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The upper Maastrichtian dinosaur fossil record from the southern Pyrenees and its contribution to the topic of the Cretaceous–Palaeogene mass extinction event

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ABSTRACT

In the present paper, the fossil record of the archosaurs (dinosaurs, crocodylomorphs and pterosaurs) of the southern Pyrenees before the Cretaceous–Palaeogene (K–Pg) transition is revised. On the basis of this fossil record, a well-dated succession of dinosaurs and other archosaurs is established within polarity magnetochrons C30 and C29r. Almost 150 sites with dinosaur remains have been identified, containing hadrosauroid ornithopods, titanosaur sauropods and theropods, as well as egg sites and tracks. Fossil remains of dinosaurs and other archosaurs are abundant in C29r, disappearing abruptly near the top of the "Lower Red Garumnian" unit of the Tremp Formation. Thus this should be located very close to, or coinciding with the K–Pg boundary. These data suggest that the disappearance of the dinosaurs and other archosaurs was geologically abrupt in the southern Pyrenees, but to date there is no incontrovertible evidence of the presence of the impact level that marks the Cretaceous–Palaeogene boundary. Interestingly, what is highlighted in the southern Pyrenees is that the vertebrate-rich upper Maastrichtian continental sites were replaced by similar sedimentological facies characterized by the virtual absence not only of dinosaurs but also of any vertebrate remain throughout the lower Palaeocene. This could mean that the Danian terrestrial ecosystems of the southern Pyrenees took longer than other areas of the world to recover their biodiversity after the K–Pg extinction event.

1. Introduction

At the end of the Cretaceous the Earth underwent a major set of dramatic events. These include changes in global and regional climatic patterns (Li & Keller, 1998), marine regressions (Miller et al., 2005) and a huge asteroid striking the Earth (Alvarez, Alvarez, Asaro, & Michel, 1980; Smit & Hertogen, 1980). In addition, fissures on the Indian continent spewed forth thousands of cubic kilometres of volcanic material (Courtillot et al., 1988; Tobin et al., 2012). All these events have been suggested to be the cause of the Cretaceous–Palaeogene (K–Pg) mass extinction although there is a general consensus that it most probably derived from environmental consequences of the extraterrestrial impact that occurred 66 Ma (Renne et al., 2013; Schulte et al., 2010). Researchers analyse the patterns of extinction and survival in the biota and measure the effects of such events on the faunas living at

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the time by examining the fossil record to find out which organisms survived the K–Pg mass extinction event and which did not (Archibald & Fastovsky, 2004; Brusatte et al., 2015; Canudo, 1997; MacLeod et al., 1997; Molina et al., 2006). A good example is the sudden extinction of typical late Maastrichtian planktonic foraminifera coinciding with evidence of an extraterrestrial impact, a hypothesis proposed by Alvarez et al. (1980) and Smit and Hertogen (1980) on the basis of studies of planktonic foraminiferal successions and other evidence in sections from Gubbio (Italy) and Caravaca (Spain), respectively. At present, the connection between these two events is accepted (Schulte et al., 2010), notwithstanding the possibility that there may have been other factors that contributed to the extinction. Since the proposal of the meteorite hypothesis, vertebrate palaeontologists have been searching for evidence of the relationship between the extinction of the dinosaurs and the meteorite impact (Brusatte et al., 2015). The extinction of the majority of dinosaurs (except Aves) within a relatively small period of time is well documented in quite a few regions of the planet; moreover, the impact of a large extraterrestrial object 66 million years ago has been sufficiently substantiated on the Yucatán Peninsula in Mexico (Schulte et al., 2010). There has been a long debate about the events that contributed to the decline of dinosaurs, and to what extent these events may have been responsible for their extinction (Archibald et al., 2010; Brusatte et al., 2015; Fastovsky & Sheehan, 2005). More importantly, scientists still debate whether the extinction was geologically gradual or abrupt (instantaneous) and how this is linked with the perturbations propounded by the impact hypothesis.

Geological instantaneousness is a very inexact amount of time, particularly in continental environments, where hiatuses are the rule rather than the exception. Vertebrate palaeontologists cannot resolve time spans of less than tens of thousands of years at a temporal distance of 66 million years. The same palaeontological record can be preserved regardless of whether the extinction took a minute or many thousands of years. In 10,000 years, a whole class of gradual processes and extinctions may occur, represented by a geologically instantaneous extinction. This pattern is fundamental to the question of ascertaining whether the extinction was an instantaneous catastrophe or rather a phenomenon that spread gradually over time. Non-avian dinosaurs disappeared from the fossil record in all the continents at the end of the Cretaceous, at the boundary with the Palaeogene. This disappearance is a global phenomenon and “so dramatic that the absence of dinosaur fossils was often considered sufficient to assign a Cenozoic age to strata above dinosaur-bearing rocks” (Brusatte et al., 2015). Nonetheless, there are few places in the world that have a good record of the last dinosaurs, i.e. a record containing rocks of a late Maastrichtian age, the geological age that lasted from 69 to 66 million years ago. Documenting the global extinction of the dinosaurs will clearly require us to have a dinosaur record for the Late Cretaceous in many areas around the world (Archibald & Fastovsky, 2004; Le Loeuff, 2012); that is, it will call for a search for stratigraphically complete fossil records around and containing the K–Pg boundary. The western interior of North America is the area where the biodiversity of the last dinosaurs is best known, even though this is not without controversy (Brusatte et al., 2015; Fassett, Zielinski, & Budahn, 2002; Fastovsky & Sheehan, 2005). The Hell Creek Formation in North America is one of the few places in the world where there is a continuous sequence in continental facies between the Cretaceous and Palaeogene. The iridium peak that marks the Cretaceous-Palaeogene boundary has also been found at the top of this formation (Clemens & Hartman, 2014).

The second-best region for studying the evolution and extinction of latest Cretaceous dinosaurs is southwestern Europe. In particular, the southern Pyrenees region (Spain) provides an expanded continental record of the uppermost Cretaceous and lowermost Palaeogene (López-Martínez, Ardèvol, Arribas, Civis, & González-Delgado, 1998; Oms et al., 2007; Riera, Oms, Gaete, & Galobart, 2009). For the last 15 years, intensive research in the area by the research teams involved in studying the extinction of latest Cretaceous dinosaurs in the Pyrenees has considerably improved what is known of vertebrate biodiversity (including dinosaurs) and the associated environmental and chronological framework. Such studies include the systematics and biodiversity of tetrapods and their biodiversity just before the K–Pg boundary (Blanco, Bolet, Blain, Fondevilla, & Marmi, 2015; Blanco, Méndez, Marmi, 2015; Dalla Vecchia et al., 2013; López-Martínez et al., 2001; Cruzado-Caballero, Pereda-Suberbiola, & Ruiz-Omeñaca, 2010; Cruzado-Caballero, Ruiz-Omeñaca, Canudo, 2010; Pereda-Suberbiola, Canudo, Company, Cruzado-Caballero, & Ruiz-Omeñaca, 2009; Pereda Suberbiola, Canudo, Cruzado-Caballero, et al., 2009; Prieto-Márquez, Dalla Vecchia, Gaete, & Galobart, 2013; Riera et al., 2009; Torices, Currie, Canudo, & Pereda Suberbiola, 2015; Vila et al., 2013), the study of hundreds of dinosaur eggshells and clutches (Sellés, Vila, & Galobart, 2014a; Vila, Galobart, Oms, Poza, & Bravo, 2010, Vila, Jackson, Fortuny, Sellés, Galobart, 2010; 2011), and of dinosaur and crocodile footprints (Vila et al., 2013, 2015). In addition to our interest in the continuity of the facies and vertebrate successions across the K–Pg boundary, the position of the Iberian Peninsula is of particular palaeobiogeographical relevance. At the end of the Cretaceous, what is now Europe was an archipelago (Dercourt, Gaetani, Vrielvynck, Barrier, & Biju, 2000), with the area known as the Ibero-Armorican domain (comprising what is now Provence, the Pyrenees and the northern and southern Iberian Ranges) as the largest island in the European archipelago (Philip & Floquet, 2000). Moreover, the Iberian Peninsula was situated in the vicinity of the Tethys region, where the effects of the impact may have been especially marked. Indeed, in the marine environments of the Pyrenees one finds some of the classic sites in investigations into the Cretaceous–Palaeogene boundary (Molina, Arenillas, & Arz, 1998; Smit & Hertogen, 1980).

Accordingly, the main goal of this paper is to provide an overview of the record of the last dinosaurs and other archosaurs at the upper Maastrichtian localities of the southern Pyrenees and to discuss this record in the light of the K–Pg extinction event. New significant data from the Campo reference section are also provided.

2. Geographical and geological context

The study area is located in the Pyrenees of northern Catalonia and Aragón (NE Iberian Peninsula; Fig. 1). The Pyrenees is an east-west-oriented mountain chain with a basement roughly coincident with the France–Spain border. The Pyrenees resulted from the collision between the micro-continental Iberian Plate and the southwestern promontory of the European Plate during the Alpine orogeny that took place from the late Campanian to Eocene (Muñoz, 1989; Puigdefàbregas et al., 1986; Teixell, 2004). The thick outcrops of the South-Pyrenean Zone of Maastrichtian and Palaeocene age are known as the Tremp Formation. Mey, Nagtegaal, Roberti, and Hartelvelt (1968) defined this formation, and later it was ranked as the Tremp Group, which was divided into several formations on the basis of internal stratigraphic differences (Cuevas, 1992; Pujalte & Schmitz, 2005). However, here we use “Tremp Formation” due to the absence of significant stratigraphical discontinuities in this lithologic unit. The Tremp Formation is also referred to as the “Garumnian” facies. This unit accounts for the terrestrial and lagoonal sediments deposited at the end of the Cretaceous and the beginning of the Palaeogene (see historical review in Rosell, Linares, & Llompart, 2001). The Tremp Formation is