale/carbonate alternation that changes upsection into green shales bearing carbonate nodules (Figs. 3; 4E–G). The thickness of the formation diminishes northward. The stratotype of the Vacebollère Fm. was defined to the South of the Canigó Massif (42º22'37.14"N-02º4'35.34"E), to the East of the Valcebollère village, between the Duraneau and Puigmal summits, along the Faitou valley (Laumonier *et al.*, 1996). There, Cavet (1957) described a greenish and shaly-carbonate alternation (named the Faitou Complex), which was included into the Canaveilles Series. Laumonier (1988) named it the Valcebollère horizon and was then proposed to mark the base of the Jujols Group, directly overlying the Thuir d'Evol carbonate horizon (defined in the Conflent area). Laumonier *et al.* (1996) subsequently grouped the Thuir d'Evol and Valcebollère horizons in a single Valcebollère Fm., thus lowering the base of the Jujols Group. They correlated the Valcebollère Fm. with the massive carbonate levels of Carliba (Vallespir area) and Llanars (Puigmal area). Laumonier *et al.* (2004) revised the Jujols Group marking its base at the base of the Tregurà Fm.

A parastratotype is selected at the Roques Blanques section, along the road N260 (42º18'47.22"N-02º8'48.29"E; section 1 in Fig. 3). The upper part of the formation is crosscut by the road and consists of two massive carbonate packages, 10 to 30m-thick, separated by a thin 5–8m-thick green marly interval (Fig. 4E).

Thick, massive limestones are absent in the Faitou-Valcebollère section (section 2 in Fig. 3) (where the former Faitou Complex was defined by Cavet, 1957), along the Faitou valley (42º22'37.14"N-02º4'35.34"E).

Remarkable outcrops of the Valcebollère Fm. occur in the Puigmal area close to Llanars, la Roca and Abella villages (42º19'28.63"N-02º20'23.30"E); in the Vallespir area along the Gorges de la Fou (42º27'33.35"N-02º36'24.90"E); and in the Aspres Massif, along the road D2 near Sainte Colombe de las Illas (42º37'24.31"N-02º38'28.15"E). Finally, in the Conflent area, the formation is exposed to the North of the Thuir d'Evol village (Fig. 1B).

The Courbis Limestone of the Valcebollère Fm. in the Aspres Massif (Fig. 1B) has yielded the acritarch

Archaeodiscina cf. *umbonulata* VOLKOVA, 1968. *A. umbonulata* is a cosmopolitan species ranging approximately from Cambrian Age 3 to Early Cambrian Age 4 (Laumonier *et al.*, 2015a; T. Palacios, personal communication, 2016). Associated with the Courbis Limestone, some centimetric layers of grainy phosphorites have been identified, for the first time, marking the topmost part of the Valcebollère Fm.

Serdinya Formation (new) and Font Frède Member

In the Jujols Schists Series of the Aspres Massif, Cavet (1957) differentiated two siliciclastic units (named lower and upper Jujols Schists) that overlie the carbonate interbeds of the Valcebollère Fm. In the Aspres Massif, the Serdinya Fm. defined herein corresponds to the Upper Jujols Schists *sensu* Cavet (1957) once excluded the (post-Sardic) Upper Ordovician deposits. In the remaining tectonostratigraphic units, the new Serdinya Fm. corresponds to the Jujols and Font Frède fms. *sensu* Laumonier *et al.* (2004). Cavet (1957) characterized this part of the succession by the presence of lenticular and coarse-grained sandstones (the so-called "micro-conglomérates") alternating with quartzite and shale strata. In the northern part of the Aspres Massif, Laumonier (1988) and Laumonier *et al.* (1996, 2015a) reinterpreted the coarse sandstones of the Jujols Upper Schists (*i.e.* Mas d'Escossy) as cropping out in reverse position and deposited below the Valcebollère Fm., so as part of the Evol Fm. (former Alins Fm.). New reconnaissance fieldwork questions this interpretation, as depositional structures (scouring bases and grading of coarse-grained sandstones) suggest an opposite way-up. In addition, as we consider here the Coubris, Can-Ceste and Reyroux levels as part of the Vacebollère Fm., we interpret the overlying coarse-grained sandstone strata as part of the Serdinya Fm. In addition, the rank of the Font Frède Fm. *sensu* Laumonier *et al.* (2004) is changed into member within the Serdinya Fm. due to reduced lateral extension and gradual character of its basal part.

The stratotype of the Serdinya Fm. is located near the Col Diagre, in the Conflent area (42°35'2.40"N-02°16'35.90"E). This formation consists of gray to greenish shales alternating with centimetre to decimetre-thick sandstone beds. The Serdinya Fm. (Figs. 3 and 4E) conformably overlies the Valcebollère Fm. and is topped by the Sardic unconformity. Acritarchs recovered from the uppermost part of the Serdinya Fm. in the southern slope of the Canigó Massif (Puigmal area) has yielded a broad Furongian-Early Ordovician age (Casas and Palacios, 2012).

PALAEOGEOGRAPHIC TRENDS AND CORRELATION WITH SURROUNDING PYRENEAN UNITS

In the southern slope of the Canigó Massif (Puigmal and Vallespir areas) and in the Roc de Frausa Massif, the top of the Canaveilles Group is marked by the presence of volcano-sedimentary complexes (Fabert and Finestrelles members) capping a monotonous succession of shales and greywackes (Olette Fm.). The influence of volcanic outflows away from this area is limited, as stated by the absence of the Finestrelles Mb. in the northern Conflent area and Aspres Massif. The presence of the Puig Sec Mb., which developed on topographic highs of these volcano-sedimentary complexes, is also recognized in the same southern massifs.

The Valcebollère Fm. displays a distinct southeast-to-northwest proximal-distal trend of lithologies (Fig. 3), grading from massive-to-bedded marbles/limestones in the Puigmal (Llanars, la Roca, Abella and Roques Blanques) and Vallespir (Gorges de la Fou) areas to shale/carbonate alternations and shales bearing carbonate nodules parallel to stratification in the northern areas (Faitou-Valcebollère section, Fig. 3) (Fig. 1B). Obviously, this lithological gradation from massive carbonates to shales bearing centimetric nodules (facies known as "schistes troués" in the Montagne Noire and "facies rizadas" in the Iberian Chains; Courtessole, 1973; Álvaro and Vennin, 1997) characterizes a northwestward pinching out of carbonate production. The thickness of the formation also decreases westward and northward, as observed in the Conflent area and Aspres Massif.

Laumonier *et al.* (1996, 2004) proposed different correlations throughout the Central and Eastern Pyrenees. Three areas are selected here for comparison: the Cap de Creus Massif, the Pallaresa dome (Central Pyrenees) and the La Salut Alpine thrust sheet.

Recent research on the pre-Sardic, volcano-sedimentary deposits in the Cap de Creus Massif (Fig. 1) did not include the local stratigraphic setting in any broader lithostratigraphic framework (Carreras *et al.*, 1994; Losantos *et al.*, 1997; Carreras and Druguet, 2013), precluding any detailed correlation with the lithostratigraphy of the Eastern Pyrenees (see remarks in Laumonier *et al.*, 1996). Recently, a volcano-sedimentary succession has been described including U/Pb dating of zircon (Castiñeras *et al.*, 2008; Casas *et al.*, 2015). These authors dated several metarhyolithic tuffs, one at the base of the succession yielded an age of 577±3Ma (Casas *et al.*, 2015) whereas the metatuffs located at the uppermost part of the succession yielded radiometric ages of 560.1±10.7Ma, (Castiñeiras *et al.*, 2008), 563.2±4.5Ma, and 557.9±3.0Ma (Casas *et al.*, 2015). Based on published age distribution curves and new field observations, these levels are reinterpreted herein as volcanoclastic breccias mimicking the Finestrelles Mb. (Fig. 5). Their recalculated maximum depositional age, based on Casas *et al.* (2015) data, ranges from 570.2±2.0Ma to 541.7±9.2Ma (see

methodology in Padel, 2016). Consequently, the volcano-sedimentary series developed in the Cap de Creus Massif can be considered herein as reflecting the easternmost development of the volcanic episodes recorded by the Finestrelles Mb.. Further correlation of the pre-Sardic deposits of the Cap de Creus Massif with surrounding Pyrenean areas would require detailed reappraisal and dating of the complete succession.

Zandvliet (1960), Wennekers (1968), Hartevelt (1970), Zwart (1979) and García-Sansegundo (1992) contributed, among others, to the elaboration of the pre-Sardic stratigraphic framework in the Central Pyrenees. In the Pallaresa dome (Central Pyrenees), a thick (>4000m) siliciclastic-dominant succession crops out from the Certascan Lake to the Llavorsí syncline (Laumonier *et al.*, 1996). It is divided into three formations (Laumonier *et al.*, 1996): the Alos d'Isil, Lleret-Bayau and Alins fms. The base of the Alos d'Isil Fm. is in tectonic contact with Devonian strata (Laumonier *et al.*, 1996) and is crosscut by Variscan intrusions and Ordovician metagranites. The top of the Alins Fm. is unconformably overlain by the Upper

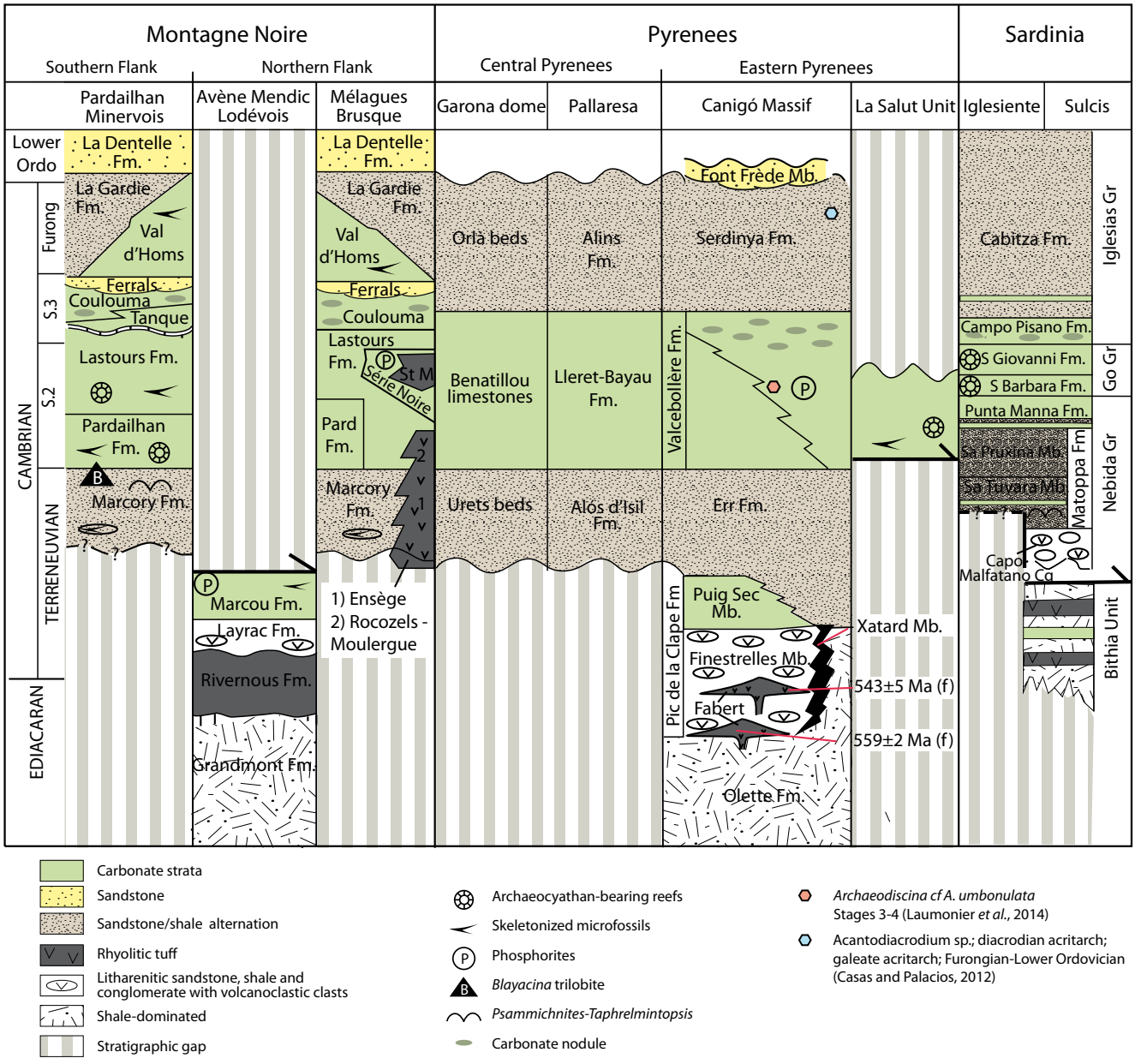

FIGURE 5. Stratigraphic comparison of the Ediacaran-Lower Ordovician successions from the Montagne Noire, the Eastern Pyrenees and Sardinia. SPZ: Southern Pyrenean Zone; S: Series; Furong: Furongian; Ordo: Ordovician; Pard: Pardailhan; St M: St Meen; Go Gr: Gonnesa Group; Fm.: Formation; Mb.: Member; Gr: Group; Cg: conglomerate. See text for explanation.

Ordovician Rabassa conglomerate Fm. (Zandvliet, 1960; Zwart, 1979). The Alos d'Isil and Alins fms. are dominated by shales locally alternating with thin- to medium-grained sandstones. They are separated by the metasandstones and marbles of the Lleret-Bayau Fm. These formations were studied by Zandvliet (1960) and redefined by Zwart (1979), who suggested their lateral equivalence with the Jujols Schists Series *sensu* Cavet (1957), broadly equivalent to the Jujols Group as reviewed above. Laumonier *et al.* (1996, 2004) correlated the Pallaresa series with the Evol Fm. from the Eastern Pyrenees (Fig. 5). However, as mentioned above, the Lleret-Bayau Fm. of Laumonier *et al.* (2015a, b) cannot be lithologicaly differentiated from the Valcebollère Fm. and both formations never co-occur in a single section, as a result of which both units should be synonymized (see discussion above). It is also noticeable that all the carbonate units in the Central Pyrenees (*i.e.* Lleret Bayau Fm. from the Pallaressa dome and Ransol Fm. from the Hospitalet Massif) were considered as synonymous, and grouped in the Lleret Bayau Fm. in the Aspres Massif (Can Ceste, Riuros and Coubrils limestones; Eastern Pyrenees) (Fig. 1B) by Laumonier *et al.* (1996, 2004). Early Cambrian acritarchs were subsequently reported from the Coubris limestone (Eastern Pyrenees), which was moved from the Lleret-Bayau to the Valcebollère Fm., whereas all other previously reported limestone levels remained in the Lleret-Bayau Fm. without further lithological arguments (Laumonier *et al.*, 2015a, b), despite the lack of any other geochronologic or biostratigraphic control. Finally, Laumonier (2015a, b) considered both the Lleret-Bayau and Valcebollère fms. as lateral equivalents of the Palaeozoic rocks of the La Salut thrust sheet (Laumonier *et al.*, 1996, 2004, 2015a, b).

Considering the fluctuating concepts and correlations of the Lleret-Bayau Fm., and the lack of any other stratigraphic constraint, we suggest the Pallaressa succession should be correlated with the Jujols Group (as revised above), being the Alos d'Isil, Lleret-Bayau and Alins fms. lateral equivalents of the Err, Valcebollère and Serdinya fms., respectively (Fig. 5). In the same way, the Jujols Group may be correlated with the pre-Sardic rocks of the Garona Dome, which have been subdivided into three terms by García-Sansegundo and Alonso (1989), from bottom to top: the Urets beds, the Bantaillou limestone and the Orlà beds. Again, these terms may be equivalent to the Err, Valcebollère and Serdinya fms., respectively (Fig. 5). Tentatively, the Culet limestones cropping out more to the west, in the Lis-Caillaouas Massif (Bouquet *et al.*, 1999) may be also correlated with the Vallcebollère Fm.

The Palaeozoic rocks of the La Salut Alpine thrust sheet (Fig. 1B), up to 50m-thick, is the only Cambrian formation of the Pyrenees bearing shelly fossils. Abad (1988) described the presence of archaeocyathan patch reefs alternating with green to brownish shales, and assigned the sponges to the Cambrian Age 3. Restudies by Perejón *et al.* (1994) and Menéndez *et al.* (2015) confirmed a late Cambrian Age 3. Current investigation on skeletonized microfossils from peri-reefal limestones suggests a Cambrian Age 3-4 (Padel, 2016). The detailed preservation of pristine microfacies and microbial textures in these limestone strata, contrasting with the traditional marble aspect of any Cambrian carbonate from the Eastern Pyrenees, points to an allochthonous provenance of this Alpine thrust sheet (Pujadas *et al.*, 1989), where the Cambrian limestones thrust Eocene strata and, in turn, are unconformably overlain by Eocene strata. Biogeographic affinities of archaeocyaths point to close similarities with similar assemblages from SW Sardinia and the Montagne Noire (Perejón *et al.*, 1994). Transverse (N-S trending) displacement related to the Alpine deformation is about 150-160km (Muñoz, 1992), so the original Palaeozoic basin should be located northward from present-day arrangement. A lateral prolongation of the archaeocyath-bearing carbonates cropping now in SW Sardinia and southern Montagne Noire may be envisaged.

CORRELATION WITH SURROUNDING DOMAINS FROM NW GONDWANA

Since the pioneer work of Cavet (1957), the Ediacaran-Lower Ordovician succession of the Pyrenees has been traditionally compared to chronostratigraphically constrained successions from the Montagne Noire (southern French Massif Central). These lithostratigraphic correlations between both Variscan massifs have remained, up to recently, the main way to interpolate the age of the Canaveilles and Jujols groups (Cavet, 1957; Laumonier *et al.*, 1996, 2004). The stratigraphic framework of the southern and northern Montagne Noire has recently been updated (Álvaro *et al.*, 1998, 2014) and better constrained based on recent biostratigraphic (Devaere *et al.*, 2013, 2014) and geochronologic studies (Roger *et al.*, 2004; Pitra *et al.*, 2012; Padel *et al.*, 2017).

In the Avène-Mendic parautochthon of the northern Montagne Noire, the metarhyolites of the Rivernous Fm. (542.5±2.4Ma and 539.2±2.7Ma; Padel *et al.*, 2017b) and the volcaniclastic breccias and litharenites of the Layrac Fm. would represent the lateral equivalents of the Fabert and Finestrelles members of the Pic de la Clape Fm., respectively (Fig. 5). Underlying both volcanogenic units, the sulfidic black shales and arkoses of the Grandmont (Avène-Mendic parautochthon) and Olette fms. (Eastern Pyrenees) are consequently age-correlated, dating their uppermost part as late Ediacaran. In the same way, a common episode of carbonate productivity can be correlated throughout the overlying Marcou Fm. (Cambrian Age 2-3) of the Mélagues

thrust slice in the northern Montagne Noire (Devaere *et al.*, 2013) and the Puig Sec Mb. of the Pic de la Clape Fm. (Puigmal area). The Valcebollère Fm. and, as tentatively suggested above, the Lleret-Bayau and the Bantaillou limestone fms. from the Central Pyrenees, can be confidently considered as representative of the important Cambrian Age 3-4 episode of carbonate production highlighted by the Lastours and Pardhailhan fms. (Álvaro *et al.*, 2010) (Fig. 5). The upper part of the Valcebollère Fm. (limestone/shale alternations and monotonous shales bearing carbonate centimetre-thick nodules) is laterally equivalent with the La Tanque-Coulouma transition. A distinct lithological difference between the Eastern Pyrenees and the Montagne Noire is marked by the absence, in the former, of the Guzhangian (regional Languedocian) regression represented by the onset of the Ferrals Fm. (Álvaro *et al.*, 2007). The regression recorded by the input of sandstones marking the uppermost part of the Serdinya Fm. (Font Frède Mb.) may represent the onset of the early Tremadocian regression represented in the Montagne Noire by the La Dentelle Fm. (Fig. 5).

The 1500–3000m-thick Cambrian-to-Lower Ordovician succession of Sardinia is divided into the Nebida, Gonnesa and Iglesias groups (Pillola, 1990). In the Malfatano Cap, the base of the Nebida Group is represented by the polygenic and volcanoclastic Malfatano Conglomerate Mb. of the Matoppa Fm. (Costamagna *et al.*, 2008; Costamagna, 2015). The Bithia Fm., a complex package including metarhyolithes, schists and marbles, underlies these conglomerates at the Malfatano Cap and is commonly presented as the basal unit of the succession (Costamagna, 2015). However, age, thickness and contacts of the Bithia Fm. are still debated (Pillola *et al.*, 1998; Costamagna *et al.*, 2008; Costamagna, 2015). Some biostratigraphic data suggest a Precambrian to earliest Cambrian age (Pittau Demelia and Del Rio, 1982; Gandin *et al.*, 1987; Bechstädt and Boni, 1994). Costamagna (2015) recovered some metamorphised archaeocyaths from the marbles of the Bithia Fm. but their poor preservation precludes any precise taxonomic determination. Bechstädt *et al.* (1988) considered the Bithia Fm. as a metamorphized tectonic repetition of the overlying formations. However, U-Pb dating of metavolcanic rocks reported an Ordovician age for this formation (457.01±0.17Ma, CA-TIMS, Pavanetto *et al.*, 2012; 462.1±4.3Ma, LA-ICPMS, Cruciani *et al.*, 2018). The Malfatano Conglomerate Mb. of the Matoppa Fm. is considered herein as the base of the Cambrian succession until the significance of the Bithia Fm. is solved. This member is interpreted as reflecting the last stage of the Cadomian Orogeny by Costamagna (2015). The Malfatano Metaconglomerate is therefore suggested herein as a possible equivalent of the Finestrelles Mb. (Eastern Pyrenees) and the Rivernous and Layrac fms. (northern Montagne Noire). The lower siliciclastic deposits of the Sa Tuvara Mb. (Matoppa Fm.) overlie the metaconglomerate and should represent a lateral equivalent of the Err (Eastern Pyrenees) and Marcory (Montagne Noire) fms. The upper carbonate and siltstone alternations of the Matoppa Fm. have yielded a Cambrian Age 3-4 fauna (Pillola, 1990) which was correlated with the Pardailhan Fm. of Montagne Noire (Álvaro *et al.*, 2010) (Fig. 5).

The Matoppa Fm. is conformably overlain by the Punta Manna Fm., the uppermost heterolithic unit of the Nebida Group. The following Gonnesa Group is mainly composed of massive archaeocyathan-bearing carbonates. This group can be correlated with the Lastours Fm. in the southern Montagne Noire (Álvaro *et al.*, 2010). The upper part of the Matoppa Fm., the Punta Manna Fm. and the Gonnesa Group were deposited during the Cambrian Epoch 2 and are interpreted as lateral equivalents of the Valcebollère Fm. and La Salut limestones (Fig. 5). The carbonate sequence of the Gonnesa Group is overlain by the Iglesias Group, which begins with the carbonate-shale alternations and/or nodular limestones of the Campo Pisano Fm. that can be considered as a lateral equivalent of the Coulouma Fm. (Álvaro *et al.*, 2003, 2010) and the upper part of the Valcebollère Fm. The Campo Pisano Fm. is conformably overlain by the fine-grained siliciclastic rocks of the Cabitza Fm., correlated herein with the Serdinya Fm.

In SW Sardinia, according to Loi *et al.* (1995), a regressive trend culminating with local coarse-grained sandstones, is recognized in the middle member of the Cabitza Fm. (*sensu* Gandin and Pillola, 1985; Pillola, 1989), biostratigraphically represented by the so-called CAB-4 fossil assemblage, correlatable with the late Languedocian. This sandy-dominant level might represent the Ferrals regression, but somewhat delayed in time. The Acerocare Regressive Event is proposed close to the Cambrian-Ordovician boundary, which lies at the so-called Cabitza "tubi" part and is directly overlain by the first occurrence of Tremadocian graptolites (CAB-6; Loi *et al.*, 1995). Therefore, the lack of the Guzhangian Ferrals Fm. regression in the Eastern Pyrennes, present in the Iberian Peninsula, the Montagne Noire and somewhat diachronous in SW Sardinia, might be related to peneplanation of source areas, unable to yield coarse-grained sediments.

The South-North, proximal-distal palaeogeographic trend recorded in the Ediacaran-Lower Ordovician of the Eastern Pyrenees is repeated across the Axial Zone-southern-northern (proximal-to-distal) Montagne Noire transect. Moreover, the biogeographic affinity displayed by the archaeocyaths of the Alpine La Salut thrust sheet, and the comparative analysis of zircon provenance (Padel, 2016) point to closer palaeogeographic affinities between the Eastern Pyrenees and Sardinia than between the Pyrenees and the Montagne Noire. As a result, in addition to the estimated 150-160km accumulated in a South-North

Alpine displacement of the Pyrenean thrust sheets (Muñoz, 1992), other pre-Alpine movements may be envisaged to solve the present-day relationship between the Pyrenees and the Occitan Domain (*sensu* Álvaro *et al.*, 2016). Dextral shearing along the southern branch of the South Armorican Shear Zone, between 315-305Ma (Martínez-Catalán, 2012 and references therein), may account for an original westernmost position of the Montagne Noire and the French Central Massif in pre-Variscan, early Palaeozoic times.

CONCLUSIONS

From recent U-Pb zircon radiometric ages, paleontological data and stratigraphic relationships, based mainly on the position of conspicuous carbonate levels, a new stratigraphic succession for the pre-Ordovician succession of the Eastern Pyrenees is proposed. The Eastern Pyrenees display a (pre-Sardic) Ediacaran-Lower Ordovician succession like neighbouring basins of the eastern branch of the Ibero-Armorican Arc, such as those recorded in the Montagne Noire and SW Sardinia. A distinct volcanic activity is episodically recorded in the Ediacaran Canaveilles Group, characterized by interbedded metabasites and the onset of acidic-dominated volcanosedimentary complexes (Pic de la Clape Fm.) which led to the episodic development of carbonate production on the top of volcanogenic palaeoreliefs (Puig Sec Mb.) in the southern (palaeogeographically proximal) part of the Eastern Pyrenees. The influence of the Cadomian Orogeny and development of carbonate platforms across the Ediacaran-Cambrian boundary interval mimics the evolution recorded in the Montagne Noire. The Cambrian Series 2 comprises another episode of carbonate production (Valcebollère Fm.) similar to those recorded in the Montagne Noire (Pardailhan and Lastours fms.) and SW Sardinia (upper part of the Nebida Group and Gonnesa Group). A distinctive lithology characterizes the Cambrian Series 3, due to the absence of the Guzhangian Ferrals Regression (Montagne Noire) and the dominance of clayey-dominated substrates across Furongian and earliest Tremadocian times (Serdinya and Cabitza fms. in the Eastern Pyrenees and SW Sardinia, respectively). Based on acritarchs, we suggest the Font Frède Mb. as representative of the regressive conditions documented by the onset of the Tremadocian La Dentelle Fm. An unconformable and erosive contact marks the top of the Ediacaran-Lower Ordovician succession, represented by the onset of the Sardic Phase.

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