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The end-Cretaceous dinosaur succession in Europe: The Tremp Basin record (Spain)

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ABSTRACT

The succession of Maastrichtian deposits in the Tremp basin (South Pyrenean area, Spain) has provided long sections, with numerous dinosaur sites found in the Arén and Tremp Formations. The dinosaur record consists on titanosaur sauropods, dromaeosaurid theropods, hadrosaur ornithopods (including lambeosaurines) and nodosaurid ankylosaurians. Correlation of the sections enabled a clear succession of dinosaur localities to be established and thereby the succession of dinosaur faunas. Titanosaur remains, are present throughout the series, but are particularly abundant in the basal strata. Theropods and hadrosaur ornithopods are found all through the series. Lambeosaurine hadrosaur remains are restricted to sandstone channel beds close to the K/T boundary. The palaeoenvironmental conditions in each site were deduced from the sedimentological study, which allows establishing a relationship between environments and dinosaur taxa, and thus the over- or under-representation of taxa in the vertical succession to be unravelled. Titanosaurs and ornithopods are common in (but not exclusive to) marine-to-continental transitional and continental environments, respectively. Ankylosaurians are so far restricted to marine-to-continental transitional environments, but the sample is scarce. The fossil richness and the possibility of correlations among the different local sections make the Tremp Basin one of the best places in Europe to understand the final history on non-avian dinosaurs. The fossil record from the Tremp Basin suggests that they were well-diversified during the whole Maastrichtian until their extinction (as observed in North America and Asia). Sauropods were still present at the end of the Maastrichtian and lambeosaurines occurred at least in the upper part of the Maastrichtian.

1. Introduction

The best record of Maastrichtian dinosaur faunas and the Cretaceous–Tertiary boundary event in continental deposits is from the Western Interior of North America (see Archibald and Fastovsky, 2004; Fastovsky and Sheehan, 2005; and literature therein). However, recent works have provided new insights in Asian assemblages (Godefroit et al., 2009) and their relationship with the Cretaceous–Tertiary boundary (Bajpai and Prasad, 2000; Zhao et al., 2002). European dinosaur-bearing sites are important in providing a more global understanding of the last history of non-avian dinosaurs and the Cretaceous–Tertiary boundary event. However, the lack of long, well-dated sections containing numerous dinosaur-bearing horizons has hampered the understanding of the latest Cretaceous dinosaur history in Europe (Buffetaut and Le Loeuff, 1991; López-Martínez, 2003).

Some authors have recognized a succession of two dinosaur assemblages, concluding that a faunal replacement took place in the Ibero–Armorican island of the European Archipelago during the Maastrichtian (Le Loeuff et al., 1994; Buffetaut and Le Loeuff, 1997; Buffetaut et al., 1997). According to those authors, a late Campanian–early Maastrichtian assemblage with dromaeosaurid and abelisaurid theropods, titanosaurid sauropods, nodosaurid ankylosaurians and rhabdodontid ornithopods was replaced by a hadrosaurid–dromaeosaurid assemblage during the Late Maastrichtian. The titanosaurid abundance decreased until the complete disappearance of those dinosaurs prior to the Late Maastrichtian. The rhabdodontids, common in late Campanian and early Maastrichtian European sites, are not found in the Late Maastrichtian, while hadrosaurids appeared during the Late Maastrichtian.

Subsequent studies in the Pyrenean area (Laurent et al., 1999; Canudo, 2001; López-Martínez et al., 2001; Laurent et al., 2002), revealed that this bipartition is partly unsubstantiated. The theropod, titanosaur, nodosaurid, and hadrosauroid record is continuous from the Late Campanian to the Latest Maastrichtian. Additionally, the presence of nodosaurids is documented in the Late Maastrichtian (Pereda-Suberbiola, 1992; Laurent et al., 1999).

In this study, we document the Maastrichtian dinosaur succession in the Tremp Basin. Excellent continuous outcrops together with long, complete stratigraphic sections containing numerous sites with dinosaur remains make the Tremp Basin an ideal setting to gain

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insight into the dinosaur evolution during the Maastrichtian in the largest island of the European archipelago.

2. Geological setting

The Tremp Basin occurs in the Lleida province of Catalonia (north-eastern Spain). It is a piggy-back basin carried on the Montsec thrust sheet, located in the south-central Pyrenean thrust unit. It is bounded to the north by the Cotiella Sheet and the Sant Corneli Anticline (Cotiella–Bòixols Mesozoic unit) and to the south by the Montsec thrust front (see Vergés and Muñoz, 1990 and references therein). A 3000 m-thick section composed mainly of Cretaceous and Palaeogene rocks is exposed in the basin. The study area is located in the easternmost part of the basin as shown in Figs. 1 and 2. The beds with dinosaur remains belong to the top of the Arén Sandstone Formation and to the Mesozoic portion of the Tremp Formation (both formations named by Mey et al., 1968).

The Arén Sandstone Formation consists on late Campanian–Maastrichtian beach (Ghibaudo et al., 1974), barrier-island systems (Nagtegaal, 1972; Nagtegaal et al., 1983; Díaz Molina, 1987) and deltaic deposits (Mutti and Sgavetti, 1987). The sandstones are mainly composed of quartz grains and show medium- and large-scale cross-bedding (Nagtegaal et al., 1983). The Arén Sandstone Formation is overlain by and interfingered with the lowermost part of the Tremp Formation.

The Tremp Formation, also commonly known as "Garumnian" (Leymerie, 1862), is exposed along the southern Pyrenees and is composed of continental deposits through the Cretaceous–Tertiary transition. In the Tremp Basin, the Tremp Formation reaches its maximum thickness (up to 800 metres thick). Four informal lithologic units of variable thickness within the Tremp Formation can be recognized in the southern Pyrenees (Rosell et al., 2001; Fig. 3), which are, from base to top: (1) a marine-to-continental transitional grey unit mainly consisting of grey marls with abundant invertebrates, lignites, limestone, and sandstone layers; (2) a fluvial lower red unit that includes red mudstones, sandstones, and palaeosols; (3) the lacustrine Vallcebre Limestones and laterally equivalent strata that contain charophytes and *Microcodium* (in the sense of Kabanov et al., 2008); and (4) a fluvial upper red unit that is composed of red mudstones, sandstones, and conglomerates (for further details see Rosell et al., 2001 and references therein). Dinosaur remains occur in the grey unit and in the lower red unit.

The Tremp Formation in the Tremp Basin has been divided into different local units by different authors. For example, Cuevas (1992) established five formations and four members and elevated the Tremp Formation category to that of a Group. However, the use of Tremp Group is not widespread and the criteria applied to establish the boundaries between the formations are rather confusing (e.g., different shades of red). Thus, in this work we have adopted Rosell et al. (2001) units, which additionally have a broader (regional) range. The correspondence between Rosell et al. (2001) and Cuevas (1992) units, respectively, is as follows: the grey unit is an equivalent of the Posa Formation; the lower red unit of the Conques and Talarn formations; the Vallcebre Limestones and laterally equivalent strata of the Suterranya and St. Salvador de Toló Formation; and the upper red unit of the Esplugafreda and Claret formations.

The Maastrichtian age of the Cretaceous portion of the Tremp Formation (grey and lower red units) in the Tremp Basin has been constrained by the occurrence of rudists, ostracodes, charophytes and palynomorphs in the lowermost beds and charophytes in the uppermost beds (Liebau, 1973; Pons, 1977, 1982; Feist and Colombo, 1983; De Porta et al., 1985; Médus et al., 1988; Fig. 3). This dating is consistent with the most recent integration of biostratigraphic data by Baceta et al. (2004). About 430 metres below the base of the Arén Formation, in the underlying Vallcarga Formation (Salàs Marls Member), ammonite and inoceramid faunas indicate a late Campanian age—*Nostoceras* (*Bostrychoceras*) *polyplocum* and *"Inoceramus" pyrenaicus*–*"Inoceramus" launartensis* zones, respectively (Mercedes, 2005; see also Niebuhr, 2004). Furthermore, the grey unit (in the sense of Rosell et al., 2001) has been well-dated magnetostratigraphically as Early Maastrichtian in the Fontllonga and Vallcebre sections (Galbrun et al., 1993 and Oms et al., 2007a, respectively). On the other hand, some authors have postulated a latest Campanian age for the grey unit in the study area based on inferred correlations (Ardèvol et al., 2000; López-Martínez et al., 2001). Regarding the Cretaceous–Tertiary boundary in the study area, although several authors have used different biostratigraphic criteria for its location (such as the disappearance of dinosaurs, the presence of Palaeocene gastropods and charophytes, and the more frequent occurrence of *Microcodium*), it is generally agreed that it is located within the Vallcebre Limestones and laterally equivalent strata (e.g., Masriera and Ullastre, 1983; Eichenseer and Krauss, 1985; Rosell et al., 2001). At least the lower part of this unit (Tossal de la Doba Limestones) is Maastrichtian. However, the precise location of the K/T boundary is not well established.

3. Stratigraphic succession

Several sections of a 450-metre-thick vertical succession were measured to analyse the sedimentary context of the study area and its

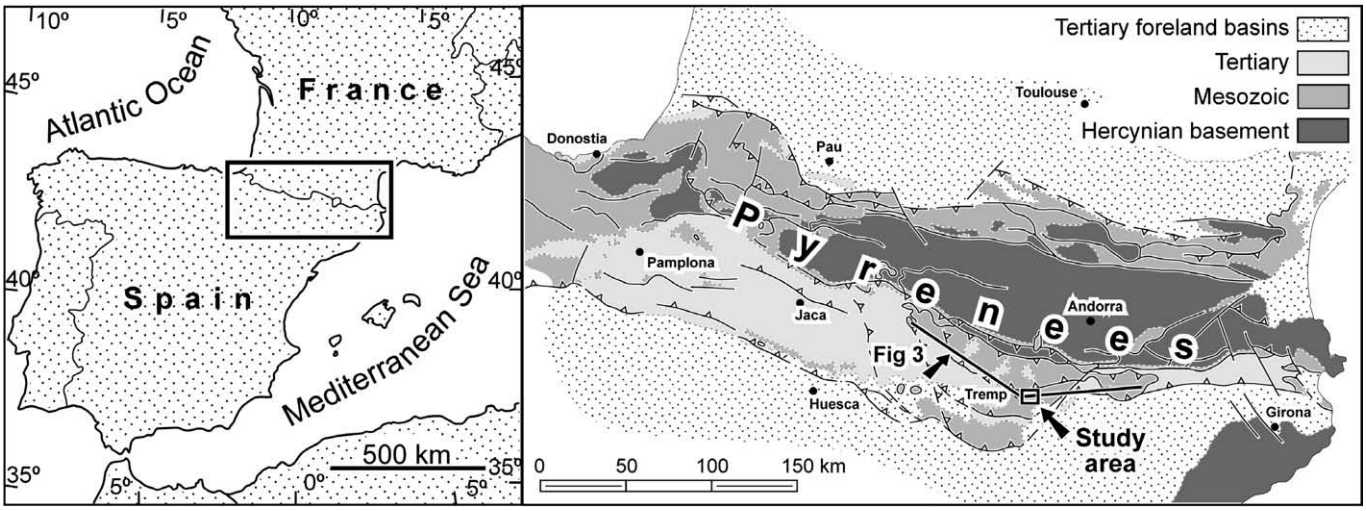

Fig. 1. Geological map of the Pyrenees and location of the study area and Fig. 3 (adapted from Vergés and Muñoz, 1990).