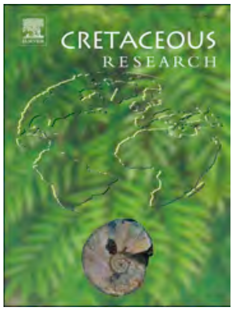

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Chronostratigraphy and new vertebrate sites from the upper Maastrichtian of Huesca (Spain), and their relation with the K/Pg boundary

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Abstract: *The transitional-continental facies of the Tremp Formation within the South-Pyrenean Central Unit (Spain) contain one of the best continental vertebrate records of the Upper Cretaceous in Europe. This Pyrenean area is therefore an exceptional place to study the extinction of continental vertebrates across the Cretaceous/Paleogene (K/Pg) boundary, being one of the few places in Europe that has a relatively continuous record ranging from the upper Campanian to lower Eocene. The Serraduy area, located on the northwest flank of the Tremp syncline, has seen the discovery of abundant vertebrate remains in recent years, highlights being the presence of hadrosaurid dinosaurs and eusuchian crocodylomorphs. Nevertheless, although these deposits have been provisionally assigned a Maastrichtian age, they have not previously been dated with absolute or relative methods. This paper presents a detailed stratigraphic, magnetostratigraphic and biostratigraphic study for the first time in this area, making it possible to assign most vertebrate sites from the Serraduy area a late Maastrichtian age, specifically within polarity chron C29r. These results confirm that the vertebrate sites from Serraduy are among the most modern of the Upper Cretaceous in Europe, being very close to the K/Pg boundary.*

Key words: *K/Pg boundary; Maastrichtian; magnetostratigraphy; biostratigraphy; vertebrates; Pyrenees.*

Introduction

Recognizing the K/Pg (Cretaceous/Paleogene) boundary in continental deposits is a complicated task due to several biases that affect the continental record (Barret *et al*., 2009; Butler *et al*., 2011; Smith *et al*., 2001; Mannion *et al*., 2011; Smith and McGowan, 2011; Upchurch *et al*., 2011). Even so, great efforts have been made in recent years to detect the continental K/Pg boundary and ascertain its relation with faunal and floral extinctions, especially in North America (e.g., Fastovsky and Sheehan, 2005; Archibald *et al*., 2010; Brusatte *et al*., 2015; and references therein), but also in Europe (Canudo *et al*., 2016; and references therein) and Asia (Jiang *et al*., 2011; and references therein).

In the European scenario, the greatest difficulty in knowing how the vertebrate faunas were affected by the K/Pg extinction event is as a result of the fragmentary nature of the continental geological record during the Late Cretaceous and early Paleogene. Nonetheless, major advances have been made in the last few years, and new outcrops, mainly in Romania, France and Spain, are being discovered and datings carried out (Puértolas-Pascual *et al*., 2016; and references therein).

In Eastern Europe (Romania), the Maastrichtian continental vertebrate assemblages have been examined and dated by biostratigraphy, magnetostratigraphy and radioisotopic techniques (Antonescu *et al*., 1983; Van Itterbeeck *et al*., 2005; Codrea *et al*., 2010, 2012; Panaiotu and Panaiotu, 2010; Bojar *et al*., 2011; Panaiotu *et al*., 2011; Vremir *et al*., 2014; Csiki-

Sava *et al*., 2015). However, the vertebrate sites are located in excessively broad age ranges, the correlation between the different sites remains problematic and more accurate datings are required (Buffetaut and Le Loeuff, 1991; Gheerbrant *et al*., 1999; Codrea *et al*., 2012; Vremir *et al*., 2014).

Similar concerns occur with respect to the Upper Cretaceous and lower Paleogene of France. Apart from the Provence area, where several biostratigraphic, magnetostratigraphic, chemostratigraphic and sedimentological studies with a good chronostratigraphic control have been carried out (Cojan *et al*., 2003; Cojan and Moreau, 2006), most of the northern Pyrenees still lack accurate datings or correlations (Buffetaut and Le Loeuff, 1991; Laurent *et al*., 2002). Therefore, despite the abundant Maastrichtian vertebrate fossil record recovered from southern France, only limited biostratigraphic data (Bessiére *et al*., 1980, 1989; Bilotte, 1985; Garcia and Vianey-Liaud, 2001; Marty, 2001) and one new magnetostratigraphic study (Fondevilla *et al*., 2016b) are available, and further studies and correlations are still necessary (Dinarès-Turell *et al*., 2014).

The continental vertebrate record of the uppermost Cretaceous of Spain is one of the most complete and most studied in Europe (e.g., Company and Szentesi, 2012; Ortega *et al*., 2015; Pereda-Suberbiola *et al*., 2015; Canudo *et al*., 2016). Most of these vertebrate sites are located within the Tremp Basin, in the Pyrenees of Aragon and Catalonia (Spain), specifically in the Maastrichtian transitional and continental facies of the Tremp Formation. The Tremp Formation has been exhaustively prospected and studied, providing abundant new vertebrate fossil remains including dinosaurs, crocodylomorphs, testudines, mammals, fishes, amphibians and squamates (e.g., López-Martínez *et al*., 1999, 2001; Peláez-Campomanes *et al*., 2000; Riera *et al*., 2009; Pereda-Suberbiola *et al*., 2009; Blain *et al*., 2010; Cruzado-Caballero *et al*., 2010, 2013, 2015; Puértolas *et al*., 2011; Marmi *et al*., 2012, 2016; Vila *et al*., 2012, 2013, 2015; Moreno-Azanza *et al*., 2014; Puértolas-Pascual *et al*., 2014, 2016; Sellés *et al*., 2014a, 2014b, 2016; Blanco *et al*., 2014, 2015a, 2015b, 2016, 2017; Company *et al*., 2015; Torices *et al*., 2015; Canudo *et al*., 2016).

In addition to the record of the vertebrates themselves, there is a relatively continuous geological record ranging from the Maastrichtian to the end of the Thanetian (López-Martínez *et al*., 2006), which is probably the best dated and correlated in Europe for this time interval and which may contain the Cretaceous/Paleogene boundary. This makes the southern Pyrenees and the Tremp Basin one of the best areas in the world for studying vertebrate associations across the K/Pg boundary, allowing comparisons with the extinction patterns reported from other parts of the world (Brusatte *et al*., 2015; Csiki-Sava *et al*., 2015; Canudo *et al*., 2016; Puértolas-Pascual *et al*., 2016).

Ever since the 1980s, therefore, a great effort has been put into dating the fossil vertebrate sites and searching for the K/Pg boundary within the transitional and continental deposits of this sector of the Pyrenees. Outstanding in this context are works on the biostratigraphy of rudists (Vicens *et al*., 2004), charophytes and palynomorphs (Feist and Colombo, 1983; Médus *et al*., 1988; Galbrun *et al*., 1993; López-Martínez *et al*., 2001; Villalba-Breva and Martín-Closas, 2011, 2013; Villalba-Breva *et al*., 2012; Vicente *et al*., 2015), foraminifers (López-Martínez *et al*., 2001; Díez-Canseco *et al*., 2014), on eggshells (Vila *et al*., 2011; Sellés *et al*., 2013; Sellés and Vila, 2015), magnetostratigraphy (Galbrun *et al*., 1993; Oms *et al*., 2007; Pereda-Suberbiola *et al*., 2009; Vila *et al*., 2011, 2012; Canudo *et al*., 2016; Fondevilla *et al*., 2016a) and dinosaur occurrences (Riera *et al*., 2009; Vila *et al*., 2016).

The Serraduy area, located in the Aragonese northwestern branch of the Tremp Basin, has been prospected by the Aragosaurus-IUCA research group of the University of Zaragoza for over 10 years. This has resulted in the discovery of around 40 new paleontological sites with hundreds of vertebrate remains. These findings include important specimens such as the holotype of the eusuchian crocodylomorph *Agaresuchus subjuniperus* (Puértolas-Pascual, Canudo and Moreno-Azanza, 2014) and the smallest hadrosaurid known in Europe to date (Company *et al*., 2015), probably a new dwarf taxon.

Despite the importance and potential of these vertebrate sites, a chronostratigraphic framework for the Serraduy sector has not yet been provided. Serraduy is located between other areas with vertebrate sites such as Campo to the west and Arén to the east, corresponding to the northwestern-most branch of the Tremp Formation within the Tremp Basin. In these nearby sectors (Campo and Arén, Huesca), previous magnetostratigraphic studies have stated that the vertebrate sites of the Tremp Formation in these areas lie within magnetic polarity chrons C30n and C29r, being late Maastrichtian in age (Pereda-Suberbiola *et al*., 2009; Canudo *et al*., 2016).

On the basis of works of magnetostratigraphy (Fondevilla *et al*., 2016a) and biostratigraphy (Díez-Canseco *et al*., 2014) on the more eastward-lying Isona sector of the Tremp syncline, however, some authors have detected the possible presence of important hiatuses in some areas of the Tremp Basin. These gaps reveal that most of the succession and vertebrate content in that area correlates to the early Maastrichtian (mostly chron C31r), suggesting an older age (Fondevilla *et al*., 2016a) for many vertebrate sites than previously thought (Vila *et al*., 2012). In accordance with these new datings (Pereda-Suberbiola *et al*., 2009; Díez-Canseco *et al*., 2014; Canudo *et al*., 2016; Fondevilla *et al*., 2016a), the chronostratigraphic study of the areas of Campo-Serraduy-Arén may thus acquire greater relevance, given that the lower part of the Tremp Formation exposed in Campo and Arén contains the only continental record of chron C30n in the whole Tremp syncline (Fondevilla *et al*., 2016a).

To test all these hypotheses, we here describe for the first time the magnetostratigraphy, biostratigraphy and a preliminary study of the fossil vertebrate assemblage of the Serraduy area. According to our biostratigraphic and magnetostratigraphic results, most of the "lower red unit" of the Tremp Formation up to the top would be included within magnetic polarity chron C29r, and most of the vertebrate sites would therefore have a late Maastrichtian age, being located very close to the K/Pg boundary. Unfortunately, the paleomagnetic and biostratigraphic data from the lower half of the studied sections are not conclusive enough to give a specific age or reveal the presence of hiatuses in this area.

Geographical and geological context

The studied area is located in the Aragonese part of the Tremp Basin within the Pyrenean range (Serraduy area, Huesca, Spain) (Fig. 1A, B). The Pyrenees are a 430-km-long east-west-oriented continental collisional fold-and-thrust belt, located in the northeastern Iberian Peninsula between France and Spain (Fig. 1A); they formed as the result of the oblique collision and compressive episodes between the Iberian microplate and the European plate. This process took place during the Alpine orogeny, from Late Cretaceous until early Miocene times (Garrido-Megías and Ríos, 1972; Puigdefabregas and Souquet, 1986; Muñoz, 1992; Ardèvol *et al*., 2000; Sibuet *et al*., 2004; Teixell, 2004). The Tremp Basin is located within the South-Pyrenean Central Unit or SPCU (Séguret, 1972), which corresponds with the central sector of the Southern Pyrenees (between the Nogueras thrust fault in the north and the Sierras Marginales frontal thrust in the south) (Fig. 1A). Several syn-sedimentary synclines (Ager, Tremp, Coll de Nargo and

Vallcebre) associated with the emplacement of south-verging thrust-sheets developed during the Late Cretaceous, acting as different sub-basins (Fondevilla *et al*., 2016a; Oms *et al*., 2016). The fossil remains studied here are from the Arén and Tremp Formations (Mey *et al*., 1968) within the Tremp Basin and the northern flank of the east-west-oriented Tremp syncline.

The Tremp Formation, which forms part of what is informally known as the "Garumnian" facies (Leymerie, 1862), was deposited during the Upper Cretaceous–Paleocene, when the Pyrenees Basin was completely filled by coastal and continental deposits due to the end-Cretaceous marine regression (Rosell *et al*., 2001), representing the last infilling episode of the South-Pyrenean Basin (Mey *et al.*, 1968; López-Martínez *et al*., 1999; Oms *et al*., 2016). The SPCU has an extension of 5000 km^2, of which the Tremp Formation is estimated to encompass about 1000 km^2 (López-Martínez *et al*., 2006). This formation crops out in the central and western part of the SPCU, reaching a thickness of about 900 m in the depocenter near the locality of Tremp (López-Martínez *et al*., 1999). In the northern areas, such as the Tremp syncline, the bottom of the Tremp Formation is underlain by and laterally interdigitated with upper Campanian–Maastrichtian mixed-platform marine deposits that correspond to the beach, barrier-island and deltaic sandstones of the Arén Formation (Fig. 1C) (Ardèvol *et al*., 2000). In the southern outcrops, such as the Àger syncline, the Arén Formation is replaced by more calcareous deposits corresponding with the limestones Les Serres Formation (Souquet, 1967; López-Martínez *et al*., 2006). Above, the Tremp Formation is overlain by Ilerdian (lower Eocene) marine sediments of the alveoline limestones Cadí Formation, or marly deposits laterally equivalent to the Figols Group (Fonnesu, 1984; Eichenseer and Luterbacher, 1992; López-Martínez *et al*., 1999, 2006).

The sedimentary succession of the Tremp Formation can be linked with two main stages of compressive tectonics (Puigdefàbregas and Souquet, 1986). The first stage occurred during the late Santonian–late Maastrichtian and was characterized by active tectonics, particularly intense during the late Santonian and Campanian, which caused the inversion of the previous Mesozoic rift structures and the development of a foreland basin. During this period, the basin was filled by mainly siliciclastic deposits which progressively passed to marine facies towards the west, where the open sea was located. The second stage occurred during the late Maastrichtian–early Eocene, this being a period of smooth tectonics and almost uniform subsidence represented predominantly by carbonate-marl deposits.

The Tremp Formation has been divided into different local units by several authors. Cuevas (1992), and later Pujalte and Schmitz (2005), divided the series into five formations and four members, elevating the Tremp Formation to the category of group. However, the classification of the Tremp Formation as a group is not widespread within the literature and some authors indicate that the boundaries between the formations of this group can be confusing (Riera *et al*., 2009). For this reason, Galbrun *et al*. (1993) and Rosell *et al*. (2001) divided the Tremp Formation into informal units with a wider regional rank. The correspondence between the different units of each author is as follows (Fig. 2): “grey unit” or “Grey Garumnian” of Rosell *et al*. (2001) (Posa Formation according to Cuevas, 1992; Unit 1 according to Galbrun *et al*., 1993); “lower red unit” or “Lower Red Garumnian” of Rosell *et al*. (2001) (Conques Formation and Talarn Formation according to Cuevas, 1992; Unit 2 according to Galbrun *et al*., 1993); “Vallcebre limestones” and lateral equivalents of Rosell *et al*. (2001) (Suterranya Formation and St. Salvador de Toló Formation according to Cuevas, 1992; Unit 3 according to Galbrun *et al*., 1993); “upper red unit” or “Upper Red Garumnian” of Rosell *et al*. (2001) (Esplugafreda

Formation and Claret Formation according to Cuevas, 1992; Unit 4 according to Galbrun *et al.*, 1993). In this study we have used the division proposed by Rosell *et al.* (2001) since this is the most widespread in the literature. Thus, the four units into which the Tremp Formation is divided are the following (Galbrun *et al.*, 1993; Rosell *et al.*, 2001, López-Martínez *et al.*, 1999, 2006):

"Grey unit" (Posa Formation, Cuevas, 1992): Peritidal deposits composed of grey marls, calcarenites and limestones. The fossil assemblage is formed by marine to freshwater taxa, such as charophytes, foraminifers, molluscs, ostracods, rudists, corals, plants and vertebrates (Liebau, 1973; Álvarez-Sierra *et al.*, 1994; Arribas *et al.*, 1996; López-Martínez *et al.*, 2001, 2006; Díez-Canseco *et al.*, 2014; Vicente *et al.*, 2015; Canudo *et al.*, 2016). In some sectors of the Tremp Basin, swampy deposits with an abundant accumulation of vegetal remains and lignite are observed (Oms *et al.*, 2014). This unit was deposited in wide and shallow protected areas of variable salinity that are interpreted as tidal-plain, lagoonal and estuarine environments, located laterally and proximally to the barrier-island or deltaic deposits of the Arén Formation (Nagtegaal *et al.*, 1983, Díaz-Molina, 1987; Ardèvol *et al.*, 2000; López-Martínez *et al.*, 2006; Riera *et al.*, 2009; Díez-Canseco *et al.*, 2014).

"Lower red unit" (Conques Formation–Talarn Formation, Cuevas, 1992): Detrital deposits composed of violet, brown, ochre, greenish or reddish lutites with a high degree of bioturbation and alternated with brown and ochre hybrid sandstones organized in channeled or tabular strata. This unit may also contain grey marls and microconglomerates and, more rarely, limestones and gypsum. In several areas, such as the Ager and Vallcebre synclines, the top of the "lower red unit" is characterized by the presence of the so-called "Reptile Sandstone", where the last vertebrate remains before the K/Pg boundary can be found just a few meters below the overlying "Vallcebre limestones" (Llompart, 1979; Masriera and Ullastre, 1983; Lopez-Martínez *et al*., 1998; Gómez-Gras *et al*., 2016; Vicente *et al*., 2015; Canudo *et al*., 2016). Between the last levels with evidence of dinosaurs and the Danian "Vallcebre limestones" and lateral equivalents, there is a transitional section composed of lutitic–marly deposits and local intercalations of gypsum, where the presence of fossils is practically non-existent. This transitional section, which may contain the K/Pg boundary, is associated with a change in the sedimentary conditions from detrital to chemical deposits (López-Martínez *et al*., 2006). Among the fossil content of this unit, red algae, foraminifers, charophytes, ostracods, crustaceans, molluscs, plants and vertebrate remains have been recovered (Liebau, 1973; López Martínez *et al*., 1998, 2001, 2006; Díez-Canseco *et al*., 2014; Vicente *et al*., 2015; Canudo *et al*., 2016). This unit has been interpreted as overbank facies deposited on tidal floodplains laterally associated with point bars of tide-influenced meandering fluvial channels (Díaz-Molina, 1987; Eichenseer, 1987; Cuevas, 1992; Rosell *et al*., 2001; López-Martínez *et al*., 2006; Oms *et al*., 2007; Riera *et al*., 2009; Díez-Canseco *et al*., 2014).

"Vallcebre limestones" and lateral equivalents (Esplugafreda Formation, Cuevas, 1992): Carbonatic unit composed of highly recrystallized, nodular and brecciated whitish massive limestones. It is highly variable in thickness, ranging from being absent (Isclés, Tremp and Barcedana–Toló sections) or just 4 m thick (Serraduy section) up to 100 m thick (Sta. Mª de Meyá and Campo sections) (López-Martínez *et al*., 2006). The fossil content is very scarce, but *Microcodium*, charophytes, benthic and planktonic foraminifers, ostracods, molluscs, dasycladal algae and calcispheres may appear (López-Martínez *et al*., 2006; Díez-Canseco *et al*., 2014). This unit has been associated with lacustrine environments of variable salinity near the coast (Rosell *et al*., 2001; López-Martínez *et al*., 2006). The 87Sr/86Sr isotopic ratio and the presence of euhaline seawater dasycladal algae and planktonic foraminifera may indicate sporadic connections of these lakes with the open sea (López-Martínez *et al*., 2006; Díez-Canseco *et al*., 2014). Unlike the Arén Formation and the lower units of the Tremp Formation, the K/Pg transitional strata and the Danian "Vallcebre limestones" and lateral equivalents are isochronous throughout the Tremp Basin (López-Martínez *et al*., 2006; Vila *et al*., 2013).

"Upper red unit" (Esplugafreda Formation–Claret Formation, Cuevas, 1992): This Paleocene unit is the most heterolithic, and is formed by a succession of lutites, sandstones, carbonates and gypsums. The bottom is characterized by the presence of lutites with an intense red color. Towards the top, the succession may contain conglomerates, paleosols and occasionally evaporite deposits, indicating a paleoclimatic shift towards more arid conditions. The presence of oncolites, stromatolites and *Microcodium* is also common (Rossi, 1993; Arribas *et al*., 1996; López-Martínez *et al*., 2006). This unit shows a new phase of detrital sedimentation in the basin with thick textured deposits including conglomerates, especially in the eastern sector of the Tremp syncline. In contrast, in the Ager syncline and the northwest sector of the Tremp syncline, the presence of carbonated deposits representing internal platform environments is more common (López-Martínez *et al*., 2006).

Stratigraphy

Stratigraphic succession of the Serraduy area

The characterization of the sedimentary succession of the Tremp Basin in the Serraduy area is mainly derived from two detailed stratigraphic sections studied in the field, the Larra (La) and Barranco Serraduy (BS) profiles (Fig. 3A), an exhaustive analysis of several outcrops in the whole area, as well as a new detailed mapping (Fig. 3B). The Larra profile is located in the western sector and comprises a 67-m-thick outcropping succession, whereas the Barranco

Serraduy profile, which is 175 m thick, is situated in the eastern area (Fig. 3). On the basis of these profiles, the studied infill consists of sandstones that progressively pass into heterolithic deposits comprising marls, calcarenites, mudstones, sandstones and limestones. According to regional data, these deposits correspond to the Arén Formation and the lower part of the Tremp Formation, with an age range from Maastrichtian to Danian.

The lower part of the succession corresponds to the Arén Formation and presents a well-exposure of outcrops, about 67 m thick, in the Barranco Serraduy area (Fig. 3A). This unit consists of brownish fine to coarse-grained sandstones with a massive texture, with medium to large-scale trough cross-bedding or parallel and cross-lamination contained in m-thick tabular beds. The presence of fragmentary dinosaur, turtle and crocodylomorph bones at the top of this formation is common. The unit exhibits a coarsening-upwards trend, except for the last seven meters, which change to a fining-upwards trend, and the sandstones grade up into an alternation of greyish massive marls and brownish calcarenites that represents the transition to the Tremp Formation (Fig. 3A). This transition is easily recognized in the area as a whole and is characterized by intensive bioturbation, oxide haloes, abundant bioclasts of bivalves and isolated bone remains.

The Tremp Formation is a very heterogeneous lithological unit that has been divided into four subunits (the “grey unit”, “lower red unit”, “Vallcebre limestones” and “upper red unit”). In this work, we focus only on the three lower subunits, which represent mixed carbonate–terrigenous deposits at the base, a middle section composed mainly of terrigenous deposits and an upper carbonated part.

The basal deposits, the “grey unit” (~15 m thick), correspond to a succession of greyish massive marls and calcarenites in dm- to m-thick tabular strata (Fig. 3A), with bioturbation, carbonate nodules, soft intraclasts and oxide haloes. Invertebrates such as bivalves, ostracods and gastropods, and vertebrate remains such as dinosaur and turtle bones, are common in the calcarenite levels.

The "lower red unit" consists of m-thick tabular mudstone bodies with tabular or channeled dm- to m-thick intercalations of fine- to coarse-grained sandstones, and rare cm- to dm-thick calcretes and marls; isolated channels comprising very coarse-grained sandstones are also present. The thickness of the unit changes from 56 to 77 m between the Larra and Barranco Serraduy profiles respectively (Fig. 3A). The mudstones (of varied colors) are massive, with common bioturbation and carbonate nodule mottling. The presence of coal, amber and microvertebrate remains is also common in the darkish beds. The root traces are filled with sand, carbonates or oxidations. Occasionally, they intercalate with cm- to dm-thick lenticular strata of brownish fine-grained sandstones with irregular bases and vertically bioturbated towards the top. The brownish sandstones appear in tabular or erosive levels: the former are massive beds although they sometimes present parallel lamination, scattered floating pebbles and vertical burrows; the latter exhibit a pervasive development of sedimentary structures dominated by trough cross-bedding, parallel and cross lamination, and asymmetric ripples. Rare calcrete levels with spherical carbonate nodules or crusts and frequent oxidizations have also been recognized. These deposits, especially the coarse- and very coarse-grained, include most of the vertebrate paleontological sites in the Serraduy area, with a great variety of fossil remains including hadrosaurid, testudine and crocodylomorph bones, as well as hadrosaurid and crocodylomorph ichnites.

The upper part of the profiles comprises a 5-m-thick tabular body of whitish limestones (mudstone to wackestone), with scarce fossil content mainly restricted to foraminifers and charophytes. This has been ascribed to the “Vallcebre limestones” subunit (Fig. 3). Above it is the upper part of the Tremp Formation called the “upper red unit”. This unit is more terrigenous and has similar lithological characteristics to the “lower red unit”. Nevertheless, its fossil content is scarce, and no vertebrate remains have been recovered.

Stratigraphic correlation

The stratigraphic correlation of the area has been based mainly on photogeology, the accurate physical correlation of beds in the field, and the lithological features of sedimentary bodies. The “grey unit” and the “Vallcebre limestones” represent two distinctive rock bodies, and this has also allowed the physical correlation between profiles (Figs. 3B and 4). Since most of the studied sediments of the “lower red unit” do not clearly crop out (Fig. 4), the detailed physical correlation of deposits has only been possible for thick sandstone beds located along the subunit (Figs. 3 and 4). These sandstones form m-thick tabular packages that have been physically correlated from visual inspection during fieldwork, as well as from analysis of aerial photographs (1:18000-scale) and 1:5000-scale satellite orthoimages.

In the area as a whole, the lower and upper boundaries of the “grey unit” and the lower boundary of the “Vallcebre limestones” are considered good correlation levels since: i) the thickness of these subunits is relatively homogeneous (Fig. 3A); ii) the contacts between subunits are not related with erosive surfaces; iii) the boundaries present the same lithofacies and sedimentary characteristics in different zones; and iv) lateral facies changes to other units are not recognized. Thus, these boundaries can be considered continuous and isochronous limits, at least in the study area, allowing their use as a regional datum.

On the other hand, the correlation of the “lower red unit” is based on five characteristic packages of sandstones, two of which can be recognized in the whole area and permit the correlation between the Larra and Barranco Serraduy profiles (Fig. 3A, B). Throughout the whole area, the first correlation level (L1 in Figs. 3 and 4) presents numerous dinosaur ichnites at the base and is always associated with a purple-greyish mudstone (Fig. 3A). In the western area, L1 comprises a tabular body of brownish fine- to medium-grained sandstones with parallel lamination that grade upwards to massive sandstones with bioturbation on the top. The underlying tabular body of grey-purple mudstones exhibits root bioturbation, vegetal remains and fossil vertebrates. Towards the southeast, L1 passes laterally into a thick body of greyish medium- to coarse-grained sandstones, which is composed of tabular and channeled strata. These beds are interfingered with purple bioturbated mudstones and show hadrosaurid dinosaur tracks at the base (Fig. 3A).

The second level (L2 in Figs. 3 and 4) comprises fine- to medium-grained massive sandstones with intense pedogenization and bioturbation in the western zone; L2 shows a negative-upwards trend. L2 corresponds to greyish sandstones that are fine- to very coarse-grained with trough cross-bedding, cross-lamination and ripples. This level displays sharp variations in thickness between the Larra and Isábena River outcrops. Towards the east, in the Barranco Serraduy outcrop, the variation in thickness continues to increase, and L2 forms a group of strata (~7 m thick) with a coarsening-upwards trend located 5 m above L1. The presence of hadrosaurid ichnites is also common at the base.

Level 3 is a cm-thick bed of brown fine-grained massive sandstones with scarce lateral continuity. L3 is located near to the Isábena River outcrop (Fig. 3B) and is not observed in other areas.

The fourth correlation level, which is up to one meter thick, is constituted by brown medium-grained sandstones with parallel lamination that passes vertically into cross-lamination. L4 presents a characteristic small slump (~20 cm thick) at the base and massive bioturbated sandstones (~15 cm thick) in the upper part. This level is easily recognizable in both western and eastern areas, from the Isábena River outcrop to near Barranco Serraduy (Fig. 3B).

The fifth level (L5 in Figs. 3 and 4A) is a fining-upward bed composed of 20 cm of greyish microconglomerates with slight channel geometry at the base and 60 cm of fine-grained massive sandstones with bioturbation. In the western area, from the Larra to Isábena River outcrops (Figs. 4A, B), this level presents good lateral continuity (Fig. 3B) and shows spectacular hadrosaurid dinosaur ichnites at its base.

On the basis of the vertical arrangement of the guide levels, chronostratigraphic refinement is possible for the studied sediments. Comparison of the thickness of the “lower red unit” between the Larra and Barranco Serraduy profiles shows clear variations, the succession being thicker in the latter (Fig. 3A). Accordingly, the average sedimentation rate for the Barranco Serraduy succession was slightly higher than for the Larra section. Consequently, the correlation results also allow us to constrain the vertical position of paleontological sites. This new correlation reveals that the most recent Cretaceous vertebrate remains correspond to dinosaur tracks and bones in L5 (the Camino de Rin 2 site) near the Larra section, which is located ca. 15 m lower than the Danian “Vallcebre limestones” (Fig. 3A).

Sedimentological interpretation

Characterization of the sedimentary environments requires exhaustive sedimentological analysis in order to establish and interpret correctly the different facies associations not studied in this work. Even so, the Serraduy area deposits may correspond with the evolution from coastal to continental environments, an interpretation previously proposed by several authors for the Tremp Basin (e.g., Eichenseer, 1987; Díaz-Molina, 1987; Cuevas, 1992; Rosell *et al*., 2001; López Martínez *et al*., 2006; Díaz-Molina *et al*., 2007; Oms *et al*., 2007, 2016; Riera *et al*., 2009; Villalba-Breva *et al*., 2012; Díez-Canseco *et al*., 2014; Canudo *et al*., 2016; Fondevilla *et al*., 2016a).

The sedimentary features, especially the sedimentary structures and grain-size distribution, indicate that the Arén Formation in this area corresponds with a barrier-island or deltaic environment. The presence of m-scale coarsening-upwards sequences, facies associations and stacking patterns in the studied interval are similar to those described by Navarrete *et al.* (2013) for barrier-island and washover fan deposits interbedded within mudflat lagoonal deposits. The Tremp Formation mainly represents terrestrial environments, but the presence of planktonic foraminifers (see below) indicates continuous entrances of marine water into the more protected areas. Thus, the lowermost subunit ("grey unit") has been interpreted as a transitional marine-to-continental environment connecting tidal systems with the barrier island. The "lower red unit" is predominantly composed of reddish-brownish and greyish-darkish mudstones representative of back-barrier mudflats, whereas the brownish tabular and erosive sandstones represent fluvial channels and their overbank deposits in the floodplains. Thus, frequent water-level oscillations and cyclic flooding of the mudflat area can be inferred from the sedimentary features. Several characteristics, such as mottling, oxide haloes and crusts, resulted from the migration and differential accumulation of iron, also indicating common water-table oscillations. In this context, the reddish colors of the mudstones suggest frequent subaerial exposure, probably in low water-level events. The vertical bioturbation and carbonate precipitation in the traces indicate the existence of vegetation with root penetration in search of the water level during dry periods. Darkish and greyish mudstones were deposited under anoxic conditions that favored the preservation of organic matter. This facies indicates the occurrence of high water-level periods, in which the mudflat areas were flooded. Isolated and anastomosed channeled sandstone bodies with freshwater charophytes (see below) indicate the existence of low-energy, meandering fluvial channels. Tabular, poorly sorted sandstone bodies and bioturbation traces filled with sands in mudstones reveal sharp flooding events related to high-energy water discharges. These floods occurred as a consequence of the overflow in the fluvial channels and the floodplain. The "Vallcebre limestones" represent the establishment of an extensive freshwater lake.

Material and methods

In order to ensure the replicability of this research, all the paleontological material figured in this study, including the vertebrate remains and foraminifers, is properly labeled with MPZ abbreviations (Museo Paleontológico de la Universidad de Zaragoza) and housed in the Museo de Ciencias Naturales de la Universidad de Zaragoza (Zaragoza, Spain).

The methodology applied in this study (magnetostratigraphy and biostratigraphy) is detailed and explained in the corresponding section.

Magnetostratigraphy

Paleomagnetic sampling and laboratory procedures

115 levels were sampled as part of the Serraduy magnetostratigraphic study, 21 from the Arén Formation (SB) and 94 from the Tremp Formation (SR). Both magnetostratigraphic

profiles were generated in the vicinity of the Barranco Serraduy (BS) stratigraphic section. SB consists of 6 levels of blue-grey marls from the Campo Member, and 14 levels of sandstones with one level of grey marls from the Arén Formation. In the SR profile, 17 levels correspond to the “grey unit” of marls and calcarenites of the Tremp Formation. Another 73 levels are defined as an alternation of red, grey and versicolor mudstones, with some levels of sandstones in the so-called “lower red unit”. Finally, 4 levels of the Paleocene “Vallcebre limestones” were sampled at the top of the SR section (Fig. 5).

The complete SB profile was sampled with a portable gas-powered and water-cooled drill and directly oriented in the field with a magnetic compass and an inclinometer, providing from 1 to 3 samples per level, each divisible into 1 to 3 standard-sized specimens. In the SR profile, 62 levels were drilled with a portable electrical water-cooled drill, hand samples (blocks) were taken from 29 levels and in 3 levels both drilled and hand samples were collected. These were oriented in situ with a magnetic compass. Hand samples were collected because of how easily broken up (being disaggregated) the finest materials corresponding to the “lower red unit” were. They were consolidated with sodium silicate dissolved in distilled water to try to make the consolidator percolate to the interior of each piece. Once hardened, about 3 cubes per block were sectioned with a disc cutter, maintaining the face perpendicular to the strike line and parallel to the dip line, both oriented in the field, as the marker for the paleomagnetic analysis.

The sampled levels in the SB profile were established each 1 m from the SB01 to SB06 marls, every 2–4 m at the beginning of the sandstones, and every 6 m afterward, due to the homogeneity of the materials. The sampled SR profile levels were separated by 1 m whenever possible. In total a sequence of 173 m was sampled.

Thermal (Th) and alternating field (Af) demagnetizations were carried out in the paleomagnetic laboratory of the University of Burgos, using a 755 superconducting magnetometer (2G) with an alternating field inductor demagnetizer system (for automatic Af), a TD48-DC (ASC) oven and a LDA3 (Agico) alternating field demagnetizer (for manual Af). A total of 198 samples (1 to 3 samples per level) were demagnetized with different stepwise temperatures and applied alternating fields according to the sample lithology. 145 of these were Th-demagnetized, heating up to 400–575°C for marls, sandstones, calcarenites and limestones, and up to 475–675°C for mudstones (several samples of all lithologies were heated up to 675°C in order to check their magnetic behaviors), 39 with automatic Af, 14 with manual Af trying to improve the accuracy of the method, and an Af protocol with an initial thermal step of 130°C to delete the part of the signal carried by goethite (all Af up to 100 mT).

Principal component analysis (PCA) and great circle (GC) analysis were performed with Remasoft 3.0 software (Chadima and Hrouda, 2006). Virtual Geomagnetic Poles (VGPs) were calculated, through the isolated paleomagnetic directions considered primary. In cases where overlapping prevents the isolation of stable paleomagnetic components, GCs were calculated. Together with the stratigraphic column, the VGP latitudes obtained from PCA paleomagnetic directions are symbolized with a point, whereas for the primary components verified by GC a bar occupies the status corresponding to normal or inverse latitude (-90° to 0° or 0° to 90°) (Fig. 5).

In addition, rock-magnetic measurements were carried out at the University of Burgos with a variable field translation balance (VFTB). Powdered whole-rock specimens from 14 representative samples from all lithologies were submitted to experiments on IRM acquisition and backfield curves, hysteresis loops and strong field magnetization versus temperature (Ms-T) curves. Analysis of these measurements was performed with RockMagAnalyzer 1.0 software (Leonhardt, 2006).

Paleomagnetic behavior

The natural remanent magnetization (NRM) behavior was analyzed separately in accordance with the lithology because of the big variations among lithologies. Sandstones and green/violet mudstones in general show low NRM intensities (0.1–0.5 mA/m) and a heterogeneous paleomagnetic behavior, being paleomagnetically unstable (it is not possible to isolate a reliable paleomagnetic component). In marls and red beds two paleomagnetic components can be identified on the basis of the unblocking temperature ranges and the coherence of the directional data.

Blue-grey marls

These rocks appear below the Arén Formation (Campo Member), at the bottom of the Tremp Formation (“grey unit”) and intercalated with continental sediments of the Tremp Formation (“lower red unit”) (Fig. 5).

Marls of the Campo Member (samples SB01-SB06 and SB11) show homogeneous paleomagnetic behavior, with NRM intensities between 1.1 and 1.78 mA/m, and display two different components in thermal (Th) demagnetization. A low-temperature component MB (unblocking temperatures between 250/300–450 ºC) with a northwards direction and positive inclinations (Fig. 6A) is isolated in all samples. This component does not go to the origin in some samples (Fig. 6B, C), going systematically to the southern quadrant with negative inclination (Fig. 6B). Great circle analysis (Fig. 6E) allows us to infer this high-temperature component (up to 500 ºC) with negative inclination (component MA), but this cannot be isolated because of spurious component formation during heating. Alternating field (Af) demagnetization diagrams show only one recognizable component (6/15–40/60 mT), which corresponds with component MB (Fig. 6A) with a slight overlapping with MA when this appears, as can be observed in the equal-area demagnetization diagram (Fig. 6B), but it is noteworthy that the overlapped component is almost trending to the origin, preventing recognition of the presence of two components.

The NRM intensity is lower in the marls of the Tremp Formation (SR samples), around 0.4–0.5 mA/m. A low-temperature component (250–400 ºC) is recognizable, and with some exceptions it goes to the origin, mainly in the basal marls (SR01-SR17); this component shows the same behavior as the already described MB component for the SB samples. However, a few samples (SR-01A, SR26-1) show an overlapping of components either (i) in the definition of great circles (Fig. 6E), indicating the presence of a high component (Fig. 6C), or (ii) by a cluster-end showing a south declination and negative inclination (Fig. 6D).

Therefore, most samples of SB and SR marls show the low-temperature MB component (between 250/300 ºC and 350/400 ºC) with normal polarity (positive inclination towards the north). This component does not go to the origin because of the presence of a high-temperature component (up to 350/400 ºC) with reversed polarity, which cannot be isolated because of the formation of spurious components but is clearly evidenced by analyzing the great circles.

According to the NRM behavior (low coercivity and unblocking temperatures between 150–500? ºC), and the magnetic rock properties (Fig. 6F), both components are carried by magnetite. Thermomagnetic curves show a major growth of magnetic minerals (magnetite according to the Curie temperature in the cooling curve) in agreement with that observed in the NRM.

Red mudstones

Red and orange mudstones appear throughout the Tremp Formation, mainly in the upper section. Most samples show low–medium NRM intensities ranging from 0.1 to 1.8 mA/m, but some of them have higher intensities around 3 mA/m. Low-intensity samples (~0.2–0.8 mA/m) usually show a single component (Fig. 7A) with unblocking temperatures from 350/550 ºC up to 620 ºC; however, the end of the component is obliterated because of a spurious component generated during heating. In some samples, generally those of a higher intensity (> 1 mA/m), component A overlaps with an intermediate temperature component between 350 ºC and 550 ºC (Fig. 7B, C); this overlapping component has low inclination and does not go to the origin. In these samples, component RA can be observed at temperatures up to 500 ºC (Fig. 7B). Finally, SR53 (Fig. 7D) shows high intensity and a single component with positive inclination toward the north, which can be interpreted as component RA according to its unblocking temperatures (550–625 ºC).

The unblocking temperatures and high coercivity (Fig. 7) point to hematite as the carrier of component RA. This is in agreement with the rock magnetism experiments (Fig. 7E), which are characterized by a high-coercivity magnetic phase with Curie temperatures over 600 ºC. Differences between the cooling and the heating in the thermomagnetic curve indicate the growth of magnetic minerals (probably magnetite or maghemite) during heating, at temperatures above 600 ºC.

Interpretation of the paleomagnetic components

Carbonatic rocks show the presence of two components with different unblocking temperatures. Component B, carried by magnetite, is characterized by low to intermediate unblocking temperatures (300–450 ºC) and does not go to the origin. Several works (e.g. Juárez *et al*., 1994; Villalaín *et al*., 1994; Osete *et al*., 2007) evidence the presence of low to intermediate unblocking temperatures (below 450–500 ºC) for diagenetic secondary magnetite, and a high-temperature component (above 450 ºC) corresponding with primary magnetite. The unblocking temperatures of secondary minerals are usually lower than those of primary ones. This is because of the small size of secondary minerals, which range from the superparamagnetic to the stable single domain (see Jackson and Swanson-Hysell, 2014). This suggests a secondary origin for component B found in the marls, but does not ensure a primary origin for the high-temperature component since the presence of two secondary magnetizations is also possible.

The paleopole reference for the Late Cretaceous of Iberia from the Lisbon Volcanics (Van der Voo and Zijderveld, 1971) corresponds to an expected direction for the section location of D=1.08º and I=47.39º. In spite of the low dip of the studied materials, the mean direction of component B is in better agreement before than after the bedding correction (BBC and ABC respectively, Fig. 8B). This fact agrees with a secondary origin for this component. We can thus consider component B to be a chemical remanent magnetization (CRM). This was acquired probably during the early diagenesis, but after the tilting of the series (note that the tilting is Maastrichian–early Paleocene [Simó et al., 1985], slightly postdating the age of the rocks). Component B partially obliterates the high-temperature component (A), which cannot be calculated because of the growth of magnetic minerals during heating. However, this is clearly evidenced by the demagnetization great circles.

Comparisons between the demagnetization great circles (Fig. 8C) calculated in carbonates (the NW–SE GC) and in red beds (the NE–SW GC) are coherent with the calculated direction of component A (Fig. 8A). This agrees with the correspondence between component A as calculated in red beds and the high-temperature component observed in carbonates.

As regards the assessment of the primary nature of component A in red beds, several hitches appear in this work regarding the interpretation of both components: (i) the thickness of the Upper Cretaceous in this locality is limited; (ii) the series shows significant changes in lithology and coloration which can produce different behavior in recording the paleomagnetic components; (iii) the absence of conglomerates and a near uniform and low dip (around 20º towards the east) along the section preclude the use of the field test to establish the primary nature of one of the components; and finally (iv) the presence of only one polarity prevents the use of the reversal test. However, several magnetostratigraphic works performed on longer sections of the same rocks (both in lithology and age) of the Tremp Basin (Galbrun *et al*., 1993; Oms *et al*., 2007; Pereda-Suberbiola *et al*., 2009; Vila *et al*., 2011, 2012; Canudo *et al*., 2016; Fondevilla *et al*., 2016a) show the presence of a component in red beds with similar paleomagnetic behavior. Reversal and tilt tests reveal a better concordance between the paleomagnetic direction and the reference in these works, showing a primary origin for this component. In accordance with these works, therefore, we consider that the component A observed in red beds is probably primary and can be considered a detrital remanence (DRM) carried by hematite.

Biostratigraphy

Planktonic foraminifera have been the basis for the micropaleontological dating of Pyrenean sections, from the deep sea to the continental shelf, mainly for Cretaceous materials. In the South-Central Pyrenees, the dinosaur-rich sites of the Arén Formation located west of the

Tremp syncline have been correlated with deep marine sediments containing planktonic foraminifera from the uppermost Maastrichtian *Abathomphalus mayaroensis* (Bolli, 1951) Zone near Campo (López-Martínez *et al*., 2001). Non-reworked planktonic foraminifera from the Maastrichtian were found in the "lower red unit" (Tremp Formation), suggesting transport after death landwards from the outer/inner shelf by tidal currents (Díez-Canseco *et al*., 2014). This and other biostratigraphic studies with planktonic foraminifera (Vicente *et al*., 2015) have indicated an early to late Maastrichtian age for the "grey unit" and "lower red unit" of the Tremp Formation and Danian for the "Vallcebre limestones".

Micropaleontological sampling and methodology

For micropaleontological studies, 94 samples were analyzed from the "grey" and "lower red units" of the Tremp Formation and the lower part of the "Vallcebre limestones". Rock samples were disaggregated in water with diluted H_2O_2, washed through a 63-µm sieve, and then oven-dried at 50°C. In each sample, between 100 and 200 specimens of foraminifers were picked from the residues and mounted on micropaleontological slides. Some were selected for scanning electron microscopy using a JEOL JSM 6400 SEM at the Microscopy Service of the Universidad de Zaragoza (Spain), and SEM photographs are provided in Figure 9.

Foraminiferal assemblages

Foraminifers are absent from the "grey unit" of the Tremp Formation. In the lower part of the "lower red unit", all samples contain planktonic foraminifers, and benthic foraminifers are very scarce. There are also relatively abundant fragments of echinoderms, marine bivalves and continental microfossils such as calcified charophyte fructifications. The preservation of the microfossils varies from poor to moderate (Fig. 9).

In the "lower red unit" of Barranco Serraduy, planktonic foraminifers indicate mixed assemblages with species of different ages. Some species are exclusively Maastrichtian, such as *Pseudoguembelina hariaensis* Nederbragt, 1991 and *Globotruncanita fareedi* (El Naggar, 1966). Other species have their first record before the Maastrichtian, but their ranges span this stage (*Heterohelix globulosa* (Ehrenberg, 1840), *Htx. planata* (Cushman, 1938), *Htx. labellosa* Nederbragt, 1991, *Htx. glabrans* (Cushman, 1938), *Pseudotextularia nuttalli* (Voorwijk, 1937), *Globigerinelloides yaucoensis* (Pessagno, 1967), *Gdes. bollii* Pessagno, 1967, *Gdes. praevolutus* Petters, 1977, *Globotruncana arca* (Cushman, 1926), *Gna. aegyptiaca* Nakkady, 1950, *Gna. bulloides* Vogler, 1941, *Gna. linneiana* (d'Orbigny, 1839), *Gna. mariei* Banner and Blow, 1960, and *Contusotruncana fornicata* (Plummer, 1931)). Finally, other species predate the Maastrichtian (*Ventilabrella eggeri* Cushman, 1928, *Sigalia deflaensis* (Sigal, 1952), *Hedbergella flandrini* Porthault, 1970 (in Donze *et al.*, 1970), *Dicarinella primitiva* (Dalbiez, 1955), *Ticinella raynaudi* Sigal, 1966, *Favusella washitensis* (Carsey, 1926), and *Whiteinella* spp.). The small benthic foraminifera mainly consist of calcareous trochospiral plano-convex species (such as *Anomalinoides* spp. and *Gyroidinoides* spp.) and planispiral *Lenticulina* spp.

Interpretation of foraminiferal faunas

Since planktonic foraminifers are almost absent from the "grey unit", no unequivocal age attributions have been obtained for this interval. Although the distinction of *in situ* and *ex situ* specimens is difficult, the foraminiferal assemblages identified in the "lower red unit" suggest that they are reworked and mixed: some of the planktonic foraminifer species identified are of different ages, and most of the benthic foraminifers indicate a contradictory bathyal depth. The studied stratigraphical interval cannot be assigned to any biozone with reworked specimens, but at least a minimum age can be assigned based on the most modern species identified in these horizons. The presence of *P. hariaensis* specimens in samples 35 and 49 suggests that the last 60 m of the “lower red unit” are late Maastrichtian in age, since the first appearance of *P. hariaensis* was calibrated at 67.3 Ma (upper part of chron C30n) according to the time-scale GTS 2012 (Gradstein *et al.*, 2012).

In the “Vallcebre limestones”, a few specimens of *Guembelitria cretacea* Cushman, 1933 and *Guembelitria blowi* Arz, Arenillas and Náñez, 2010 have been identified in samples 80 and 94. *Guembelitria* is the only genus whose survival beyond the Cretaceous/Paleogene mass extinction event has been clearly proven (Smit, 1982). However, these specimens are probably reworked, as the uppermost occurrence of *Guembelitria* is in the lower Danian, and these *Guembelitria* specimens were found in horizons equivalent to the Suterranya Limestone Formation belonging to the upper Danian (Díez-Canseco *et al*., 2014).

Vertebrate assemblage

Considering the limited extent of the outcroppings of the Tremp Formation in the Serraduy area compared to the rest of the outcrops within the Tremp syncline, this sector represents one of the areas with the richest and most diverse vertebrate assemblages in the Tremp Basin. In a studied area of approximately 1.5 km^2 of outcrops of the Tremp Formation, nearly 40 paleontological sites with more than 600 vertebrate remains distributed in about 17 stratigraphic levels have been found (Table 1). Although most of this material is currently under study, a preliminary review of the fossils recovered in recent years (mainly between 2009 and 2016) has allowed the identification of dinosaurs (sauropods, hadrosauroids and theropods), crocodylomorphs, testudines and amphibians. Within the paleontological site Camino de Rin 2, located in the upper part of the “lower red unit”, a bone fragment has been recovered that could correspond to a pterosaur mandible. However, this fossil remnant is still under laboratory preparation. The presence of pterosaurs in the Serraduy area thus remains uncertain. The most representative material recovered in the area will be described below.

Dinosaurs

Hadrosauroids

The most abundant taxa recovered in Serraduy correspond to hadrosauroids, representing between 60% and 75% of the identified dinosaur remains. This percentage variation is a consequence of the doubtful assignment of some remains to Hadrosauridae? due to their fragmentary nature. Around 20% of the bones were classified as Dinosauria indet., being unable to perform a more precise taxonomic assignment until now. The distribution of hadrosauroids through the studied stratigraphic sections and paleontological sites is also very extensive (Fig. 1), it being possible to find remains from the top of the Arén Formation through to the last levels with vertebrates before the K/Pg boundary, within the "lower red unit" of the Tremp Formation.

Most of the hadrosauroid remains are disarticulated and correspond to vertebral elements, which represent more than half of the identified bones (Fig. 10). Most vertebrae are caudal, although there are representative elements from most of the vertebral column. In addition, fragments from ribs, chevrons, femora (Fig. 11D), pubis, isolated teeth, dentaries, maxilla, autopodial bones (Fig. 11B), humerus, scapula, isolated teeth, tibiae (Fig. 11C), ulna and coracoid (Fig. 11A) have also been identified. Because most of the material is fragmentary and/or poorly diagnostic, most of the remains have been assigned to Hadrosauroidea indet. and Hadrosauridae indet.

One of the most interesting aspects observed in Serraduy is the joint presence of mature medium to large-sized hadrosaurids and mature small-sized hadrosaurids that may represent new insular dwarf species (Cruzado-Caballero *et al*., 2014; Blanco *et al*., 2015b; Company *et al*., 2015). The hypothesis of the presence of dwarf hadrosaurids in Serraduy is based on the recovery of several small vertebrae with mostly fused neural arches, several diminutive limb bones and a histological study of several rib fragments and representative elements such as a humerus and a femur (Company *et al*., 2015). These remains represented the first case of dwarfism in hadrosaurids registered in the Iberian Peninsula, this being the smallest hadrosaurid known in Europe to date (Company *et al*., 2015). In addition, the large amount of recovered vertebrae with unfused neural arches also indicates the presence of a great number of immature individuals in the area.

The presence of hadrosauroid ichnites is very widespread throughout the sector, their preservation as natural casts (convex hyporeliefs) being common at the base of most sandstone channel beds (Fig. 12). All these ichnites have been attributed to the ichnogenus *Hadrosauropodus* (Vila *et al*., 2013).

In addition, some eggshell fragments have also been recovered. Due to their external sagenotuberculate ornamental pattern, these eggshells have been tentatively assigned to *Spheroolithus europaeus* Sellés, Vila and Galobart, 2014a. However, to confirm this assignment further exhaustive microscopic study will be necessary. *Spheroolithus europaeus* was first defined near the village of Pont d'Orrit (Lleida, Spain) within the "grey unit" of the Tremp Formation (chron C30n, late Maastrichtian), representing the youngest oological record of hadrosauroids in Eurasia (Sellés *et al*., 2014a). The recovered eggshells from Serraduy have been identified up until the lower-mid part of the "lower red unit" of the Tremp Formation (172-i/04/f paleontological site). If their assignment to *Spheroolithus europaeus* is confirmed, these eggshells would therefore be even more modern than those recovered at the Pont d'Orrit locality.

Theropods

The presence of theropods within the Serraduy area is not very abundant, representing between 1% and 4% of the identified dinosaur remains. These theropod bones have been found from the “grey unit” to the middle part of the “lower red unit” of the Tremp Formation, thus constituting the youngest reliable record of non-avian theropods in the Iberian Peninsula and one of the youngest records in Europe.

The most important record corresponds to two isolated teeth that belong to two different taxa, a medium–large form and a small-sized theropod. The first specimen (MPZ 2017/804; Fig. 11F) corresponds to a medium–large tooth with serrated carinae, which was recovered at the top of the "grey unit" of the Tremp Formation, very close to the 172-i/04/e paleontological site. This tooth is very similar to Morphotype 1 described by Torices *et al*. (2015) in the Spanish sites of Blasi (Huesca, upper Maastrichtian), Montrebei (Lleida, upper Campanian–lower Maastrichtian) and Laño (Burgos, upper Campanian–lower Maastrichtian). Due to its limited diagnostic value, this morphotype has been assigned to Theropoda indet. (López-Martínez *et al*., 2001; Torices *et al*., 2004, 2015; Pereda-Suberbiola *et al*., 2015). The second specimen corresponds to a small tooth with smooth carinae, which was recovered at the Larra 4 paleontological site within the "lower red unit" of the Tremp Formation. This tooth is very similar to the teeth assigned to Coelurosauria indet. from Blasi (Huesca, upper Maastrichtian), Montrebei (Lleida, upper Campanian–lower Maastrichtian), Laño (Burgos, upper Campanian–lower Maastrichtian) and

Vicari 4 (Lleida, upper Campanian) (López-Martínez *et al*., 2001; Torices *et al*., 2004, 2015; Pereda-Suberbiola *et al*., 2015).

The other remains, also recovered in the “grey unit” and the “lower red unit” of the Tremp Formation, correspond to a possible cervical vertebra of an avian theropod (Cruzado-Caballero *et al*., 2012) and fragmentary long bones and a vertebral fragment that may correspond to undetermined theropods. Nevertheless, for the proper taxonomic assignation of these remains, further detailed studies will be necessary.

Sauropods

Among the dinosaur remains, the presence of sauropods is the scarcest, amounting to around 1% of the identified remains. The most important item is a proximal left femur fragment (MPZ 99/143; Fig. 11E) assigned to Titanosauria indet. (Canudo, 2001; Vila *et al*., 2012). This femur was recovered in the "grey unit" of the Tremp Formation, representing one of the youngest sauropods yet documented in Eurasia (Canudo, 2001; Vila *et al*., 2012; Sellés *et al*., 2016).

Other possible sauropod remains consist of a caudal vertebra from the Barranco de Serraduy 4 site (Cruzado-Caballero *et al*., 2012) and a proximal fragment from a big autopodial bone from the Camino de Fornons 1 site. However, due to the fragmentary nature of these bones, their assignment to Sauropoda still remains doubtful. For the proper assignation of these specimens, further studies as well as the recovery of new remains will be necessary. Both these remains appeared in the middle part of the "lower red unit", so if their assignment to Sauropoda is confirmed, they would be more modern than the femur, extending the presence of sauropods to chron C29r, as already seen in other sectors of the Tremp Basin (Sellés *et al*., 2016).

Testudines

Another common clade, comprising about 5% of the remains found in Serraduy, is Testudines. The presence of testudines has been recognized from the top of the Arén Formation to the last deposits with vertebrates of the “lower red unit” of the Tremp Formation. This clade is represented entirely by isolated and disarticulated plates, in most cases preventing a more accurate identification or classification in the preliminary study, and rendering further systematic studies necessary. Nevertheless, when the plates are well preserved, it is possible to observe their smooth and brilliant ornamentation crossed by very fine dichotomic sulci, suggesting highly vascularized shell bones. This characteristic ornamentation pattern is widely used to recognize bothremydids (e.g., de Lapparent de Broin and Murelaga, 1996; Murelaga and Canudo, 2005; Marmi *et al*., 2012), so most of these plates are assigned to Bothremydidae indet.

In addition, better-preserved plates allowed more accurate anatomical identification, and a left xiphiplastron and a right mesoplastron belonging to Bothremydidae from the Rim 2 site at the top of the Arén Formation have been recognized (Murelaga and Canudo, 2005).

Crocodylomorphs

Representing about 4% of the recovered bone remains, crocodylomorphs are one of the most representative taxa in Serraduy. This group of archosaurs is mainly represented by isolated teeth, although some ichnites, a eusuchian vertebra, osteoderm fragments and a complete skull have also been found (Fig. 13E). All the recovered remains have been assigned to Eusuchia. These have a highly extended stratigraphic distribution, remains being found from the top of the Arén Formation up until the last levels with vertebrates before the K/Pg boundary.

The most important taxon corresponds to the complete skull of the eusuchian crocodylomorph originally erected in Serraduy with the name of *Allodaposuchus subjuniperus*

(Puértolas-Pascual *et al.*, 2014) (MPZ 2012/288; Fig. 13E). This taxon was later assigned to the new genus *Agaresuchus* and included within Allodaposuchidae (Narváez *et al.*, 2016), a clade of endemic European eusuchian crocodylomorphs with a record until the K/Pg boundary. *Agaresuchus subjuniperus* was recovered in one of the last Maastrichtian sandstone strata (Amor 3 site), so this taxon may represent the last and youngest record of Allodaposuchidae before the K/Pg extinction event (Puértolas-Pascual *et al.*, 2014).

As regards isolated teeth, at least two different morphotypes have been distinguished. The first morphotype (Fig. 13A) corresponds to a slender conical tooth ornamented with well-marked longitudinal ridges, which was found at the top of the Arén Formation (Barranco de Extremadura site). These tooth have been assigned to cf. *Thoracosaurus* (Puértolas-Pascual *et al.*, 2016). This marine genus belonging to Gavialoidea is typical of the Upper Cretaceous–lower Paleocene of Europe and North America, which is consistent with its presence within the shallow marine facies of the Arén Formation. Teeth of the second morphotype (Fig. 13B, C) have been recovered from the “grey unit” up until the last levels with vertebrates within the “lower red unit” of the Tremp Formation. This morphotype corresponds to generalist conical teeth with an ornamentation that varies from smooth to gently longitudinally-ridged enamel. This generalist morphology is widely distributed within Crocodylomorpha and has little taxonomic value (e.g., Prasad and Broin, 2002; Turner, 2006; Andrade and Bertini, 2008; Buscalioni *et al.*, 2008). However, as this dental morphology is also typical of Allodaposuchidae, the most common clade in Europe during the Campanian–Maastrichtian, this morphotype has been tentatively assigned to cf. Allodaposuchidae. Additionally, several isolated teeth similar to those present in *A. subjuniperus* were recovered in the same site where the holotype was recovered, so these teeth have been assigned to cf. *Agaresuchus subjuniperus*.

Other bone remains correspond to osteoderm fragments and a procoelous dorsal vertebra (Fig. 13D) that have been assigned to Eusuchia indet. Further evidence of Crocodylomorpha is the presence of about five tracks (MPZ 2012/832) composed of scratch marks and one pedal impression located on a fluvial channel deposit in the uppermost part of the “lower red unit” of the Tremp Formation (Serraduy Norte site, chron C29r). The scratch marks resemble *Characichnos* whereas the pes track has been assigned to cf. *Crocodylopodus* (Vila *et al*., 2015).

Amphibians

Due to their small size, amphibian remains have only been recovered by washing and sieving techniques. In the area of Serraduy, one of the paleontological sites with the greatest potential for the study of macrovertebrates and microvertebrates is Larra 4, located within the "lower red unit" of the Tremp Formation. This site is located in a dark grey lutite layer with a high organic content, where vegetal remains (wood and amber fragments), macrovertebrates (dinosaurs, crocodylomorphs and testudines) and microvertebrates are highly abundant. Most of the microvertebrate remains are very fragmentary and need a more thorough systematic study for their proper identification.

Nevertheless, a very preliminary study of the micropaleontological content allowed us to identify several remains that may correspond with amphibians. The most outstanding remains are several distal parts of humeri. In spite of the low taxonomic value of the humerus (Evans and Milner, 1993), the large and spherical humeral ball shifted laterally and a rather long ulnar epicondyle allow us tentatively to assign these specimens to Discoglossidae indet., being very similar to other humeri assigned to this clade in other sites within the Tremp Basin (Blain *et al*., 2010; Blanco *et al*., 2016).

Discussion

Considering component A as primary (see "Magnetostratigraphy" section), the local magnetic stratigraphy of the Serraduy section can be correlated with the geomagnetic polarity time scale (GPTS) (Gradstein *et al*., 2012). According to our results, the "grey unit" and the "lower red unit" of the Tremp Formation can be assigned to a reverse polarity chron (Fig. 5).

The presence of the planktonic foraminifer *P. hariaensis* in sample SR35 indicates that this level has a maximum age of 67.3 Ma (maximum age range of the species), or younger if it is reworked. The age range for this species is between 67.3 and 66.0 Ma, its lowermost and uppermost occurrences being coincident respectively with the upper part of C30n and the K/Pg boundary in the middle part of C29r. According to López-Martínez *et al*. (2006) and Díez-Canseco *et al*. (2014), the "Vallcebre limestones unit" and lateral equivalents are late Danian in age. Because this biostratigraphic information indicates that the K/Pg boundary is located between the "lower red unit" and the "Vallcebre limestones unit", all the reverse polarity section between levels SR35 and SR90 can thus only correspond with chron C29r (Fig. 5). As a result, the K/Pg boundary can be located within the last 25 m of the "lower red unit", between the last horizon with dinosaur remains and the "Vallcebre limestone unit" (Fig. 5). Correlating the profile of Barranco Serraduy with Larra, located further west, the K/Pg boundary can be located with more precision within the last 5 m of the "lower red unit" (Figs. 3, 5).

Therefore, the upper section of the "lower red unit" is well defined as reverse polarity, pointing to the C29r (Fig. 5). However, some inconsistencies can be observed in the middle part of this formation. SR37, above the level marked by *P. hariaensis*, has reversed polarity (indicating C29r), whereas level SR53 shows normal polarity. Therefore, one part of this paleomagnetic information must be wrong. As regards its paleomagnetic properties, level SR35 has similar behavior to samples from the uppermost levels, with a non-zero ending cluster up to 500 ºC with reversed polarity. Otherwise, component RA of level SR53 (Fig. 7D) has been defined by its unblocking temperature range; however, it is possible that this component corresponds with the CRM defined as RB. The lithology of both samples can also be analyzed: the paleomagnetic component defined in SR35 is more reliable than that defined in SR53 because the former is sampled in red mudstones, similar to the upper section where coherent paleomagnetic components appear, whereas SR53 is in a level of shale located between sandstones. The greater porosity of sandstones could have favored chemical processes in level SR53. In the light of these considerations, we consider that the section between levels SR37 and SR90 belongs to subchron C29r.

The lower section of the Tremp Formation also shows reversed polarities (see “Magnetostratigraphy” section), so at the beginning it is possible to ascribe this to subchron C29r (Fig. 14). However, Fondevilla *et al*. (2016a) provide evidence of the presence of a major hiatus affecting chrons C31n, C30r and C30n in the Isona section located in the eastern sector of the Tremp syncline (Fig. 14), probably related to an abrupt migration of the basin depocenter. This would imply the presence of consecutive deposits associated with chrons C31r and C29r, with a hiatus lacking most of the upper Maastrichtian. Nevertheless, according to the magnetostratigraphic works of Pereda-Suberbiola *et al*. (2009) on Arén, and Canudo *et al*. (2016) on Campo, this major hiatus seems not to have affected the most western sectors of the Tremp Basin (Fig. 14). Therefore, the sections of Campo and Arén acquire greater relevance because the “lower red unit” exposed there is the only continental record of chron C30n in the whole Tremp syncline (Fondevilla *et al*., 2016a).

In summary, the magnetostratigraphic data presented in this work show that both the marls and red beds of the Tremp Formation in the Serraduy area are of reverse polarity. Biostratigraphic data ensure that the upper part of this formation (the last 60 m of the “lower red unit”) belong to chron C29r. However, although this cannot be fully confirmed for the lower part of the Tremp Formation (the “grey unit” and beginning of the “lower red unit”), these units probably also belong to the same chron C29r, unless there exists a hiatus such as that observed by Fondevilla *et al*. (2016a) in the Isona section. It should be pointed out that this hiatus has not been observed in Campo and Arén (Pereda-Suberbiola *et al*., 2009; Canudo *et al*., 2016), the sections closest to the Serraduy area.

Conclusions

In this work, a chronostratigraphic framework for the vertebrate sites of the Arén and Tremp Formations within the Serraduy sector of the Tremp Basin is proposed for the first time. The joint study of stratigraphy, field correlations, magnetostratigraphy and biostratigraphy has allowed most of the vertebrate sites in this area to be dated to within chron C29r, making this one of the areas with dinosaur sites closest to the K/Pg boundary anywhere in Europe. In addition, a complete faunal list of the taxa recovered in the Serraduy area is presented. This shows a great diversity of theropods, sauropods and hadrosaur dinosaurs, eusuchian crocodylomorphs, testudines, amphibians and probably pterosaurs.

The presence of dinosaurs (ichnites and bones) in the highest levels of the series has pinpointed the range of the K/Pg boundary to the last 5 m of the “lower red unit” within the

Tremp Formation, below the “Vallcebre limestones”. This suggests a high abundance of hadrosaurid dinosaurs, eusuchian crocodylomorphs, amphibians and testudines just before the great extinction event of the Late Cretaceous.

Although everything points to a late Maastrichtian age for the studied deposits, the lower half of the section unfortunately shows unclear paleomagnetic signals and inconclusive biostratigraphic content, so it has been assigned an undetermined polarity. The magnetostratigraphic results also seem to indicate the presence of a reverse polarity chron in the lower half of the section, yet we do not have the biostratigraphic data to be able to assign it to a specific chron (C31r, C30r or C29r). For this reason, the continuity of the lower part of the series or the presence of possible hiatuses cannot be determined. Further studies in the adjacent outcrops located between Serraduy and Campo (e.g. Rin or Larra sections) and between Serraduy and Arén (e.g. Iscles section) could be crucial to achieve more accurate knowledge of the chronostratigraphic framework of the northwestern-most branch of the Tremp Basin.

In conclusion, these results show the great paleontological potential of the Serraduy area, which is one of the few and most important places in the world for studying, within continental deposits, the great extinction event which affected planet Earth at the end of the Cretaceous.

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Figure captions

Figure 1. Geographical and geological situation of the Serraduy sector (Huesca, Spain). A. location of the Pyrenees within the Iberian Peninsula; B. geological map of the Serraduy sector; the red stars indicate the areas with the highest concentration of vertebrate sites; the red rectangles indicate the magnetostratigraphic sections (SB, SR) studied in this work; C. composite stratigraphic section of the studied profiles and stratigraphic vertebrate distribution.

Figure 2. Lithostratigraphic subdivision of the Tremp Formation according to different authors. Modified from Cuevas (1992) and Riera (2010).

Figure 3. A. correlation panel of the stratigraphic profiles and vertebrate sites studied in this work; B. detailed geological map of the Serraduy sector and guide level locations.

Figure 4. Landscape views of the main areas with outcrops and paleontological vertebrate sites in the Serraduy sector. A. outcrop of the Larra stratigraphic section located on the west side of the Isábena River; B. succession of the Arén and Tremp Formation in the sector located west of the Isábena River; C. succession of the Arén and Tremp Formation in the Barranco Serraduy sector located east of the Isábena River. Red stars point to the main areas with vertebrate sites; the

white dotted lines mark the contact between different units; and the colored dotted lines point to the location of the different guide levels.

Figure 5. Lithology, paleontological site positions, and the proposed magnetostratigraphy from the Barranco Serraduy section. VGP latitude logs along the Arén Formation (SB) and Tremp Formation (SR) profiles are shown by circles (black or white) when the polarity has been calculated from paleomagnetic directions obtained by principal component analysis (PCA) or by bars (white) when it has been obtained by great circle analysis (GCA).

Figure 6. A to D. demagnetization diagrams, in geographic coordinates, showing the paleomagnetic behaviors in representative samples of carbonatic rocks; A to B. samples from the SB and SR sections showing an overlap between two components with opposite direction; D. sample of the SR section with a normal polarity component at low temperatures and a dispersed high temperature cluster; E. equal area projection of the MB component and the demagnetization great circles calculated in these rocks, before and after bedding correction (BBC and ABC respectively). Note the path from normal polarity to reverse polarity followed by all samples; F. representative rock magnetic experiments of this lithology. From left to right, acquisition of the isothermal remanent magnetization (IRM), non-corrected and corrected hysteresis loop, and thermomagnetic curve. The low coercivity may indicate the presence of magnetite as the main magnetic mineral, as can be observed in the IRM and hysteresis loops; the thermomagnetic curve shows an important growth of magnetite up to 400ºC.

Figure 7. A to D. demagnetization diagrams showing, in geographic coordinates, the paleomagnetic behaviors in representative samples of red beds; A. components RA and RB with the same polarity; B and C. component RB does not go to the origin and a non-zero end cluster reveals component RA with reversed polarity; in SR78-2B, RA is partially demagnetized before the growth of the magnetic mineral during heating (up to 620ºC); D. RA and RB with normal polarity; E. representative rock magnetic experiments of this lithology. From left to right, IRM, hysteresis loop and thermomagnetic curve. The high coercivity observed in the IRM and in the hysteresis loop and the presence of a magnetic phase with Curie temperatures above 620ºC indicate the presence of hematite as the main magnetic phase. The higher magnetization of the cooling curve indicates the growth of magnetite during heating.

Figure 8. Equal-area projection of component A (A) and component B (B) with their respective Fisher means (Fisher, 1953), before and after bedding correction (BBC and ABC respectively); C. calculated demagnetization great circles (GC) and mean direction of both components; note that both components overlap with the GC mean intersection, component A being almost coincident with its mean. n: number of samples. NW-SW GCs correspond with carbonates and NE-SW GCs with red beds.

Figure 9. Some representative planktonic and benthic foraminifer species identified in the Barranco Serraduy section. From left to right and from top to bottom: *Laeviheterohelix glabrans* (MPZ 2018/25), *Heterohelix globulosa* (MPZ 2018/23), *Guembelitria blowi* (MPZ 2018/28), *Hedbergella flandrini* (MPZ 2018/24), *Ventilabrella eggeri* (MPZ 2018/22), *Pseudoguembelina hariaensis* (MPZ 2018/21), *Globigerinelloides praevolutus* (MPZ 2018/27), *Globotruncana*

bulloides (MPZ 2018/26), *Contusotruncana fornicata* (MPZ 2018/20), *Favusella washitensis* (MPZ 2018/18), *Gyroidinoides* sp. (MPZ 2018/19).

Figure 10. Vertebrae of Hadrosauridae indet. from Serraduy. A. caudal (juvenile MPZ 2017/796 from AM2 site); B. caudal (adult MPZ 2017/797 from LAR3 site); C. caudal (juvenile MPZ 2017/798 from LAR3 site); D. cervical (adult? MPZ 2017/799 from LAR3 site). In posterior/anterior, dorsal, lateral and ventral views respectively. Scale bar = 3cm.

Figure 11. Dinosaur remains from Serraduy. A. coracoid of Hadrosauridae indet. (MPZ 2017/800 from LAR2 site) in medial and lateral views; B. phalanx of Hadrosauridae indet. (MPZ 2017/801 from LAR3 site) in dorsal, lateral and ventral views; C. tibia (distal fragment) of Hadrosauridae indet. (MPZ 2017/802 from LAR3 site) in anterior, posterior and distal views; D. femur (proximal fragment) of Hadrosauridae indet. (MPZ 2017/803 from LAR3 site) in anterior, lateral, posterior, medial and proximal views; E. femur (proximal fragment) of Titanosauria indet. (MPZ 99/143 from femur site) in posterior view; F. teeth of Theropoda indet. (MPZ 2017/804 from 172-i/04/e site) in lingual and labial view (white boxes show the detailed denticles). Scale bar without number = 3cm.

Figure 12. Dinosaur ichnites of *Hadrosauropodus* indet. from Serraduy (Pedregal site).

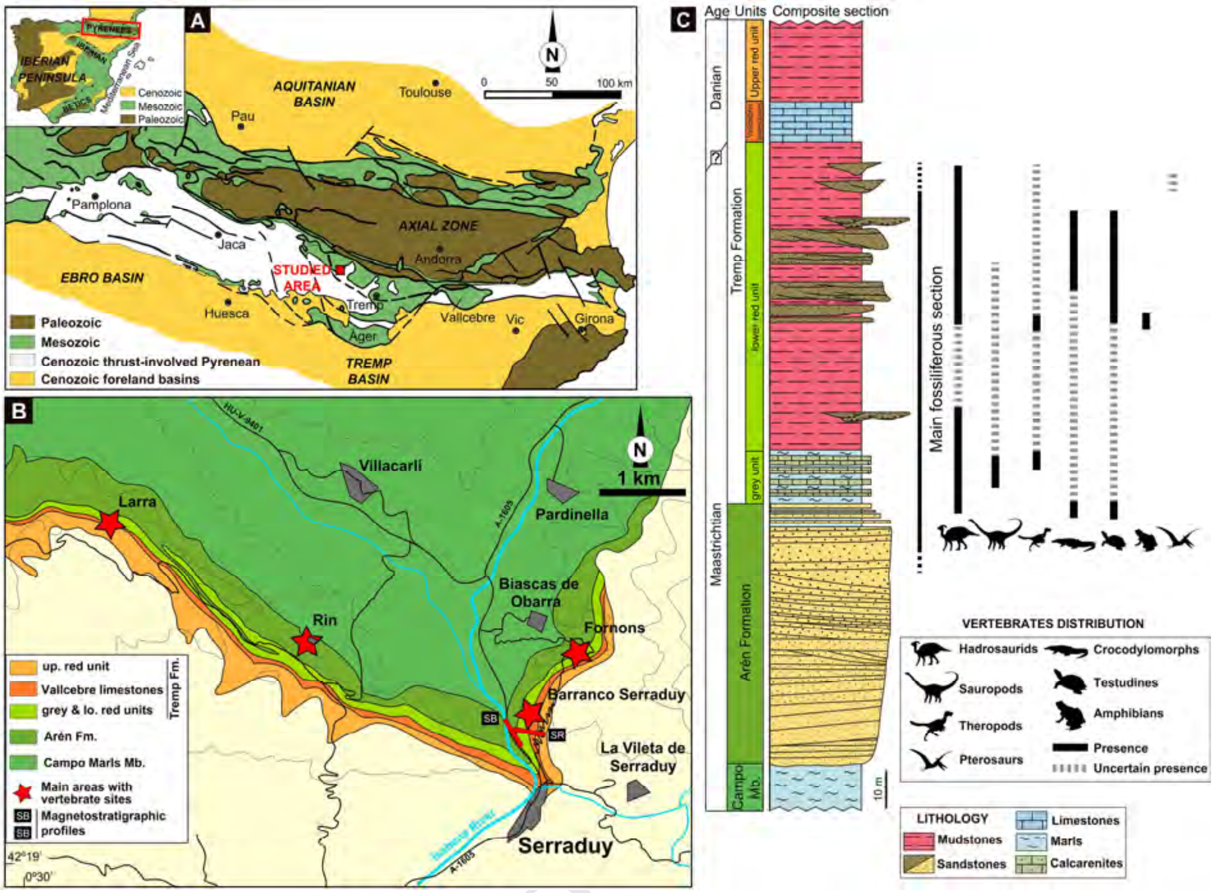
Figure 13. Crocodylomorph (Eusuchia) remains from Serraduy. A. teeth of cf. *Thoracosaurus* (MPZ 2017/806 from EXT site); B. teeth of cf. Allodaposuchidae (MPZ 2017/807 from DL3 site); C. teeth of cf. Allodaposuchidae (MPZ 2017/808 from PED site); D. dorsal vertebra of

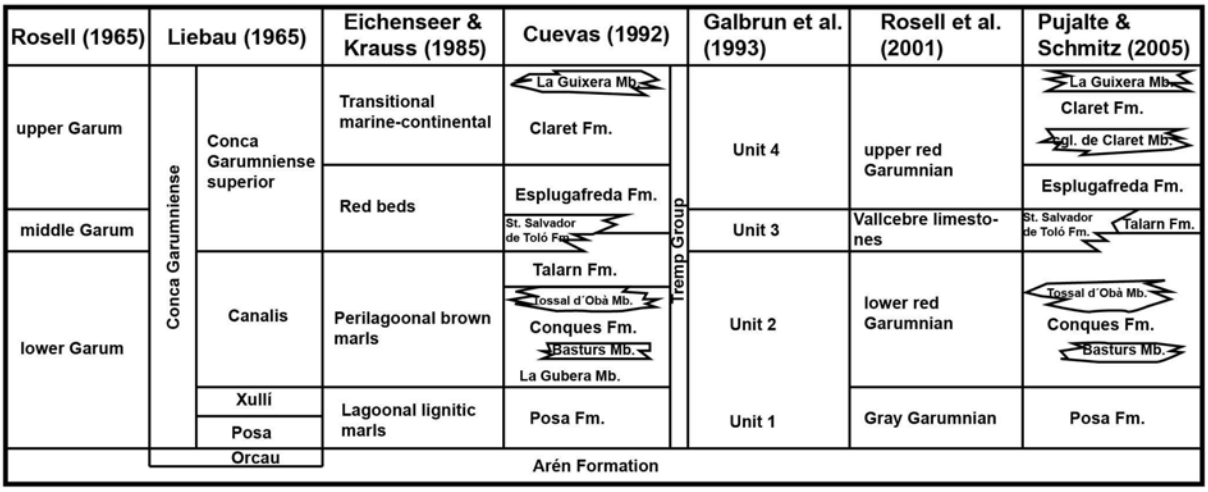
Eusuchia indet. (MPZ 2017/805 from LAR3B site); E. skull holotype of *Agaresuchus subjuniperus* (MPZ 2012/288) (from AM3 site).

Figure 14. Chronostratigraphic framework with indication of lithostratigraphy, paleomagnetic data, correlation and the K/Pg transition in the main Maastrichtian South Pyrenean continental sections with magnetostratigraphic data.

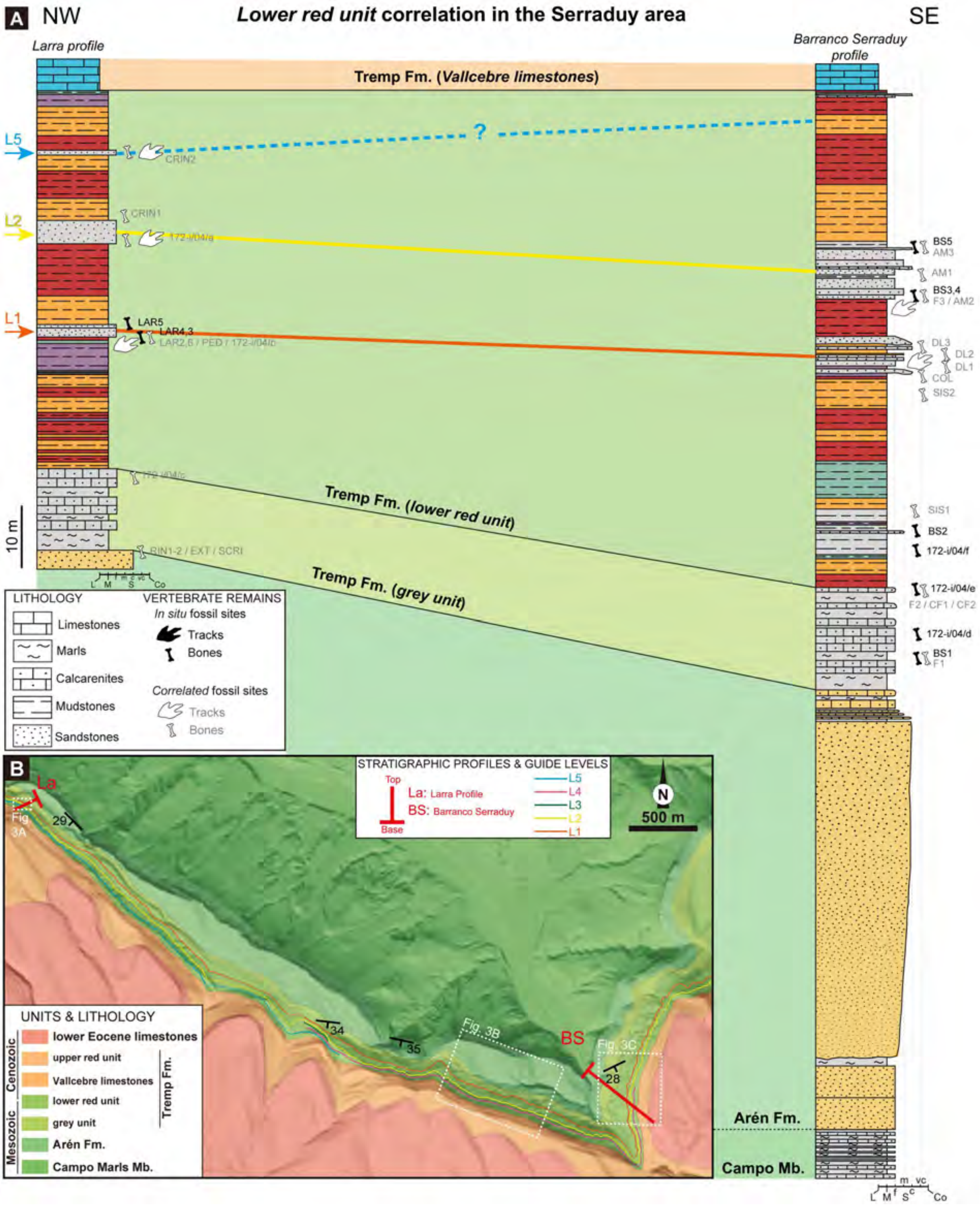
Table 1. Vertebrate faunal list for Serraduy (Huesca, Spain), upper Maastrichtian.

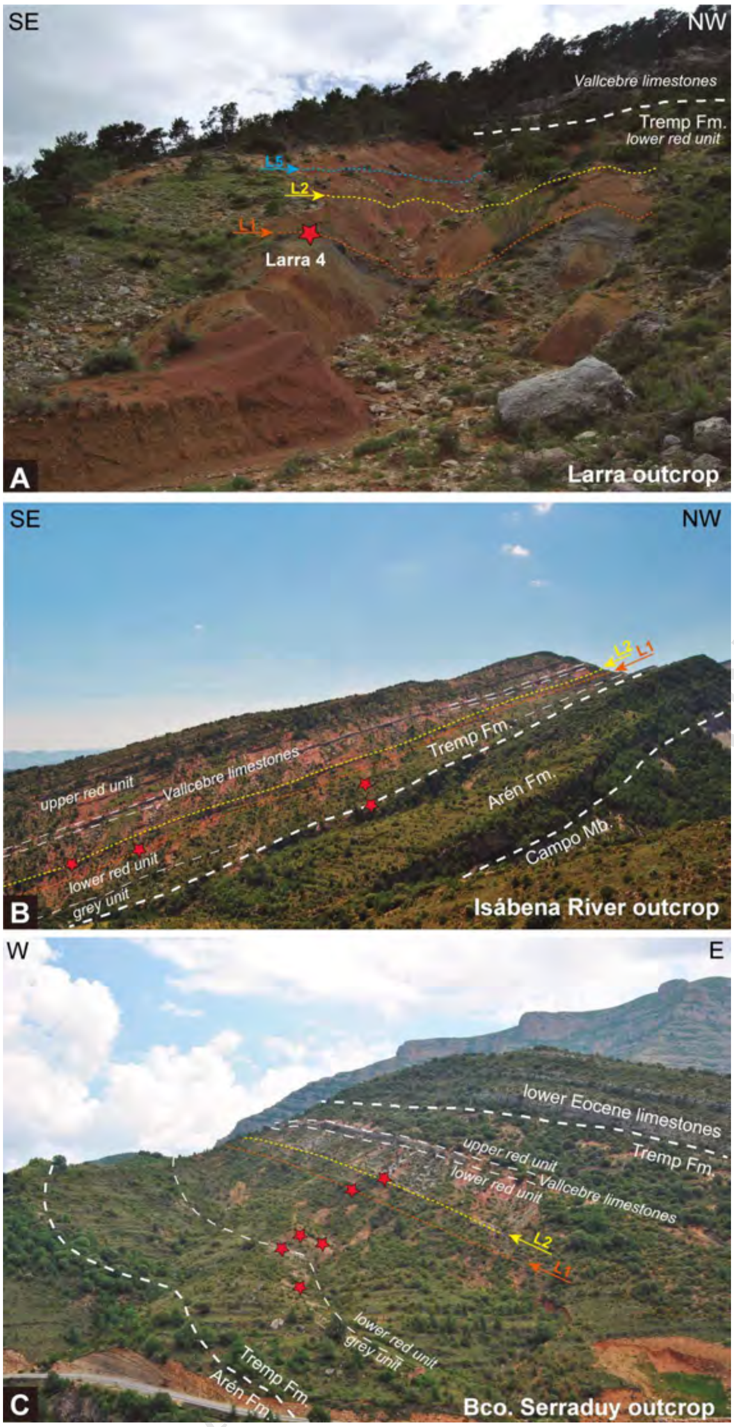
Site	**Abbreviation**	**Taxa**	**Site**	**Abbreviation**	**Taxa**
172-i/04/a	172-i/04/a	Hadrosauridae indet.	Camino Rin 2	CRIN2	Hadrosauridae? indet. Theropoda? indet. Pterosauria? indet.
172-i/04/b	172-i/04/b	Dinosauria indet.	Dolor 1	DL1	Hadrosauridae? indet.
172-i/04/c	172-i/04/c	Dinosauria indet.	Dolor 2	DL2	Dinosauria indet. Avialae? indet. Bothremydidae indet.
172-i/04/d	172-i/04/d	Dinosauria indet.	Dolor 3	DL3	Hadrosauridae indet. Avialae? indet. Bothremydidae indet. cf. Allodaposuchidae
172-i/04/e	172-i/04/e	Hadrosauridae indet. Theropoda indet.	Barranco Extremadura	EXT	Dinosauria indet. Hadrosauridae indet. Bothremydidae indet. cf. *Thoracosaurus*
172-i/04/f	172-i/04/f	Hadrosauridae indet.	Fornons 1	F1	Dinosauria indet. Hadrosauridae indet.
Amor 1	AM1	Dinosauria indet. Hadrosauridae indet. Bothremydidae indet.	Fornons 2	F2	Dinosauria indet. Hadrosauridae? indet.
Amor 2	AM2	Hadrosauridae indet. Bothremydidae indet.	Fornons 3	F3	Dinosauria indet. Theropoda? indet.
Amor 3	AM3	Dinosauria indet. Hadrosauridae? indet. Bothremydidae indet. *Agaresuchus subjuniperus*	Larra 1	LAR1	Vertebrata indet. Eusuchia indet.
Barranco Serraduy 1	BS1	Dinosauria indet. Hadrosauridae indet.	Larra 2	LAR2	Dinosauria indet. Ornithopoda indet. Hadrosauridae indet. Bothremydidae indet. cf. Allodaposuchidae
Barranco Serraduy 2	BS2	Dinosauria indet. Hadrosauridae indet.	Larra 3	LAR3	Dinosauria indet. Hadrosauridae indet. Eusuchia indet.
Barranco Serraduy 3	BS3	Vertebrata indet.	Larra 4	LAR4	Hadrosauridae indet. Coelurosauria indet. Bothremydidae indet. cf. Allodaposuchidae Discoglossidae indet.
Barranco Serraduy 4	BS4	Dinosauria indet. Hadrosauridae indet. Sauropoda indet. Bothremydidae indet. Eusuchia indet.	Larra 5	LAR5	Hadrosauridae indet.
Barranco Serraduy 5	BS5	Hadrosauridae indet. Bothremydidae indet.	Larra 6	LAR6	Dinosauria indet. Bothremydidae indet.
Camino Fornons 1	CF1	Dinosauria indet. Hadrosauridae indet. Theropoda? indet. Sauropoda? indet. Osteichthyes indet. Bothremydidae indet.	Pedregal	PED	cf. Allodaposuchidae
Camino Fornons 2	CF2	Hadrosauridae indet. cf. Allodaposuchidae	Rin 1 y 2	RIN1-2	Dinosauria indet.
Color	COL	Dinosauria indet. Hadrosauridae indet. Bothremydidae indet.	San Cristobal	SCRI	Dinosauria indet. Hadrosauridae indet.
Camino Rin 1	CRIN1	Theropoda? indet.	Sierra de Sis 1	SIS1	Dinosauria indet. Hadrosauridae indet. Bothremydidae indet.
			Sierra de Sis 2	SIS2	Dinosauria indet. Hadrosauridae indet.

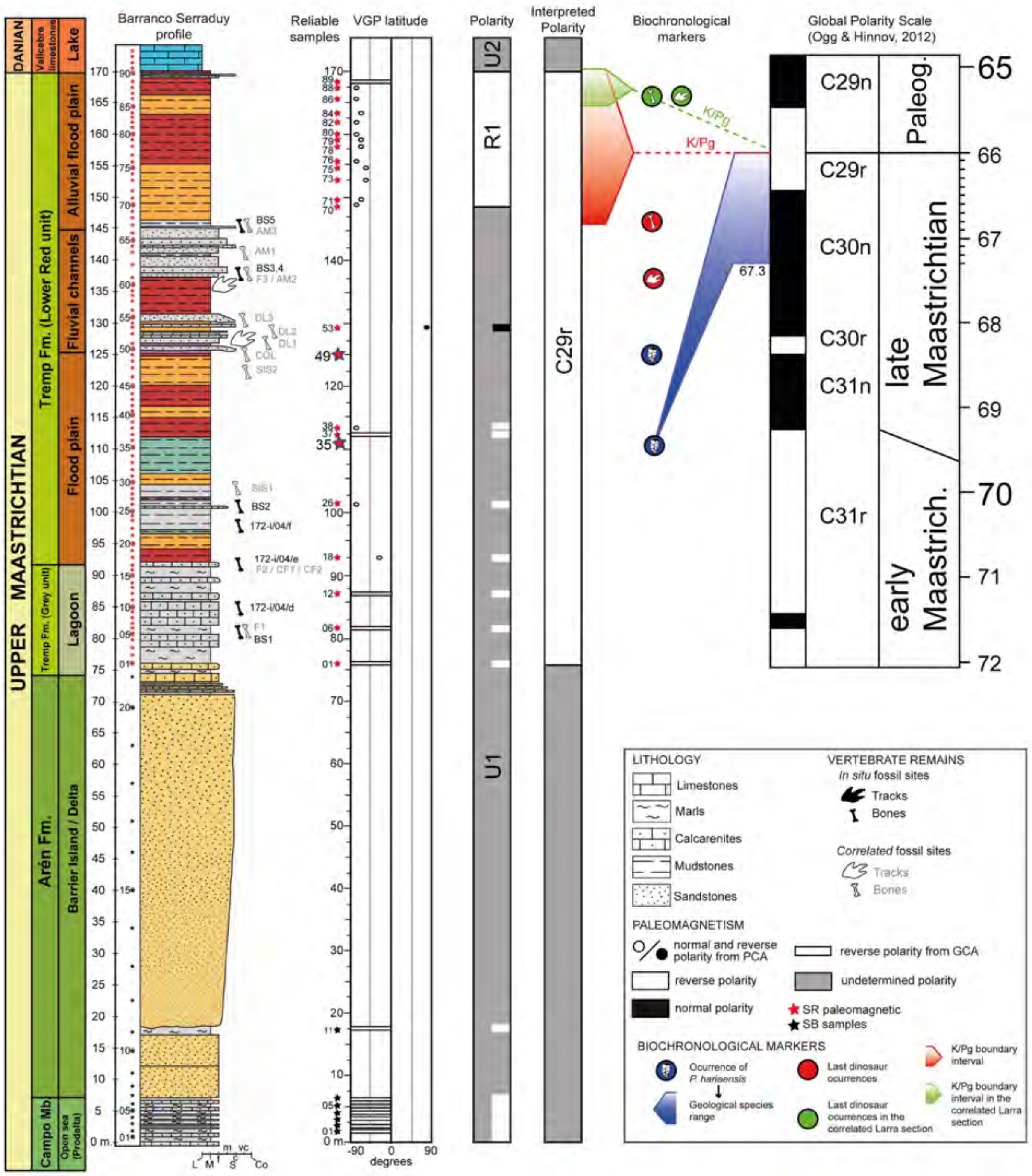

A
PYRENEES
IBERIAN PENINSULA
IBERIAN
BETICS
Mediterranean Sea
Cenozoic
Mesozoic
Paleozoic
N
0
50
100 km
AQUITANIAN BASIN
Toulouse
Pau
Pamplona
Jaca
AXIAL ZONE
Andorra
EBRO BASIN
STUDIED AREA
Huesca
Tremp
Vallcebre
Vic
Girona
Ager
TREMP BASIN
Paleozoic
Mesozoic
Cenozoic thrust-involved Pyrenean
Cenozoic foreland basins
B
HU-V-9401
Villacarli
N
1 km
Larra
Pardinella
A-1605
Biascas de Obarra
Rin
Fornons
Barranco Serraduy
SB
SR
La Vileta de Serraduy
Serraduy
Isábena River
A-1605
42°19'
0°30'
up. red unit
Vallcebre limestones
grey & lo. red units
Tremp Fm.
Arén Fm.
Campo Marls Mb.
Main areas with vertebrate sites
SB Magnetostratigraphic profiles
C
Age
Units
Composite section
Danian
Maastrichtian
?
Tremp Formation
Upper red unit
Vallcebre
lower red unit
grey unit
Arén Formation
Campo Mb.
Main fossiliferous section
10 m
VERTEBRATES DISTRIBUTION
Hadrosaurids
Sauropods
Theropods
Pterosaurs
Crocodylomorphs
Testudines
Amphibians
Presence
Uncertain presence
LITHOLOGY
Mudstones
Sandstones
Limestones
Marls
Calcarenites

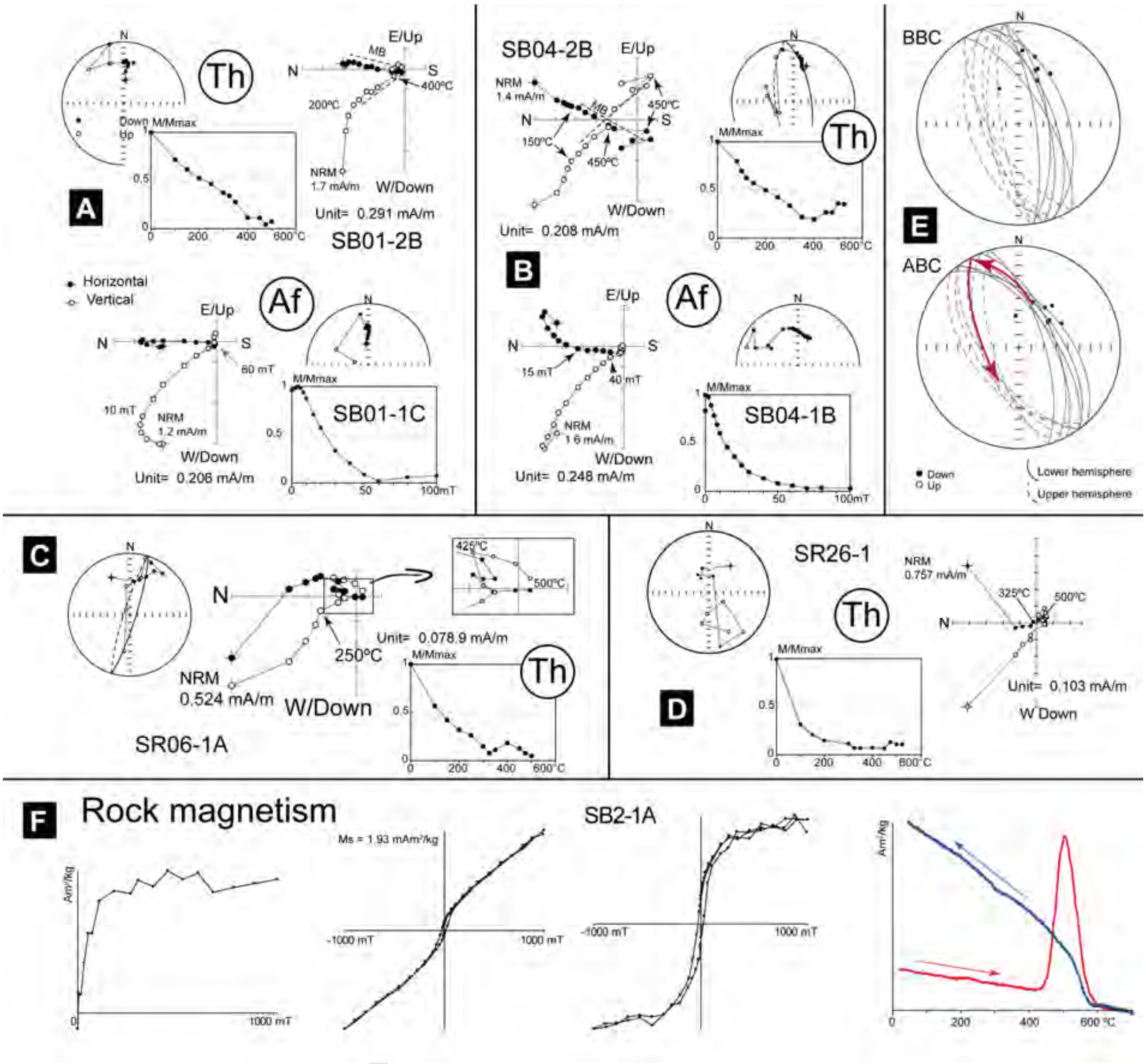


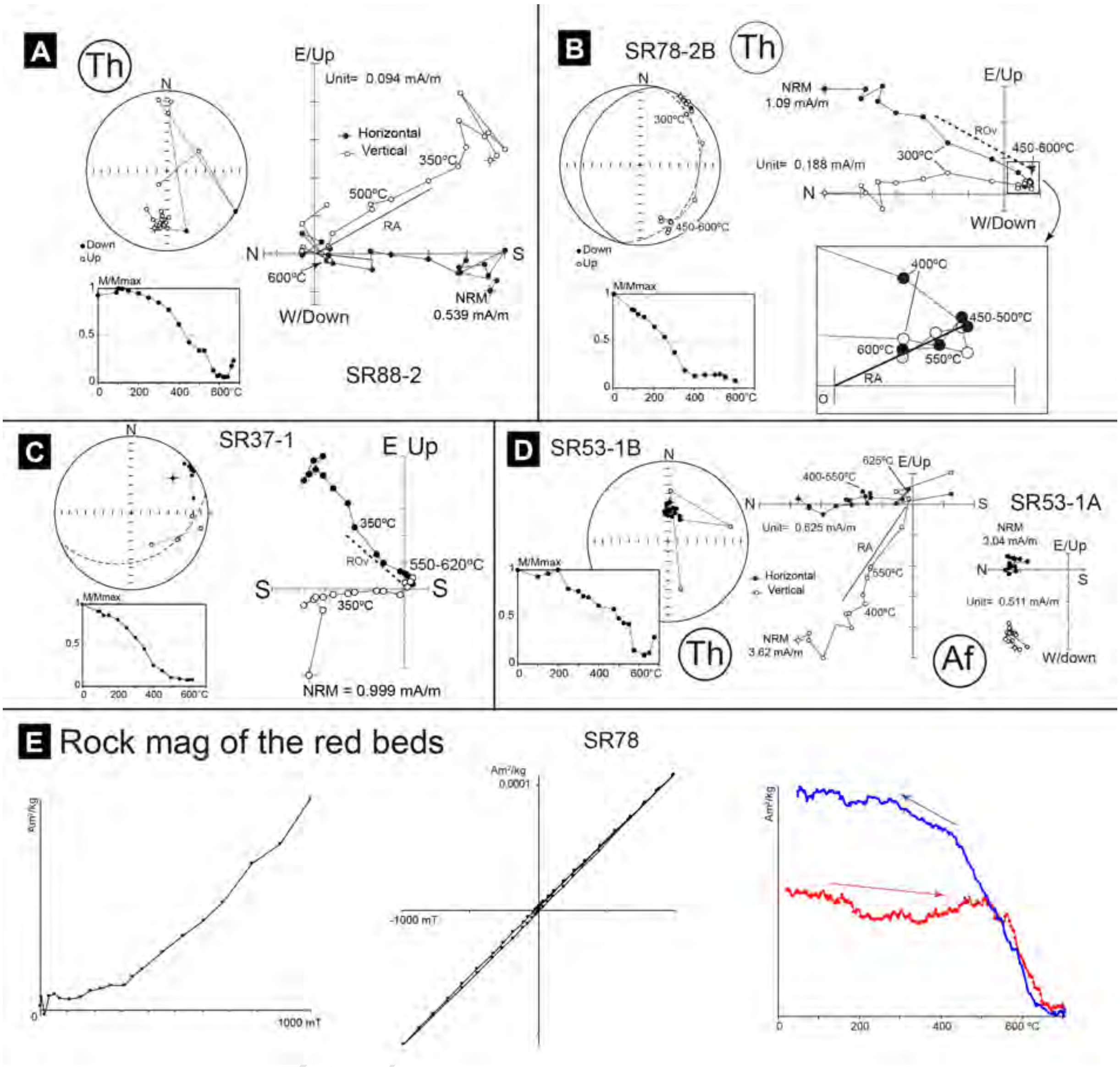
Rosell (1965)	Liebau (1965)		Eichenseer & Krauss (1985)	Cuevas (1992)		Galbrun et al. (1993)	Rosell et al. (2001)	Pujalte & Schmitz (2005)
upper Garum	Conca Garumniense	Conca Garumniense superior	Transitional marine-continental	La Guixera Mb. Claret Fm.	Tremp Group	Unit 4	upper red Garumnian	La Guixera Mb. Claret Fm. cgl. de Claret Mb.
			Red beds	Esplugafreda Fm.				Esplugafreda Fm.
middle Garum				St. Salvador de Toló Fm.		Unit 3	Vallcebre limestones	St. Salvador de Toló Fm. Talarn Fm.
lower Garum		Canalis	Perilagoonal brown marls	Talarn Fm. Tossal d´Obà Mb. Conques Fm. Basturs Mb. La Gubera Mb.		Unit 2	lower red Garumnian	Tossal d´Obà Mb. Conques Fm. Basturs Mb.
		Xullí	Lagoonal lignitic marls	Posa Fm.		Unit 1	Gray Garumnian	Posa Fm.
		Posa						
	Orcau		Arén Formation					

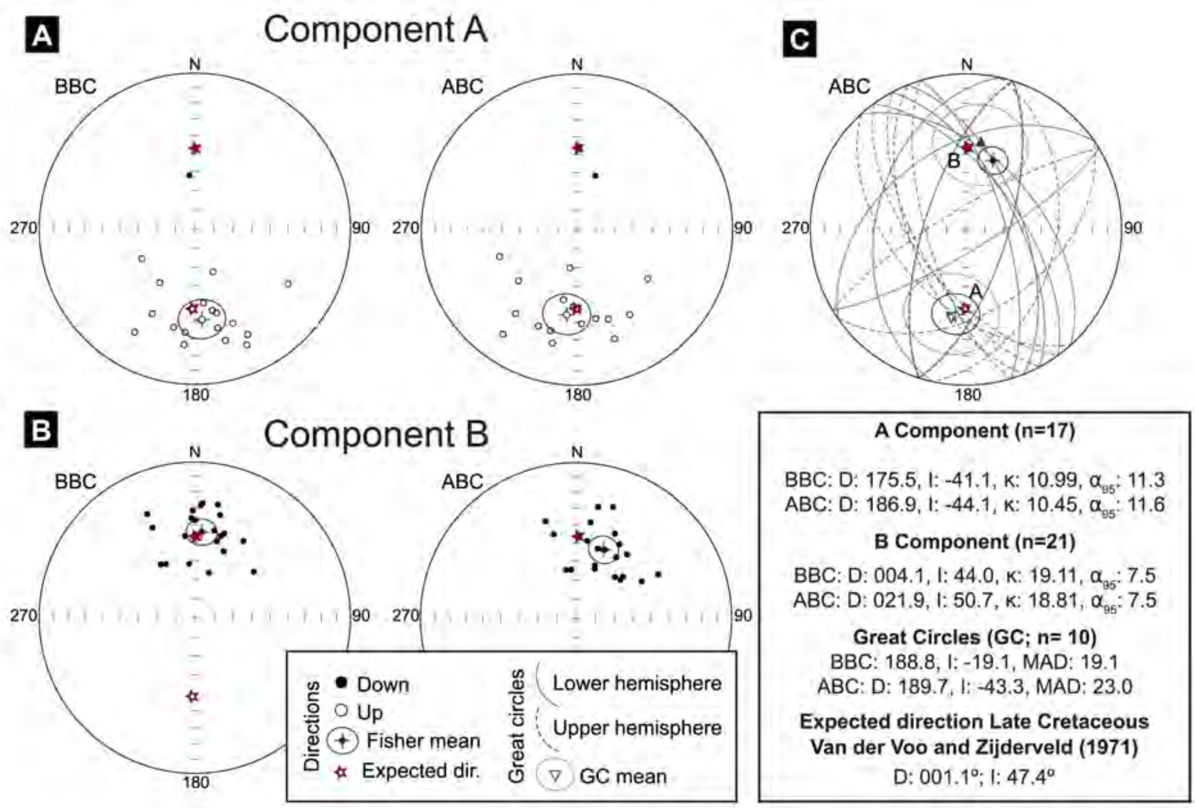

A
NW
Lower red unit correlation in the Serraduy area
SE
Larra profile
Barranco Serraduy profile
Tremp Fm. (Vallcebre limestones)
L5
L2
L1
?
CRIN2
CRIN1
172-i/04/a
LAR5
LAR4,3
LAR2,6 / PED / 172-i/04/b
172-i/04/c
RIN1-2 / EXT / SCRI
10 m
L M f m c vc S Co
BS5
AM3
AM1
BS3,4
F3 / AM2
DL3
DL2
DL1
COL
SIS2
SIS1
BS2
172-i/04/f
172-i/04/e
F2 / CF1 / CF2
172-i/04/d
BS1
F1
Tremp Fm. (lower red unit)
Tremp Fm. (grey unit)
Arén Fm.
Campo Mb.
LITHOLOGY
Limestones
Marls
Calcarenites
Mudstones
Sandstones
VERTEBRATE REMAINS
In situ fossil sites
Tracks
Bones
Correlated fossil sites
Tracks
Bones
B
La
Fig. 3A
29
34
35
Fig. 3B
BS
Fig. 3C
28
STRATIGRAPHIC PROFILES & GUIDE LEVELS
Top
Base
La: Larra Profile
BS: Barranco Serraduy
L5
L4
L3
L2
L1
N
500 m
UNITS & LITHOLOGY
Cenozoic
Mesozoic
lower Eocene limestones
upper red unit
Vallcebre limestones
lower red unit
grey unit
Tremp Fm.
Arén Fm.
Campo Marls Mb.


SE
NW
Vallcebre limestones
Tremp Fm.
lower red unit
L5
L2
L1
Larra 4
A
Larra outcrop
SE
NW
L2
L1
upper red unit
Vallcebre limestones
Tremp Fm.
Arén Fm.
Campo Mb.
lower red unit
grey unit
B
Isábena River outcrop
W
E
lower Eocene limestones
Tremp Fm.
upper red unit
lower red unit
Vallcebre limestones
L2
L1
lower red unit
grey unit
Tremp Fm.
Arén Fm.
C
Bco. Serraduy outcrop


DANIAN
UPPER MAASTRICHTIAN
Vallcebre limestones
Tremp Fm. (Lower Red unit)
Tremp Fm. (Grey unit)
Arén Fm.
Campo Mb
Lake
Alluvial flood plain
Fluvial channels
Flood plain
Lagoon
Barrier island / Delta
Open sea (Prodelta)
Barranco Serraduy profile
0 m.
L M S Co
m vc
BS5
AM3
AM1
BS3,4
F3 / AM2
DL3
DL2
DL1
COL
SIS2
SIS1
BS2
172-i/04/f
172-i/04/e
F2 / CF1 / CF2
172-i/04/d
F1
BS1
Reliable samples
VGP latitude
49
35
-90
0
90
degrees
Polarity
U2
R1
U1
Interpreted Polarity
C29r
Biochronological markers
K/Pg
K/Pg
67.3
Global Polarity Scale (Ogg & Hinnov, 2012)
C29n
C29r
C30n
C30r
C31n
C31r
Paleog.
late Maastrichtian
early Maastrich.
65
66
67
68
69
70
71
72
LITHOLOGY
Limestones
Marls
Calcarenites
Mudstones
Sandstones
VERTEBRATE REMAINS
In situ fossil sites
Tracks
Bones
Correlated fossil sites
Tracks
Bones
PALEOMAGNETISM
normal and reverse polarity from PCA
reverse polarity from GCA
reverse polarity
undetermined polarity
normal polarity
SR paleomagnetic
SB samples
BIOCHRONOLOGICAL MARKERS
Ocurrence of P. hariaensis
Geological species range
Last dinosaur ocurrences
Last dinosaur ocurrences in the correlated Larra section
K/Pg boundary interval
K/Pg boundary interval in the correlated Larra section


A
Th
N
Down
Up
M/Mmax
1
0.5
0
200
400
600°C
E/Up
N
S
MB
400ºC
200ºC
NRM
1.7 mA/m
W/Down
Unit= 0.291 mA/m
SB01-2B
Horizontal
Vertical
Af
E/Up
N
S
80 mT
10 mT
NRM
1.2 mA/m
W/Down
Unit= 0.206 mA/m
SB01-1C
M/Mmax
50
100mT
SB04-2B
E/Up
NRM
1.4 mA/m
N
MB
450ºC
S
150ºC
450ºC
W/Down
Unit= 0.208 mA/m
Th
M/Mmax
200
400
600°C
B
Af
E/Up
N
S
15 mT
40 mT
NRM
1.6 mA/m
W/Down
Unit= 0.248 mA/m
SB04-1B
M/Mmax
50
100mT
BBC
E
ABC
Down
Up
Lower hemisphere
Upper hemisphere
C
N
425ºC
500ºC
NRM
0.524 mA/m
W/Down
250ºC
Unit= 0.078.9 mA/m
M/Mmax
Th
SR06-1A
200
400
600°C
SR26-1
NRM
0.757 mA/m
325ºC
500ºC
N
Th
Unit= 0.103 mA/m
W Down
M/Mmax
D
200
400
600°C
F
Rock magnetism
Am²/kg
1000 mT
Ms = 1.93 mAm²/kg
-1000 mT
1000 mT
SB2-1A
-1000 mT
1000 mT
Am²/kg
0
200
400
600 °C


A
Th
N
Down
Up
M/Mmax
1
0.5
0
0
200
400
600°C
E/Up
Unit= 0.094 mA/m
Horizontal
Vertical
350°C
500°C
RA
N
S
600°C
W/Down
NRM
0.539 mA/m
SR88-2
B
SR78-2B
Th
N
300°C
450-600°C
Down
Up
M/Mmax
1
0.5
0
0
200
400
600°C
NRM
1.09 mA/m
E/Up
ROv
450-600°C
300°C
Unit= 0.188 mA/m
N
W/Down
400°C
450-500°C
600°C
550°C
RA
O
C
N
SR37-1
E Up
350°C
ROv
550-620°C
S
S
350°C
NRM = 0.999 mA/m
M/Mmax
1
0.5
0
0
200
400
600°C
D
SR53-1B
N
M/Mmax
1
0.5
0
0
200
400
600°C
Th
625°C
E/Up
400-550°C
N
S
Unit= 0.625 mA/m
RA
550°C
400°C
Horizontal
Vertical
NRM
3.62 mA/m
Af
SR53-1A
NRM
3.04 mA/m
E/Up
N
S
Unit= 0.511 mA/m
W/down
E
Rock mag of the red beds
SR78
Am²/kg
0
1000 mT
Am²/kg
0.0001
-1000 mT
Am²/kg
0
200
400
600 °C



A Component (n=17)

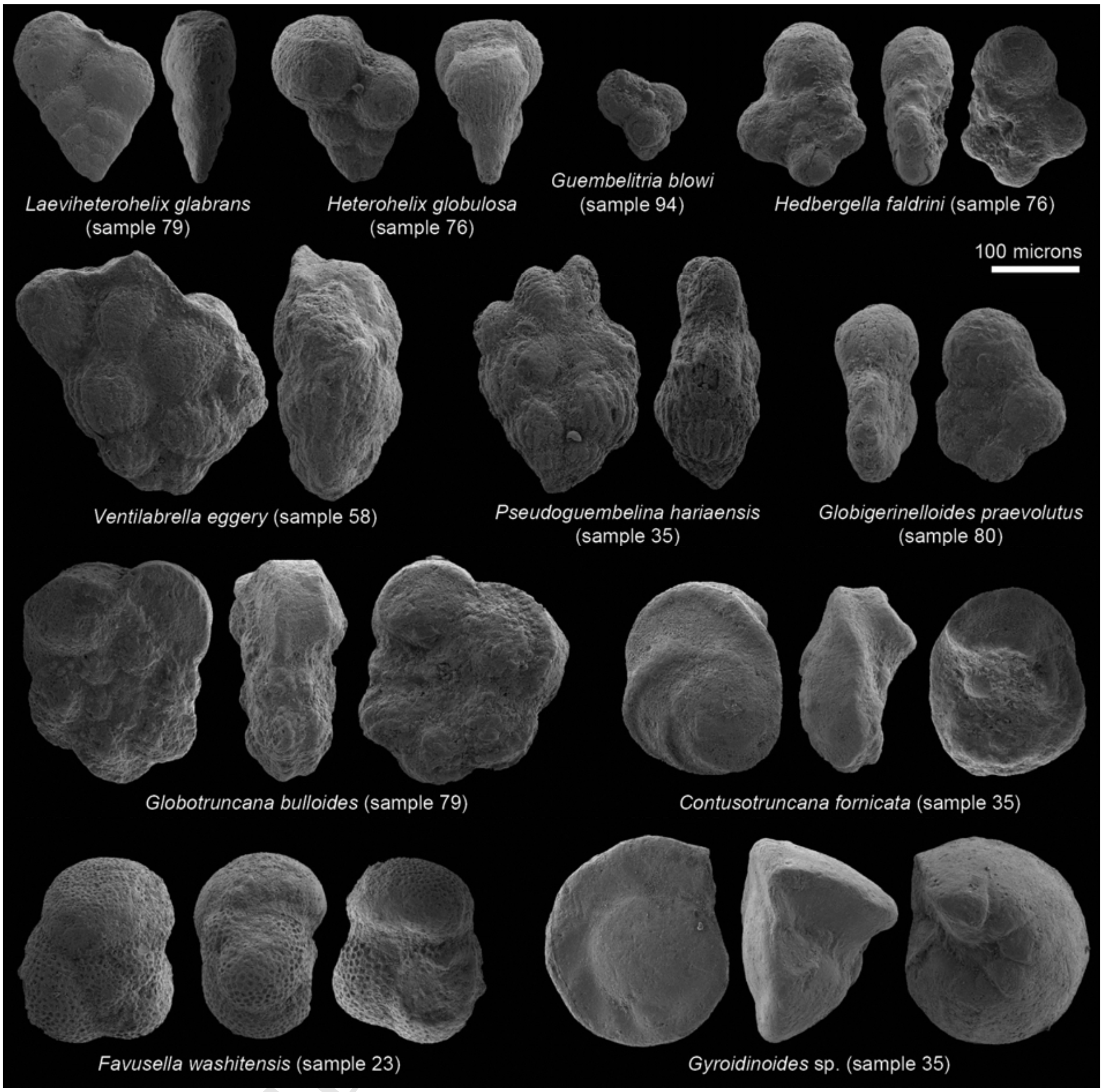
BBC: D: 175.5, I: -41.1, κ: 10.99, α_{95}: 11.3
ABC: D: 186.9, I: -44.1, κ: 10.45, α_{95}: 11.6

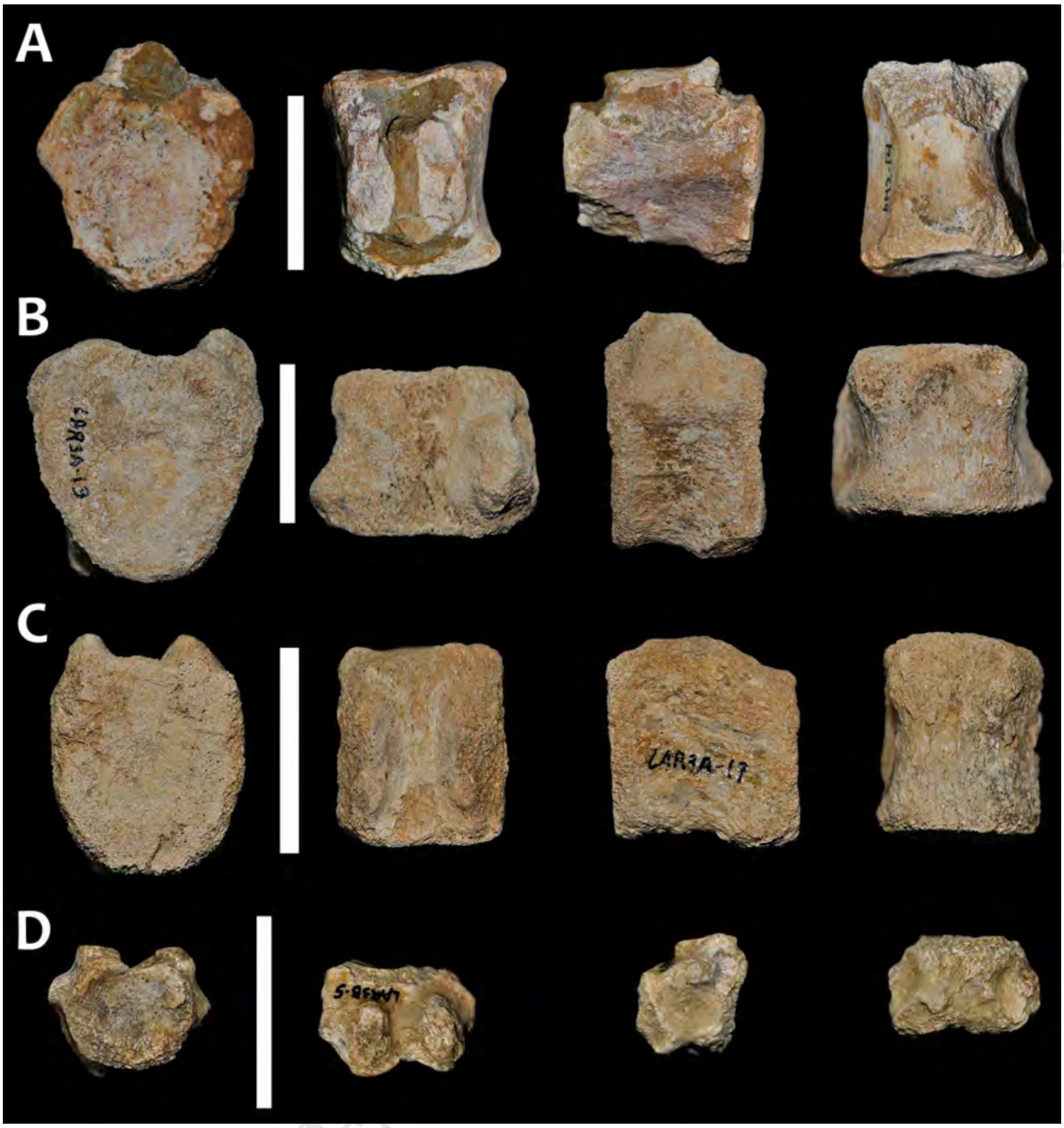
B Component (n=21)

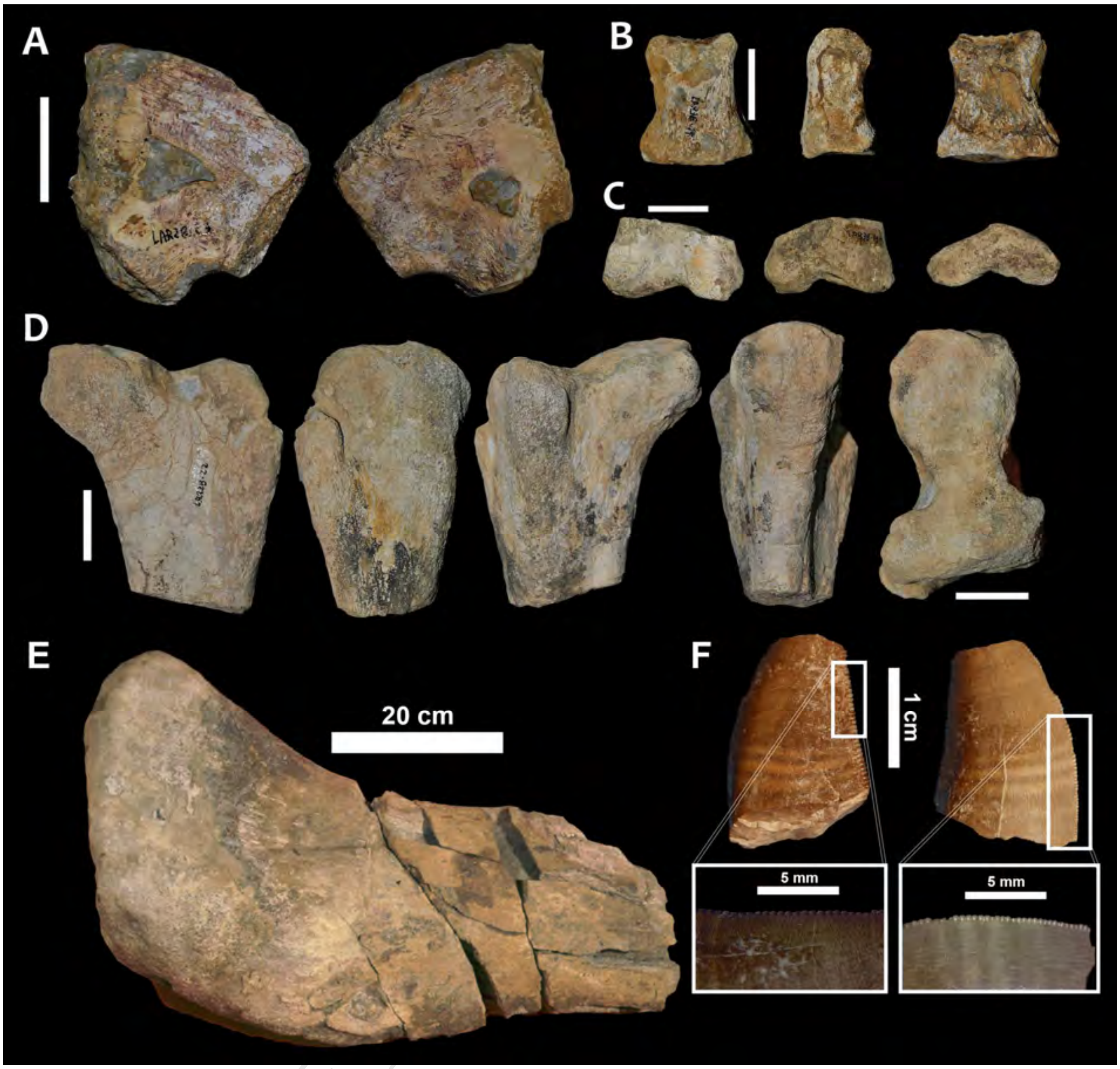
BBC: D: 004.1, I: 44.0, κ: 19.11, α_{95}: 7.5
ABC: D: 021.9, I: 50.7, κ: 18.81, α_{95}: 7.5

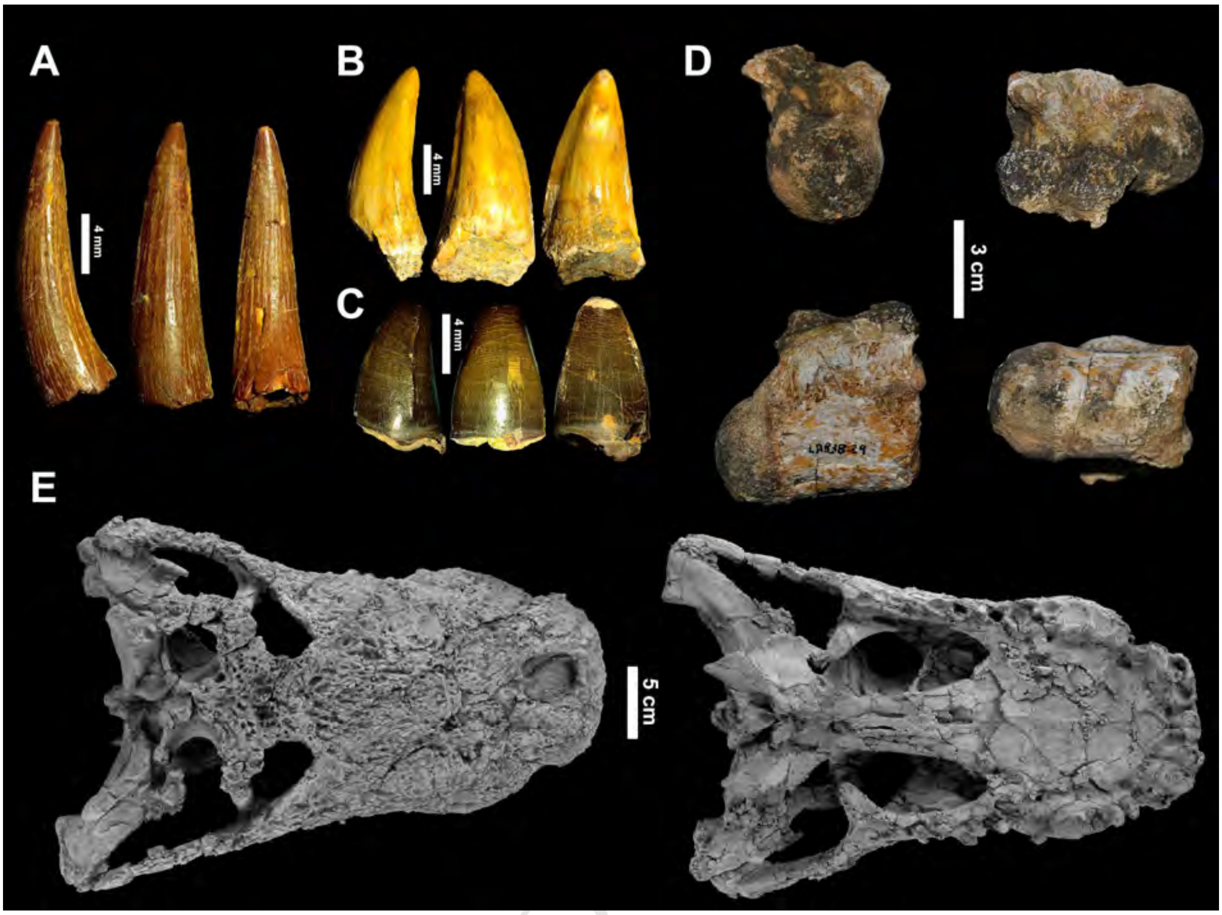
Great Circles (GC; n= 10)
BBC: 188.8, I: -19.1, MAD: 19.1
ABC: D: 189.7, I: -43.3, MAD: 23.0

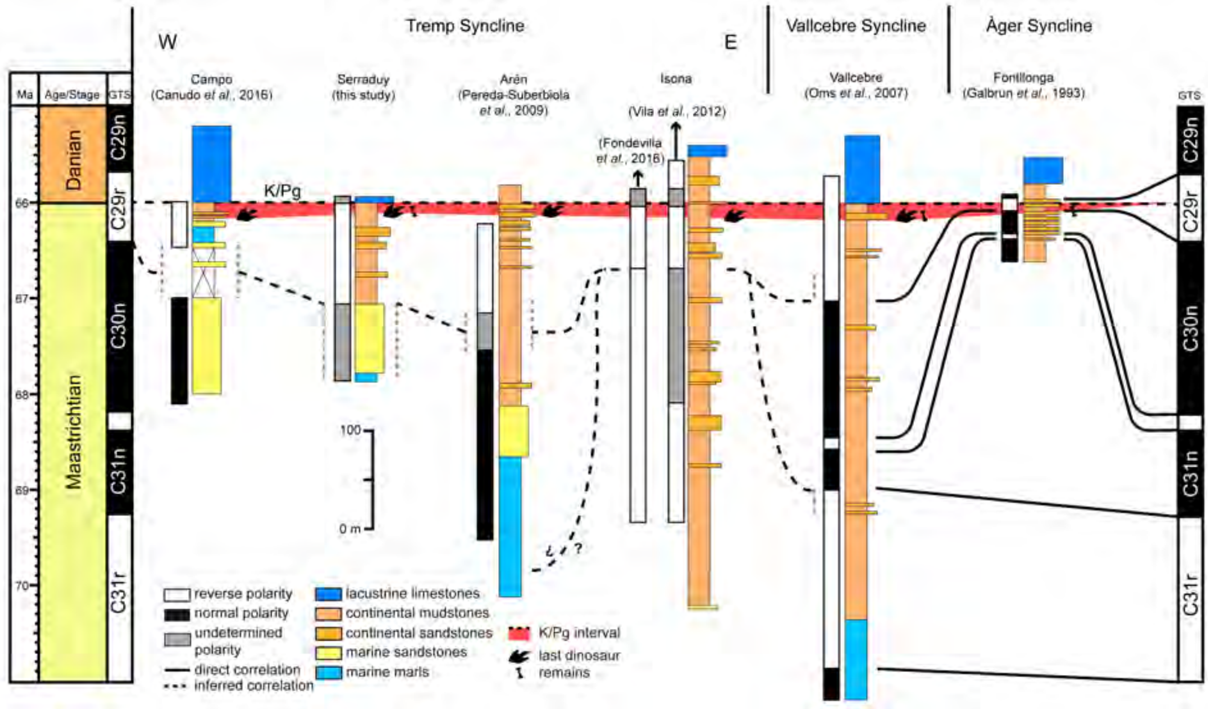
Expected direction Late Cretaceous
Van der Voo and Zijderveld (1971)
D: 001.1º; I: 47.4º


Laeviheterohelix glabrans (sample 79)
Heterohelix globulosa (sample 76)
Guembelitria blowi (sample 94)
Hedbergella faldrini (sample 76)
100 microns
Ventilabrella eggery (sample 58)
Pseudoguembelina hariaensis (sample 35)
Globigerinelloides praevolutus (sample 80)
Globotruncana bulloides (sample 79)
Contusotruncana fornicata (sample 35)
Favusella washitensis (sample 23)
Gyroidinoides sp. (sample 35)


A
B
LAR3A-13
C
LAR3A-17
D
LAR3B-5


A
B
C
D
E
20 cm
F
1 cm
5 mm
5 mm


A
4 mm
B
4 mm
C
4 mm
D
3 cm
E
5 cm


Tremp Syncline
W
E
Vallcebre Syncline
Àger Syncline
Ma
Age/Stage
GTS
Danian
Maastrichtian
C29n
C29r
C30n
C31n
C31r
66
67
68
69
70
Campo
(Canudo et al., 2016)
Serraduy
(this study)
Arén
(Pereda-Suberbiola et al., 2009)
Isona
(Vila et al., 2012)
(Fondevilla et al., 2016)
Vallcebre
(Oms et al., 2007)
Fontllonga
(Galbrun et al., 1993)
GTS
K/Pg
100
0 m
¿ ?
reverse polarity
normal polarity
undetermined polarity
direct correlation
inferred correlation
lacustrine limestones
continental mudstones
continental sandstones
marine sandstones
marine marls
K/Pg interval
last dinosaur remains