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Tidal influence in redbeds: A palaeoenvironmental and biochronostratigraphic reconstruction of the Lower Tremp Formation (South-Central Pyrenees, Spain) around the Cretaceous/Paleogene boundary

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ABSTRACT

The Upper Cretaceous–Paleogene deposits of the Grey Unit, the Lower Red Unit and the Suterranya Limestone of the Tremp Formation (South-Central Pyrenees) preserve sedimentological and palaeontological features that suggest a connection with marine settings and which allow the age of these deposits to be reviewed. The deduced sedimentary environments for the Grey Unit and the Suterranya Limestone – lagoonal and coastal lake environments respectively – agree with those proposed by previous authors. However, a new depositional setting is proposed for the Lower Red Unit, that of a mixed-energy zone in a tide-dominated delta. This new interpretation is based on the presence of inclined heterolithic stratification in point bar deposits, along with flaser and lenticular bedding and the presence of in situ marine fossils – including those of planktonic foraminifera – and glauconite grains. These foraminifera were almost certainly transported, as a suspended load, from the open sea into meandering channels on flood tides. Their associated biostratigraphy suggests a Maastrichtian age for the Grey Unit and Lower Red Unit, and a late Danian age for the Suterranya Limestone. There is a significant hiatus between latter and former units that covers most of the Danian, and presumably includes the Cretaceous/Paleogene boundary.

1. Introduction

Interpreting transitional depositional environments is difficult when sedimentary features associated with continental environments, such as reddish-coloured mudstone with abundant palaeosols or palaeochannel deposits, are profuse, and when sedimentary features and/or fossil evidence indicative of a marine influence is scant or absent. Under such conditions only a detailed, multidisciplinary study may allow accurate interpretations to be made. Such a study could provide better evidence of any marine influence masked by continental features, for instance, the presence of inclined heterolithic stratification (IHS, Thomas et al., 1987), mainly associated with tide-influenced marginal marine settings (Smith, 1987) or the precipitation of glauconite, commonly formed under marine conditions (Odin and Fullagar, 1988).

Ancient transitional environments can be reconstructed via facies analysis and by taking note of the presence of marine fossils. When marine-continental fossils occur in settings that include eroded components, they can be misinterpreted as reworked grains from older rocks. A detailed petrographic and biostratigraphic study, however, helps avoid such mistakes. Thus, a detailed analysis allows not only the determination of the in situ–ex situ nature of the fossils but also assessing environmental implications such as the role of landward transport of specimens by currents, a process frequently observed in recent examples (Murray et al., 1982).

The late Cretaceous–early Paleogene Tremp Formation (also known as the "Garumnian facies" and the Tremp Group (Cuevas, 1992)) in the South-Central Pyrenees (Spain), provides an example of such a setting. The Tremp Formation consists of greyish marl deposited in a transitional environment, followed by multicoloured marly–sandy deposits and subordinate conglomerate and limestone, all of which are given the name 'redbeds'. These deposits contain a remarkable record of dinosaur fossils, and host some of the youngest dinosaur-rich sites in the world (López-Martínez et al., 2001; Riera et al., 2009; Vila et al., 2012) as well as the youngest dinosaur tracksites in Europe (Vila et al., 2013). The redbeds' abundant vertebrate remains have traditionally been regarded as having been deposited in alluvial, fluvial and lacustrine settings (Rosell, 1965; Nagtegaal et al., 1983; Cuevas, 1992; Rosell et al., 2001; Riera et al., 2009). Numerous sedimentological and palaeontological investigations have been performed in this area (see

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"Geological Setting" for references) where, in addition, the type-section of the Tremp Formation was defined (Rosell and Llompart, 1982).

The Tremp Formation has been assigned to the Late Cretaceous–Paleogene based on stratigraphic correlations, magnetostratigraphic data and the biostratigraphy suggested by rudists, charophytes and palynomorphs (Feist and Colombo, 1983; Porta et al., 1985; Médus et al., 1988; Ardèvol et al., 2000; López-Martínez et al., 2001; Vicens et al., 2004; Oms et al., 2007; Pereda-Suberbiola et al., 2009; Riera, 2010; Vila et al., 2012; Villalba-Breva and Martín-Closas, 2013). However agreement is not complete regarding the age of these deposits, in part because of a lack of precise biostratigraphic data. Thus, despite the importance of the Tremp Formation in understanding the extinction of the last European dinosaurs, there is no agreement on the exact position of the Cretaceous/Paleogene (K/Pg) boundary, or on the age of the Tremp Formation (Riera et al., 2009).

This paper reports a sedimentological, micropalaeontological and petrographic study of the Upper Cretaceous–Lower Paleogene transitional-to-continental deposits of the Tremp Formation. The data collected, including the discovery of non-reworked planktonic foraminifera, help to refine our understanding of the Formation's depositional environments, provide new evidence regarding the age of the deposits of the lower Tremp Formation, and constraint the position of the K/Pg boundary.

2. Geological setting

The study area is located in the South-Central Pyrenees (Fig. 1), a region that corresponds to an alpine fold-thrust belt that formed during Late Cretaceous to Early Miocene, which is classically, divided into three thrust sheets referred to as the Boixols, Montsec and Sierras Marginales. These thrust sheets controlled the sedimentation of an E–W orientated foreland basin (Teixell and Muñoz, 2000). The investigated area belongs to the Tremp–Graus Basin which is located to the east of this foreland basin, and is related to the evolution of the Boixols thrust sheet (Puigdefàbregas et al., 1992) (Fig. 1a). The Tremp–Graus Basin exposes Upper Cretaceous to Cenozoic deposits showing westward deepening and a transition from continental to marine facies. The Basin is structured in the E–W trending Tremp syncline (Fig. 1a), bounded to the S by the Montsec thrust and to the N by the Sant Cornelli fault propagation anticline (eastern termination of the Boixols thrust sheet).

The present study focuses on the northern limb of the Tremp syncline, near the town of Tremp (Fig. 1a). The studied outcrops (Fig. 1b) correspond to the lower part of the Tremp Formation which overlies the Arén Formation (both by Mey et al., 1968). The Arén Formation consists of shallow, marine clastic deposits and shows progressive unconformities and facies variations related to the contemporaneous growth of the Sant Cornelli anticline (Garrido-Megias, 1973; Puigdefàbregas and Souquet, 1986; Simó, 1986; Deramond et al., 1993; Bond and McClay, 1995; Arbués et al., 1996; Guillaume et al., 2008; Shackleton et al., 2011). The latter may have emerged as an island/peninsula during the Late Cretaceous (Nagtegaal et al., 1983). Díaz-Molina et al. (2007) interpreted the upper part of the Arén Formation as a marine littoral setting after distinguishing four major facies assemblages belonging to shoreface, beachface, beach ridge plain and backbarrier-lagoon environments. The Arén Formation shows a general northwestward prograding trend. It is gradually replaced landwards (towards the E and S) by lagoonal or estuarine and continental deposits of the lower Tremp Formation (Nagtegaal et al., 1983; Eichenseer and Krauss, 1985; Willems, 1985; Díaz-Molina, 1987; Eichenseer, 1987; Krauss, 1991; Ardèvol et al., 2000; Díaz-Molina et al., 2007; Riera et al., 2009).

The Tremp Formation outcrops over some 1000 km^2 in a number of small foreland basins resulting from the Pyrenees formation (López-Martínez et al., 2006) and is found throughout the entire Tremp–Graus Basin. It is predominantly composed of multicoloured mudstone deposits and subordinate sandstone, conglomerates and limestone (Fig. 1b). The Formation is divided into four informal lithological units known as the "Grey Unit", "Lower Red Unit", "Suterranya Limestone" and "Upper Red Unit" (Rosell et al., 2001; Riera et al., 2009). Except this latter, the rest of the units can be found in the studied section (Fig. 2). These units are also known in this area as the Posa Formation or Unit 1 (Grey Unit), the Conques and Talarn formations or Unit 2 (Lower Red Unit), and the Suterranya Formation or Unit 3 (Cuevas, 1992; Pujalte-Navarro and Schmitz, 2005; López-Martínez et al., 2006).

The Grey Unit consists of greyish marl with abundant carbonate pedogenic features and intercalations of coal, limestone and sandstone, all of which are interpreted as lagoonal or estuarine facies (Rosell, 1965; Nagtegaal et al., 1983; Cuevas, 1992; Rosell et al., 2001; Riera et al., 2009). Liebau (1973) described it to contain the remains of many marine to freshwater taxonomic groups, such as charophytes, foraminifera, molluscs, ostracods, rudists, corals and vertebrates.

The Lower Red Unit is made of multicoloured (frequently mottled) and bioturbated mudstone interbedded with sandstone and conglomerate, all interpreted as floodplain and fluvial deposits (Cuevas, 1992; Rosell et al., 2001; Riera et al., 2009). The deposits of the Grey Unit and the Lower Red Unit contain fossilised dinosaur bones and tracks, and are home to world-renowned dinosaur fossil sites of hadrosaurs and sauropods (López-Martínez et al., 2001; Riera et al., 2009; Vila et al., 2012).

The top of the studied section is represented by the Suterranya Limestone (Figs. 1b and 2). This unit is formed by limestone and marl, contains charophytes, molluscs, ostracods and foraminifera, and shows abundant pedogenic features. The section top has been interpreted as having been deposited in brackish–freshwater coastal lakes or ponds (López-Martínez et al., 2006).

The age of the Tremp Formation, and of the interfingering Arén Formation in the Tremp area, is not completely established because of the scarcity of guide fossils. According to the available palaeontological data, the depositional architecture of the Upper Cretaceous–Lower Paleogene strata of the Arén Formation, and the correlated continental deposits of the Tremp Formation, the studied section would have been deposited during the very late Campanian through to Danian times (Ardèvol et al., 2000; López-Martínez et al., 2001). This agrees with the biostratigraphic evidence, at least with respect to rudists as reported by Vicens et al. (2004). However, some authors have attributed a Maastrichtian age to the Grey Unit based on the study of charophytes (Feist and Colombo, 1983; Villalba-Breva and Martín-Closas, 2013) and palynomorphs (Porta et al., 1985; Médus et al., 1988). In addition, the dinosaur-rich Arén Formation sites located west of the Tremp syncline have been correlated – based on their planktonic foraminifera contents – with the upper Maastrichtian Abathomphalus mayaroensis Biozone (detected in deep marine sediments that outcrop westward near the town of Campo; see location in Fig. 1a). Other stratigraphic correlations, based on limited magnetostratigraphic results of the lower part of the Tremp Formation (Vila et al., 2012), assign a Maastrichtian age to the Grey Unit deposits, based on correlations with the western Pyrenees (Oms et al., 2007).

The Suterranya Limestone and its equivalent stratigraphic units have been assigned to the Danian via their stratigraphic correlation with dated marine platform deposits in the Campo stratigraphic section (Fig. 1a) (López-Martínez et al., 2006). On the southern limb of the Tremp syncline, the limestone layers have also been dated as Danian, as suggested by their charophyte-containing biostratigraphy (Masriera and Ullastre, 1990). Physical and biostratigraphic correlations of this limestone are difficult due to its discontinuous exposure and low fossil content. Thus, different limestone layers of this unit (exposed in different areas of the Tremp syncline) have been described as Late Cretaceous (Díaz-Molina, 1987) or Thanetian (Feist and Colombo, 1983; Masriera and Ullastre, 1983).

The K/Pg boundary is generally placed towards the top of the studied section, although there is no agreement on its exact position. According to different researchers, it is found at the top of the Lower Red Unit