



## Transitional environments of the lower Maastrichtian South-Pyrenean Basin (Catalonia, Spain): The Fumanya Member tidal flat



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### ABSTRACT

Sedimentological, palaeontological and geochemical data provide detailed evidence of a marine-to-lagoon environmental succession around the Campanian-Maastrichtian boundary in the Ibero-Armorican domain. This regression is recorded by the succession of several environments of the south-central Pyrenees basin: open marine mixed shelf, marine restricted mixed shelf (both rudist-rich), tidal flat, lagoon and fluvial dominated. The tidal flat setting belongs to the Fumanya Member here described, which is the base of the Posa and Massana formations (Trempe Group). The Fumanya Member is 5 m thick, is built up of marly limestones and was an elongated tidal mudflat (100 km long, 25 km wide) developed in a foreland trough and was separated from the Atlantic Ocean by an island-barrier system. In the lagoon environment, marginal marine waters and continental fresh waters alternated as documented by geochemistry and fossil molluscs. The Fumanya Member is a dinosaur megatracksite, reporting the roaming activity only of sauropods in tidal flats, a likely secure area against predators. Feeding activity of these herbivores took place in the lagoonal-lacustrine environments of the Posa Formation above the Fumanya Member.

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### 1. Introduction

The Campanian–Maastrichtian boundary event is a significant interval in global environmental change, as observed in the oceanic record (see Jung, Voigt, & Oliver, 2012; Voigt, Gale, Jung, & Jenkyns, 2012) that was characterized by climatic cooling and sea-level fall. Here, we study the regression that took place around the Campanian–Maastrichtian boundary in the Southern Pyrenees (north-eastern Iberia, Ibero-Armorican domain), when fully marine palaeo-environments were replaced by the transitional and continental. Here we study this regression in terms of sedimentology, geochemical determinations and palaeontology. Of particular interest is the understanding of the Brontopodus ichnofacies from the

Fumanya megatracksite.

The studied rocks and fossils mainly belong to the Trempe Group (Cuevas, 1992), a reference record for the continental and transitional environments during the Maastrichtian in the Southern Pyrenees. The uniqueness of this record is due to the geological features (well exposed, thick and continuous sections) and the palaeontological content (environmental and taxonomic diversity). More than 150 fossil localities, described in many studies, exist. So, in the following lines, we only refer to some significant works where abundant references can be found. The plant record has several significant sites (see Villalba-Breva et al., 2015 and references). Invertebrates are common and were the goal of classical studies (Vidal, 1874). Vertebrates include pterosaurs (Dalla Vecchia et al., 2013), crocodylians (Puértolas, Canudo, & Cruzado-Caballero, 2011; Vila, Castanera, Marmi, Canudo, & Galobart, 2015), turtles (Marmi et al., 2012a), amphibians and squamate reptiles (Blain, Canudo, Cuenca-Bescós, & López-Martínez, 2010), and fish (Kriwet, Soler-Gijón, & López-Martínez, 2007; Marmi, Vila, Oms, Galobart, & Cappetta, 2010b). Dinosaur bones and teeth include

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titanosaurid sauropods (Vila et al., 2012), nodosaurid ankylosaurs, dromaeosaurid theropods (Torices, Currie, Canudo, & Pereda-Suberbiola, 2015), and hadrosauroid ornithomimids (Casanovas-Cladellas, Santafé-Llopis, & Isidro-Llorens, 1993; Riera, Oms, Gaete, & Galobart, 2009; Pereda-Suberbiola et al., 2009; Prieto-Márquez, Dalla Vecchia, Gaete, & Galobart, 2013). Dinosaur footprints and eggs are also remarkable (Loópez-Martínez, Moratalla, & Sanz, 2000; Sellés et al., 2013; Vila, Oms, Marmi, & Galobart, 2008; Vila et al., 2011).

The Fumanya site is not only an outstanding ichnological site, but also provides a very complete palaeontological record describing the whole ecosystem. In this work, we formally introduce the 'Fumanya Member' (abridged 'Fumanya Mb', see Figs. 1 to 4 and suppl. Figs. 1 to 4). The reason for introducing this unit is to better understand basin correlation and evolution to provide the palaeoenvironmental setting of these significant palaeontological sites. The formal definition of this unit follows the standard requirements of the Murphy and Salvador (1998) criteria. This member takes the name of the Fumanya abandoned village and the palaeontological sites that have the same name. For easy access and outcrop quality, the 'Fumanya sud' site (Vila, Oms, Marmi, & Galobart, 2008) can be used as the typical section (42°10'47.05"N, 1°47'46.40"E, see suppl. Figs. 3I, 4D) since very good exposures of the top of this member occur (sections 14, 15 and 16). An interpretation centre is under construction in this area. The nearby Sant Corneli mining village (Barcelona Province, Catalonia, Spain) is a good point from which to observe a cross section of the Fumanya Mb. This outcrop (42°10'58.58"N, 1°51'10.85"E) is adjacent to the village square and is where Section 19 was measured (suppl. Figs. 4A, B, C).

The first description of the Fumanya Mb was restricted to the Vallcebre syncline in the unpublished report by Aeppler (1967). Open cast coal mining activities from the late 1980s left the top of the Fumanya Mb exposed. Miners called this exposed rocks the concrete/cement level ('nivell dels ciments') since it was industrially processed to obtain cement. This level is the equivalent of the Fumanya Mb and was the sterile rock just below the exploited lignites. The Fumanya Mb top displayed abundant dinosaur footprints that were first mentioned by Viladrich (1986) and later by Le Loeuff and Martínez-Rius (1997) and Schulp and Brox (1999). Further works on the Fumanya site have shown it to contain some 3500 titanosaurid footprints (Vila et al., 2008), dated at ca. 71.5 Ma (Oms et al., 2007). Despite the ichnological interest of the Fumanya site and other nearby outcrops (Vila, Oms, & Galobart, 2005, 2013), it has been the subject of other palaeontological research, including palaeobotany (Marmi, Gomez, Martín-Closas, & Villalba-Breva, 2010a, 2012b; Villalba-Breva, Martín-Closas, Marmi, Gomez, & Fernández-Marrón, 2012), vertebrate palaeontology (Marmi, Vila, & Galobart, 2009), palaeo-ecology (Marmi, Vila, Martín-Closas, & Villalba-Breva, 2014) and heritage (Bates et al., 2008). To date, the sedimentological study of the Fumanya Mb has been restricted to the Vallcebre syncline (Riera, Marmi, Oms, & Gomez, 2010) but here its study is expanded both laterally (basin scale) and vertically (older and younger adjacent strata) to understand how the regression of the South-Pyrenean basin around the Campanian–Maastrichtian boundary took place and led to the sedimentation of the Tremp Group.

## 2. Geological setting

The sedimentary rocks and palaeontological content studied here belong to the South-Pyrenean Foreland Basin, located in the Pyrenees, the fold-and-thrust belt formed at the boundary between the European and Iberian plates. The Pyrenees have an east–west trend and are built up of a Variscan basement and a mainly

Mesozoic and Cenozoic cover. During the Late Cretaceous, this cover underwent thin skinned tectonics that was responsible for a complex foreland basin evolution. Two main foreland basins were developed: the south and north Pyrenean zones (present-day Spain and France, respectively). In the Southern Pyrenees (see references in Muñoz et al., 2013), several cover thrust sheets formed as a result of tectonic inversion, including the Bóixols-Sant Corneli, Montsec, Serres Marginals, Pedraforca and Cadí thrust sheets (see Fig. 1A, B). These sheets and thrusts are currently reactivated (out of sequence thrust propagation) but originally were growth structures confining foreland depocentres of several tens of kilometres. The tectonic balanced cross sections show that several thrust sheets underwent significant displacements, while others were hardly displaced. Generally, the footwall of these thrusts develops synclines acting as basin depocentres. These synclines are those of Àger, Tremp, Coll de Nargó, and Vallcebre (see Fig. 1B). In the north-eastern Pyrenees the Serra del Cadí thrust sheet remains as the most 'autochthonous' unit (Vergés & Martínez, 1988), while the Pedraforca thrust sheet was displaced from north of the first thrust.

The Late Cretaceous–Palaeocene sedimentary infill of the South-Pyrenean Basin is known as the Tremp Formation (Mey, Nagtegaal, Roberti, & Hartelvelde, 1968), although the informal term 'Garumnian' (Leymerie, 1862) is also widely used (see historical review in Rosell, Linares, & Llompard, 2001). Cuevas (1992) elevated the Tremp Fm category to that of the Tremp Group and Pujalte and Schmitz (2005) refined the boundaries of this last unit. The maximum thickness of the Tremp Gr is variable and ranges from 400 to 800 m. This is as a result of variations in space availability for sediment accumulation, which is ultimately related to the role of tectonic growth structures (thrusting and related diapirism). In the Tremp Basin, the base of the Tremp Formation is partially diachronic (Fig. 1B) with the Upper Campanian–Maastrichtian Areny/Arén sandstone or Areny/Arén Fm (Mey et al., 1968) and its lateral equivalents, such as Les Serres Limestone (Souquet, 1967) in the Àger basin. The top of the Tremp Fm is a marine transgression of lower Ypresian age (see integrated review in Eichenseer & Luterbacher, 1992).

The review of all the stratigraphic units found in the Garumnian is complex and completely outside the scope of this paper, so just a brief comment is provided here following the scheme of Rosell et al., (2001), who successfully divided the Garumnian (Fig. 1B) throughout the whole South-Pyrenean Basin into four units. The palaeogeographic evolution of these units can be found in Gómez-Gras et al. (2015). The first unit is the Grey Garumnian, which is the equivalent of the Posa Formation (Cuevas, 1992) in the Tremp Basin and the Massana Fm in the Àger basin (Colombo & Cuevas, 1993). These are similar formations, being the first of lagoonal and lacustrine origin (grey lutites, fine-grained sandstones, coals and charophyte limestones) and the second only of lacustrine (charophyte limestones and marls). The Posa Fm can be expanded to the Cadí area and the Vallcebre syncline (lithofacies 1 to 5 in Oms et al., 2007). The second unit is the Lower Red Garumnian of fluvial origin (mudstones and sandstones) with scarce levels of palustrine lacustrine origin (limestones). The third unit is the Vallcebre limestones and lateral equivalents, originated in lacustrine and palustrine (palaeosoils) settings, respectively. The fourth unit is the Upper Red Garumnian of fluvial, alluvial, lacustrine and palustrine origin (mudstone, sandstones, conglomerates and limestones). The two first units are Maastrichtian in age and the two second, Palaeocene. In the Grey Garumnian, the review by Rosell et al., (2001) did not mention what is here defined as the Fumanya Mb, which turns out to be an important stratigraphic unit in understanding the origin of the Tremp Group. In the scheme of these last authors, the Fumanya Mb would be the very base of the Grey Garumnian (also the very base of the Posa and Massana

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