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Integrated stratigraphy from the Vallcebre Basin (southeastern Pyrenees, Spain): New insights on the continental Cretaceous−Tertiary transition in southwest Europe

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Abstract

An integrated sedimentological, magnetostratigraphic, and paleontological study of the Vallcebre section (south eastern Pyrenees, Spain) is carried out in order to define and portray the transition from the Cretaceous to the Tertiary in a continental setting. A robust magnetostratigraphy is correlated to the standard polarity scale in light of known biochronological constraints (charophyte, marine invertebrates, eggshells and other dinosaur remains). Our results show that this section is among the thickest stratigraphic records for the continental Maastrichtian in the Old World. Sedimentology indicates a progressive regression from marine through lagoonal to entirely continental environments. The section is dominated by mudstones deposited under low energy conditions. Exceptionally, a basin-wide regression maximum is recorded some time before the Cretaceous–Tertiary boundary (K/T). This regression maximum is marked by the input of coarse-grained (alluvial) sediments that record a dramatic change in the landscape (quiet mud plains changed to sandy floodplains deposited by high-energy currents). After a period of renewed quiescence following the regression maximum, a Cenozoic flooding took place. Such terminal Cretaceous sequence of events has been recorded in shorter sections in several other basins from southwestern Europe. This energetic sediment input suggests that some time before the K/T event, a sudden paleoenvironmental reorganization took place in the continental basins of south western Europe.

Keywords: K/T boundary; Pyrenees; Magnetostratigraphy; Maastrichtian; Dinosaurs

1. Introduction

The geological record of the Cretaceous–Tertiary (K/T) transition has been studied in detail in several sections and wells all over the world (for example see Keller, 2001 and references therein). Most studies are

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devoted to marine sediments and few are located in continental basins. In continental settings, the Cretaceous–Tertiary boundary (K/T) impact layer has basically been recognized in the Western Interior of the United States of America and Canada (see Wilf et al., 2003 and references). Finding complete records outside of North America has been hampered by the scarcity of thick continental sections spanning the K/T, but exceptionally expanded successions exist in the Pyrenees.

Not all Pyrenean basins are equally understood. In areas such as the northern (French) Pyrenees or the south central Pyrenees (Tremp basin), they have been studied in detail for several decades. In contrast, in areas such as the Vallcebre syncline (south eastern Pyrenees), several geological questions remain largely unanswered. In this study, we document the stratigraphic record of the Vallcebre syncline, integrating sedimentology, magnetostratigraphy, and biochronology, to gain new insight on the K/T in the Pyrenees and allow comparison with similar records from southwestern Europe.

2. Geological setting

The Pyrenees are the Alpine fold-and-thrust belt that formed at the boundary between the European and Iberian plates. The mountain belt consists of a hercinian basement and a sedimentary cover that developed in foreland basins from the end of the Cretaceous until the Oligocene. Two groups of basins developed on both sides of the belt: the south Pyrenean and north Pyrenean zones, located in Spain and France, respectively. Within the south Pyrenees, two types of tectonic units are recognized based on the thrusting style they underwent: allochtonous units (with displacement of several tens of kilometres) and parautochtonous units. The Montsec and Pedraforca thrusts sheets are important allochtonous units that contain the piggy-back basins of Tremp and Vallcebre, respectively (see Fig. 1). Among the parautochtonous units, the Serres Marginals and Cadí sheets contain the Àger and Ripoll basins, respectively.

The continental Upper Cretaceous–Tertiary sediments found in all the southern Pyrenean basins are known as the Tremp Formation (Mey et al., 1968) or “Garumnian”. This last name was proposed by Leymerie (1862) and is widely used in Pyrenean geology (see historical review in Rosell et al., 2001). The Garumnian units were deposited following a marine regression that began near the Campanian–Maastrichtian boundary. The Garumnian strata accumulated in an E–W foreland trough connected to the Atlantic Ocean (Rosell et al., *op cit*). Two types of Garumnian sedimentary successions occur depending on their geotectonic setting. The first group consists of discontinuous successions resulting from accumulation in low subsidence settings. These successions are relatively

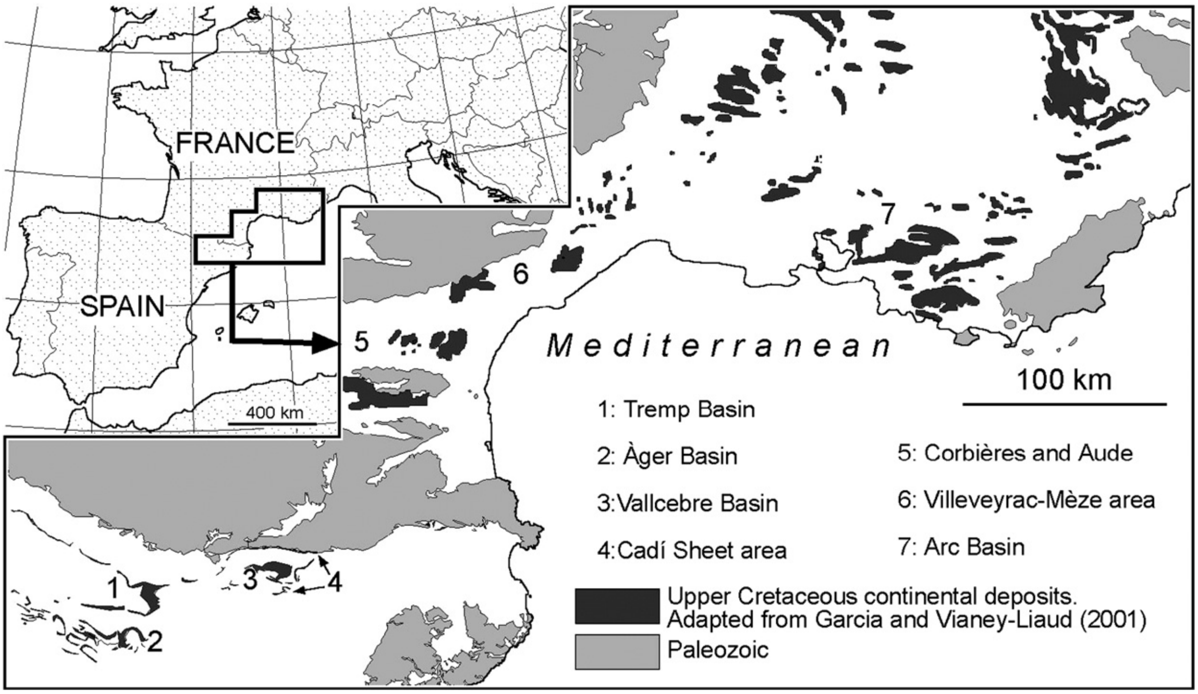

Fig. 1. Map of southwestern Europe with indication of the Upper Cretaceous continental deposits (French outcrops by Garcia and Vianey-Liaud, 2001).

thin, with coarse grained sediments and abundant erosions (and thus temporal hiatuses). The second group of successions are thicker (up to 500 m), and represents continuous stratigraphic intervals (lacking major hiatuses) dominated by mudstones.

The regional stratigraphy of the south Pyrenean Garumnian strata consists of four lithologic units (Rosell et al., 2001) which are from base to top: (a) a transitional Grey Unit (marls, coals, limestones, and sandstones), (b) a fluvial Lower Red Unit (mudstones, sandstones, oncoliths, and paleosols), (c) the lacustrine Vallcebre limestones and laterally equivalent strata and, (d) an Upper Red Unit (mudstones, sandstones, conglomerates and limestones). A conspicuous sandstone and/or conglomerate level (Reptile Sandstone of Masriera and Ullastre, 1982) occurs near the top of the Lower Red Unit, separated from the overlying Vallcebre limestone by a few metres of mudstone (also see Masriera and Ullastre, 1983, 1990; Ullastre and Masriera, 1998; López-Martínez et al., 1998). The four Garumnian lithostratigraphic units (including the conspicuous sandstone/conglomerate level) can be recognized in the folded strata of the Pedraforca thrust sheet, particularly in the Vallcebre syncline (see Figs. 2 and 3).

In the northern Pyrenees and southern France, the continental Cretaceous–Tertiary stratigraphic sequence is based on type sections in the Arc Basin (7 in Fig. 1). The Arc Basin contains deposits assigned biostratigraphically and magnetostratigraphically to the middle Rognacian (limestones of the Campanian –Maastrichtian transition), upper Rognacian (Maastrichtian red sandstones and mudstones), and Vitrollian (starting with Danian lacustrine limestones, see summary in Westphal and Durand, 1990). In these sections the last 15 m of the Rognacian consists of a conglomeratic interval (Galante or Fleurie conglomerate in the Arc Basin and northern

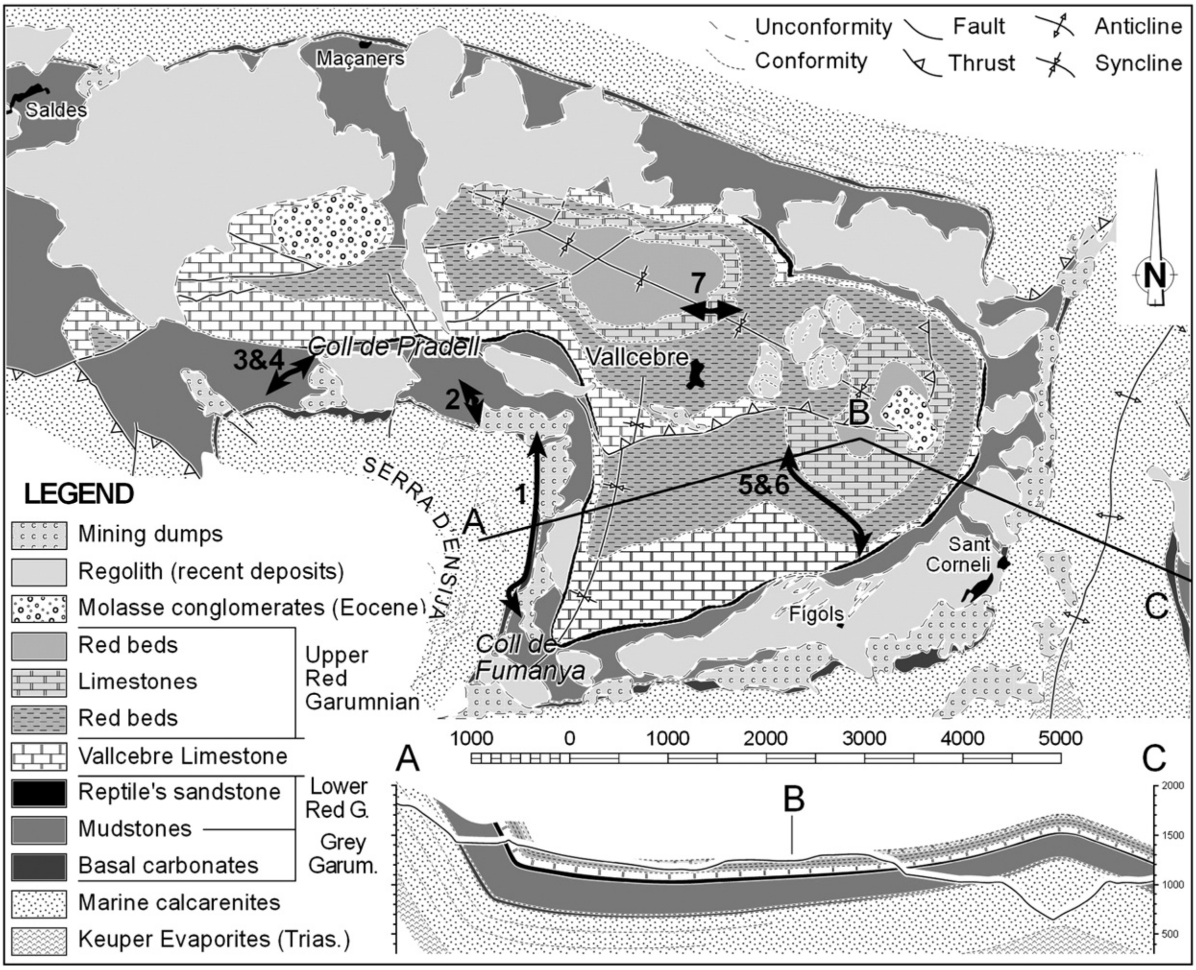

Fig. 2. Geological map and location of the studied sections 1 to 7 from the Vallcebre syncline, including some of the referred stratigraphic units (modified from Oms et al., 2004). Compare with Fig. 3.

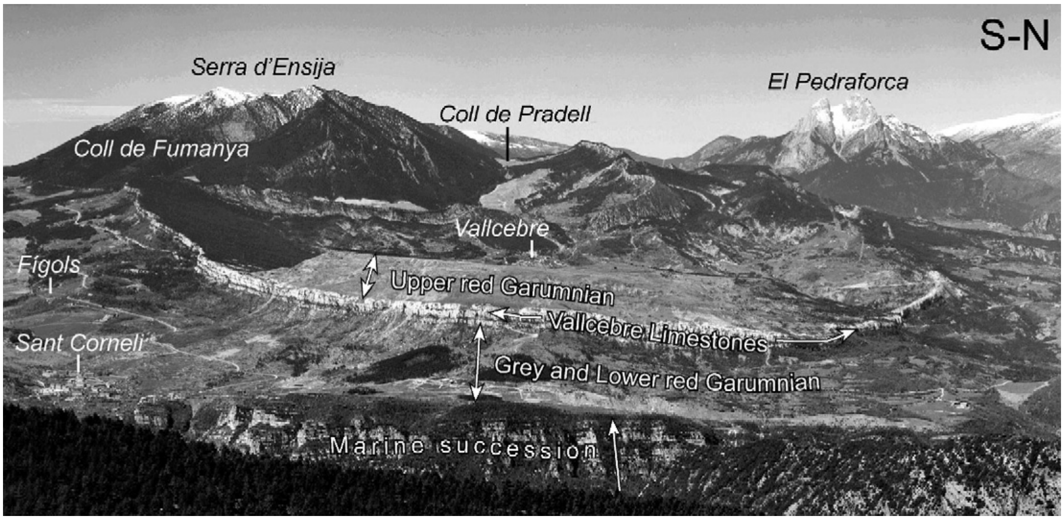

Fig. 3. Vallcebre syncline seen from the eastern wall of the Llobregat river valley. The studied section runs from Coll de Fumanya to Coll de Pradell (see the deforested areas of the opencast mines). The geomorphic expression of the Vallcebre limestone clearly depicts the homonymous syncline. Picture modified from Luigi photographer (Berga), courtesy of Consorci Ruta Minera.

Pyrenees, respectively) overlain by approximately 10 m of red mudstones leading stratigraphically up to the Vitrollian limestone.

3. The Vallcebre composite section

Only limited sedimentologic study of the Garumnian exposed in the Vallcebre syncline has been conducted to date (Aepler, 1967). In our study seven sections were measured to compile a 760-metre composite section of the formation (see Fig. 4) including several outcrops exposed on the south flank of the Vallcebre syncline. They have been measured basically along the mining road from Coll de Fumanya to Coll de Pradell, where abandoned opencast coal mines provided excellent exposures (see Fig. 3). The upper part of the studied section is located in the axis of the Vallcebre syncline. This 760-metre section could eventually be extended upwards for a few tens of metres, as a few isolated Garumnian outcrops exist which are not considered herein.

3.1. Lithostratigraphy

The Vallcebre composite section is underlain by approximately 1000 m of Upper Cretaceous coastal calcarenites with rudists reefs (Terradets Limestones formation) and unconformably overlain by Eocene continental conglomeratic molasse (Vergés et al., 1994). The base of the Vallcebre section starts with a transitional marly limestone named by the miners "concrete level" (metre level 30 to 37 in subsection 1), which contains thousands of dinosaur footprints (see Le Loeuff and Martínez, 1997; Schulp and Brokx, 1999; Vila et al., 2004, 2005). An analysis of the sedimentary facies present in the stratigraphic interval between the basal limestone and the middle of the Vallcebre limestone (metre levels 37 to 552) was conducted. A continuous facies description higher in the section (above metre level 552) is no longer possible due to covered intervals. In the studied interval, we have recognized ten lithological facies (named F1 to F10):

F1—Coals (found between metre levels 37 and 89). Six lignite beds, less than a metre thick, occur throughout the Vallcebre basin. These coals are of humic composition, have a sub-bituminous rank, and were formed in a forest–moor swamp environment probably in a subtropical humid climate (see details in García-Vallés et al., 1993).

F2—Black mudstones (meter level 37 to 135). These are organic-matter-rich marls that could be mistaken as coal. Commonly, they contain abundant invertebrate fossils such as *Corbicula*, *Cerithium*, large *Lychnus*, and a few *Ostrea* genera.

F3—Limestones. Two kinds of limestones are recognized on the basis of their texture. The first limestone is classified as wackestone to packstone (meter 42 to 84) and contains abundant charophyte remains with few invertebrate shells. Such beds underwent a

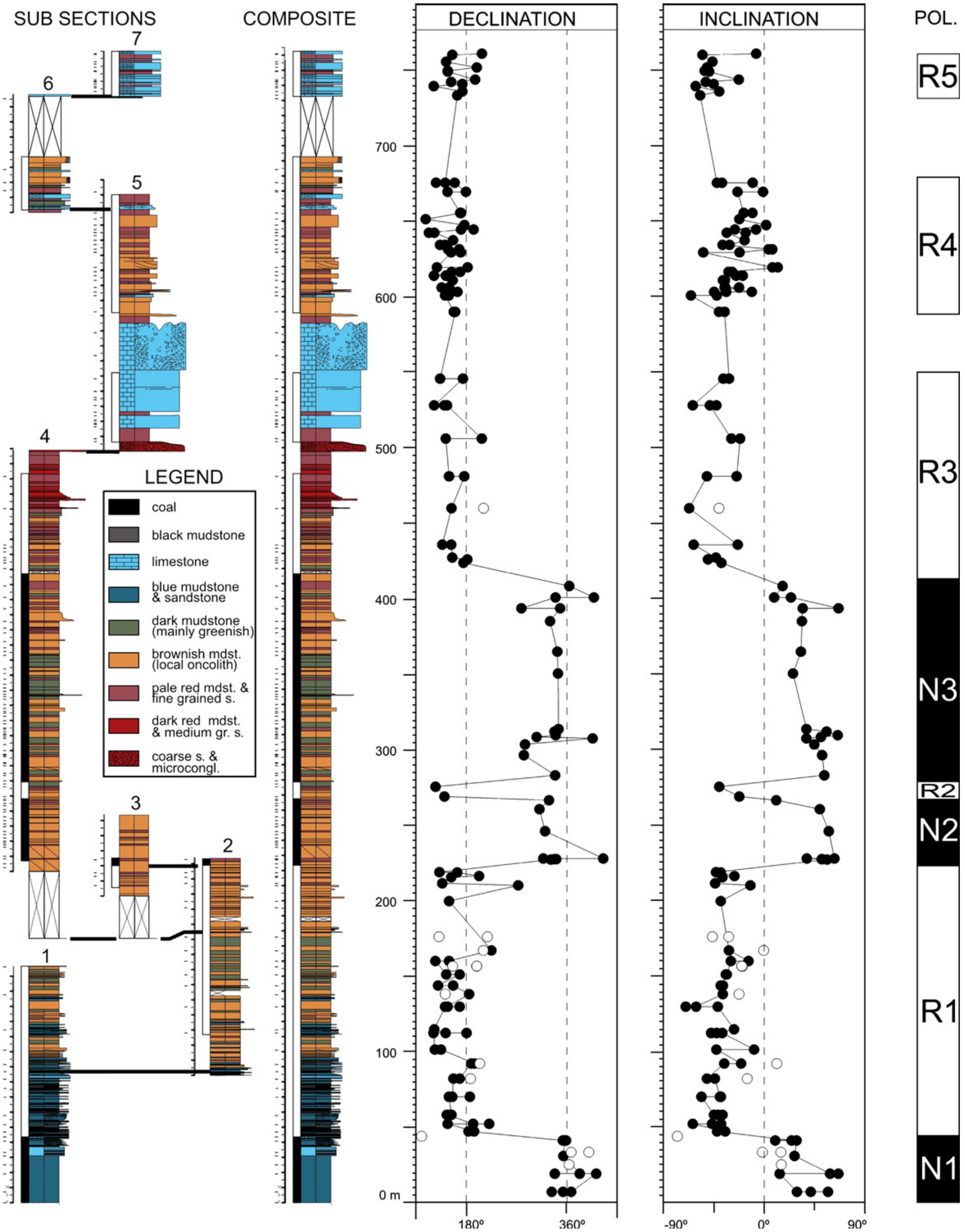

Fig. 4. Composite Vallcebre section, with individual sub sections, paleomagnetic ChRM declination and inclination data and polarity zones.

probable sporadic subaerial exposure as evidenced by small and synsedimentary microkarstification and dinosaur footprints. The second texture, a calcareous mudstone (meter 513 to 552), is dominant in the Vallcebre limestone, where charophytes are locally abundant. A systematic microfacies analysis would give some more information on this apparently monotonous limestone, but such study is beyond the scope of this paper. It is important to note that between meter level 552 and 583 the Vallcebre limestone is a breccia. Finally, a thin and continuous mudstone exists at meter level 179 and is a continuous marker bed that correlates sections 2, 3 and 4.

F4—Blue marls (from meter 37 to around meter 200). They are mixed carbonate-clastic rocks that are generally homogeneous and have abundant iron sulphide nodules. The faunal content resembles that of the black mudstones (F2). Dinosaur egg clutches and eggshell fragments are present in this facies. Rare cyanobacterial nodules are found.

F5—Blue sandstones (from meter 37 to around meter 200). These sandstones are very fine or fine grained and occur as channel-shaped bodies that display lateral accretion surfaces. We have observed that such facies grade laterally into F4 and that both share similar paleontological content.

F6—Dark mudstones (meter 100 to 364). They are dark brown to dark green in colour but they never have the black colour of F2. Bioturbation gives them a homogeneous texture but sometimes laminations are observed.

F7—Brown mudstones (meter 93 to around 455). They are homogeneous but occasionally contain coated grains (oncoids) of different size. Small oncoids (less than 1 cm) appear scattered throughout mudstones (giving the latter a lighter colour). Large oncoids (cobble and pebble size) have a clast-supported texture (with a sandstone matrix) resulting from reworking inside channel-like accreting bodies.

F8—Pale red mudstones and fine-grained sandstones (abundant from meter 370 to 513). In the lower half of the section F8 consist in mudstone beds less than a meter thick, whereas in the upper part can occur together as fining-upward couplets.

F9—Red mudstones and medium grained sandstones (meter 460 to meter 490). This facies is similar to F8, but mudstone colour is more intense (mudstones in F8 and F9 belong to 10R7/2 and 10R5.5/8, respectively, see Munsell, 2000 colour chart) and sandstones are coarser. A gradational spectrum exists between F8 and F9 (being the later less abundant).

F10—Coarse-grained sandstones and microconglomerates (Reptile sandstone, around meter 500). This 7-meter-thick unit consists of texturally and lithologically mature sediment displaying medium-and large-scale cross-bedding that was deposited under a high-energy hydric regime. The lenticular cross-bedded sandstones, the scarce mudstones interbeds and the absence of fining-up sequences and lateral accretion surfaces, indicate deposition in braided streams. This facies occurs as a laterally continuous body that can be traced all over the Pedraforca thrust sheet. Dinosaur bones and footprints are found in this sandstone, occurring at various levels within the unit.

For further paleoenvironmental interpretations, it is very important to note the absence of mottling related to plant activity and of *Spirographites* (non-marine arthropod burrows, Mayoral and Calzada, 1998) in F1 to F5, whereas both kinds of bioturbation are abundant or very abundant in F6 to F9. Similarly, the occurrence of small calcrete nodules is common in F6 to F9 and absent in the other facies.

3.2. Magnetostratigraphy

Sampling was accomplished both with a gasoline powered drill and by collecting small oriented blocks. The latter method proved to be very useful for soft mudstones. The main difficulty associated with sampling was to dig deep trenches to reach fresh outcrops. Measurements were performed with a 2-G Enterpriseshigh-resolution cryogenic magnetometer with RF SQUID sensors in the magnetically-shielded room of the Istituto Nazionale di Geofisica e Vulcanologia (Rome). After measuring the Natural Remanent Magnetization (NRM), a stepwise demagnetization was applied at least to one specimen per site. Demagnetization was done thermally, by alternating fields (AF), or through a combination of both methods depending on facies and demagnetization behaviour. Fifty-four percent of sampled levels display a good (stable) demagnetization behaviour (and are used in Fig. 4) while the remaining samples could not be considered because of the instability observed during demagnetization. Note in Fig. 4 the great number of sampled sites (horizontal lines to the left of sections) compared with the plotted values (164 sites were sampled, but 75 had to be discarded, i.e., 46%). All samples with intensities close or below 0.1 mA/m were not considered since they were generally unstable. Some samples with relatively high intensities but having a relatively unstable behaviour were also considered and are plotted as white circles, defining somewhat less reliable directions (see Fig. 4).

F1 (coals) and F2 (dark mudstones) show low intensities and unstable behaviour, so they were not considered at all. In F3 (limestones) most of the samples had also to be excluded, but after a systematic sampling (particularly in the Vallcebre limestone) a few of them provided relatively good results (Fig. 5E). On the contrary, limestone beds (not included in the facies description above), exposed in the uppermost part of the Vallcebre composite section (subsection 7) provided stable results. Demagnetization plots for the marine blue marls (basal subsection 1) and for F3 display clear patterns with normal and reverse polarities (Fig. 5A and B, respectively) and include two components generally defined above and below 20 mT respectively (the latter considered primary). F5 (blue sandstones) was avoided, so alternative sampling levels were chosen above or below. F6 and F7 (brown and dark mudstones) turned out to be unsuitable for magnetostratigraphic purposes. In such facies, the stepwise demagnetization indicates that most of the magnetization is carried by high coercitive minerals that are demagnetised at 150 °C. At this temperature, remanence intensity drops to very low values (even less than the minimum considered of 0.1 mA/m). It is suggested that iron hydroxides (which generally result from the recent weathering of rocks) carry most of the magnetization in F6 and F7. A similar situation is also recorded in the contemporaneous and similar deposits from France (see Westphal and Durand, 1990; Galbrun, 1997). In the intervals where F6 and F7 were dominant (see metres 240 to 370 in Fig. 5), intensive sampling was conducted to obtain appropriate results, but after demagnetization measurements, these lithologies had to be discarded. Lower Red Garumnian red beds (F8 and F9) may have a variable amount of iron hydroxides and other minerals that build up an eventual secondary magnetization component (see Fig. 5C, D). A linear component directed toward the origin of the demagnetization diagram can be removed partly with stepwise AF treatment up to 100 mT (after heating to 150 °C) and stepwise heating up to 590 °C, indicating that magnetite and hematite carry the characteristic component (Fig. 5C). The magnetite component can be absent in some cases

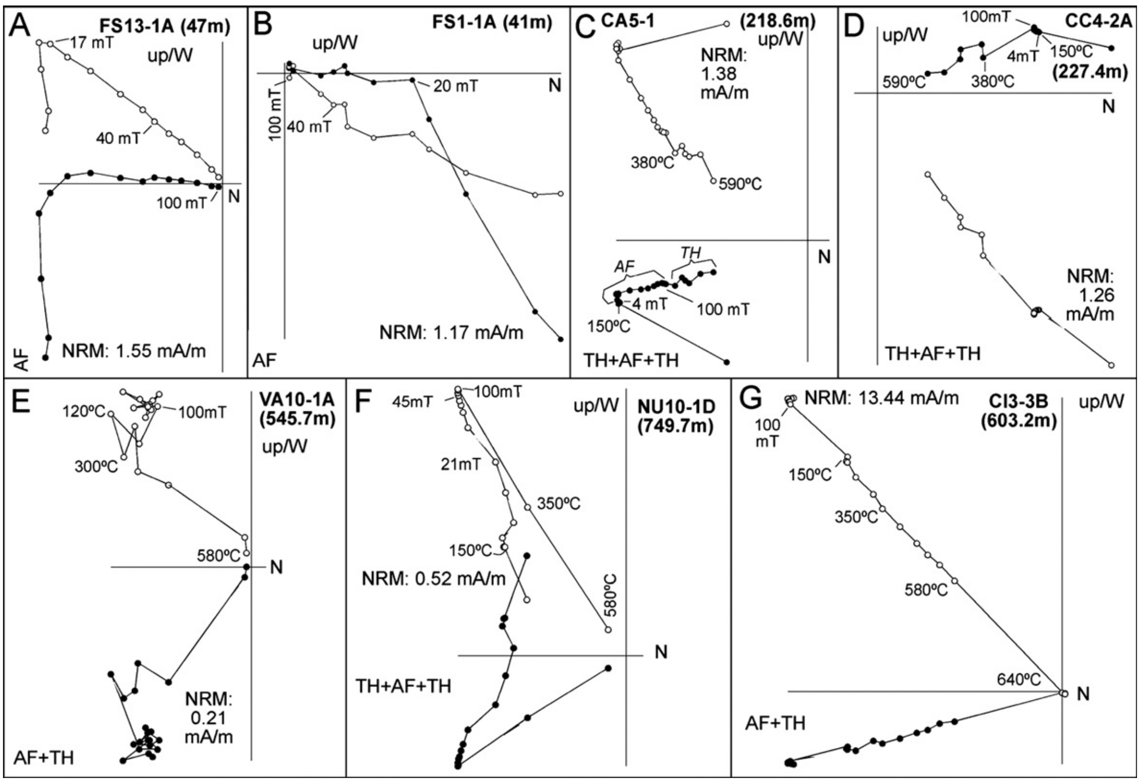

Fig. 5. A to G: tilt corrected orthogonal demagnetization plots from all the lithologies considered in the paleomagnetic calculations. Solid (open) symbols represent projections onto the horizontal (vertical) plane. Alternating field (AF), thermal (TH) or combined demagnetisation protocols for each sample are indicated. The depth on the composite section is also indicated.

(Fig. 5D). The Upper Red Garumnian red beds may also present a secondary magnetization but the characteristic magnetization component also are completely unblocked at temperatures close or higher than 600 °C (heating after full AF demagnetisation) (Fig. 5F, G), indicating that hematite is the main magnetic carrier in those red beds. Thus, mudstones of F8 and F9 are generally useful rocks for the magnetostratigraphic analysis of the section.

Several facts indicate that our ChRM components are true primary acquired remanences. First, we observe that polarity changes are not related to lithology. Second, our sampling has been done in tilted sections sometimes up to 60° (except for sections 5 to 7) and after tilt correction we observe mean directions to be rotated and antipodal, which at least indicates that characteristic magnetization was acquired before the Eocene folding (Fig. 6). Third, we have discarded all ambiguous samples that have low intensities or unstable behaviour (although some samples of medium quality, plotted in white circles in Fig. 4). Finally, the independent correlation of the section with the time indicators (following biochronological criteria, see below) reveals a succession of polarity intervals similar to that of the standard scale for the studied time period.

The calculated ChRM directions define 8 magnetozones (Fig. 4). N1 to R3 are labelled as a succession of different polarity zones, whereas R4 and R5 could be different from R3 because of the hiatus represented by the brecciated upper Vallcebre Limestone and the large covered interval (694 to 733 metres), which likely represent a significant time span.

3.3. Biochronology

Several biochronological markers (charophyte, invertebrate fauna, and vertebrate remains) are here considered to further correlate the paleomagnetic results with the standard Geomagnetic Polarity Time Scale (GPTS). One of the indicators generally used to determine the age of continental sections across the K/T boundary is their charophyte content (e.g., López-Martínez et al., 2000). The charophyte reference scale used for the Pyrenean area is based on the Montian from Mons (Belgium), the Thanetian from the Paris Basin, as well as the Begudian and Rognacian from Provence and the Auzas Marls of the Petites Pyrénées (France). These floras have been described by Grambast (1971), Masieux et al. (1979), Grambast-Fessard (1980), Galbrun et al. (1993), and Riveline et al. (1996). However, Laurent et al. (2002) mentioned work in progress that would modify this charophyte scale. In the studied Vallcebre section, Médus et al. (1988) and Feist and Colombo (1983) located the K/T boundary above the Reptile Sandstone, at the last occurrence of non-

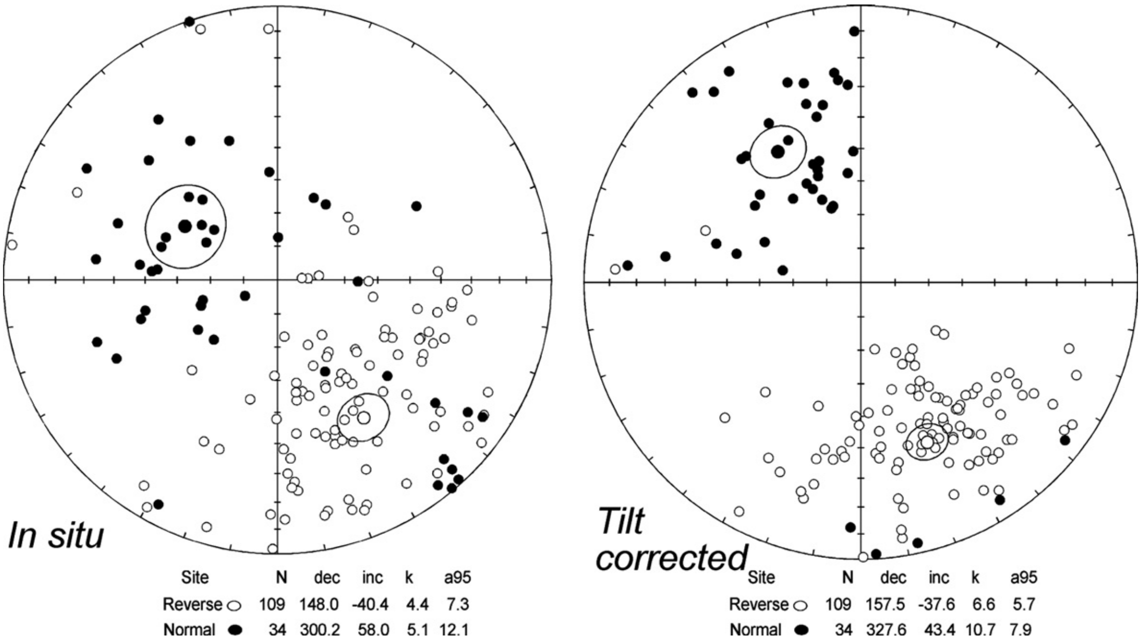

Fig. 6. Stereographic (equal area) projection of the ChRM components for the Vallcebre syncline composite section, before (*in situ*) and after tectonic correction (tilt corrected). Fisher statistics for the mean directions are provided and the 95% confidence ellipse is indicated. Note that the mean values for both normal and reversed polarities are antipodal and indicate a tectonic counterclockwise vertical-axis rotation.

reworked *Peckichara sertulata* in the mudstone interval separating the latter sandstone bed and the Vallcebre Limestone. This limestone is of Cenozoic age based on the absence of the aforementioned charophyte species and the appearance of the Tertiary species *Dughiella bacilaris*. The pollen and ostracod taxa reported by Médus et al., 1988, provide little additional information but are consistent with the ages given by charophytes. The most recent integrated chronology of the Cretaceous–Tertiary transition in the south Pyrenees was done by López-Martínez et al. (2000). Based on marine planktonic foraminifera and charophyte succession, this work confirms that the last appearance of *Peckichara sertulata* takes place within paleomagnetic chron C29r at the K/T boundary.

The age of the Vallcebre section studied here is also constrained by the underlying marine series, where the rudist *Hippurittes radiosus* is found. This rudist has a narrow stratigraphic distribution in the Pedraforca thrust sheet (Vicens, 1992) and the rest of the Pyrenees, and has been correlated with deep marine sediments of terminal Campanian age (Vicens et al., 2004).

Since 2002, dinosaurs research in the Vallcebre syncline has led to the discovery of more than 14 sites containing dinosaur egg remains (Bravo et al., 2005), which may be useful fossils for dating (Garcia and Vianey-Liaud, 2001). Egg material is found as egg clutches, isolated eggs, and eggshell fragments of several oospecies (Bravo et al., 2005). The two most abundant oospecies are *Megaloolithus siruguei* and *Megaloolithus mammillare*. A site with 5 eggshells fragments of *M. mammillare* has been found around metre level 112 of the composite section.

Although not considered a firm evidence, the presence–absence of several other dinosaur remains, such as footprints and bones, may be useful in constraining the age of deposits. In the lowermost part of the section, thousands of sauropod footprints occur together with few possible theropod footprints (e.g., Le Loeuff and Martínez, 1997; Schulp and Brokx, 1999, Vila et al., 2004, 2005). It is remarkable that the most recent (i.e., stratigraphically highest) dinosaur remains are found in the Reptile Sandstone (F10) along with ornithopod footprints and bones (Pereda-Suberbiola et al., 2004). No dinosaur fossils have been found above this sandstone bed despite intensive searching.

4. Discussion

The succession of sedimentary facies, together with paleobiological indicators, allow to define four facies associations that we interpret to correspond to distinct sedimentary environments (see Fig. 7): lagoon (F1 to F5 facies), marginal lagoon (F6 and F7 facies), distal alluvial plain (F8 and F9 facies), and proximal alluvial plain (F10 facies). These environments are consistent with the general interpretations for the south Pyrenean Garumnian (see generalizations in Rosell et al., 2001, description of the Tremp Basin in Cuevas, 1992 and Liebau, 1973, and description of the Vallcebre basin in Aepler, 1967). The vertical succession of facies through the stratigraphic section reveals several facies shifts (see Fig. 8) and provides a high-resolution record of paleoenvironmental variations for most of the Garumnian unit. The vertical facies succession (Fig. 8) shows a gradual regression through the section, with aquatic facies becoming less abundant. The correlation of these ecological variations with the rest of the southwestern European continental K/T boundary sections is difficult because no comparable data exist.

Our paleomagnetic study reveals a clear correlation between the unblocking temperature and alternating

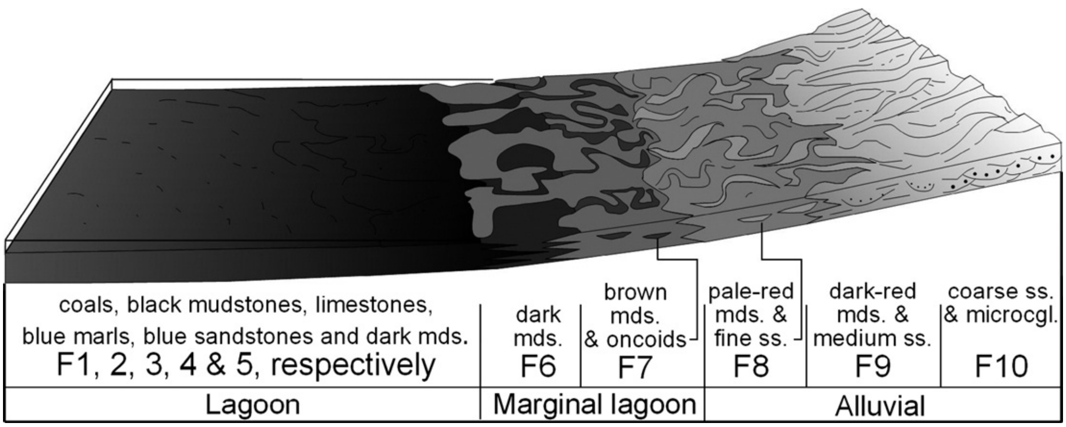

Fig. 7. Sedimentological model based on the ten observed facies.

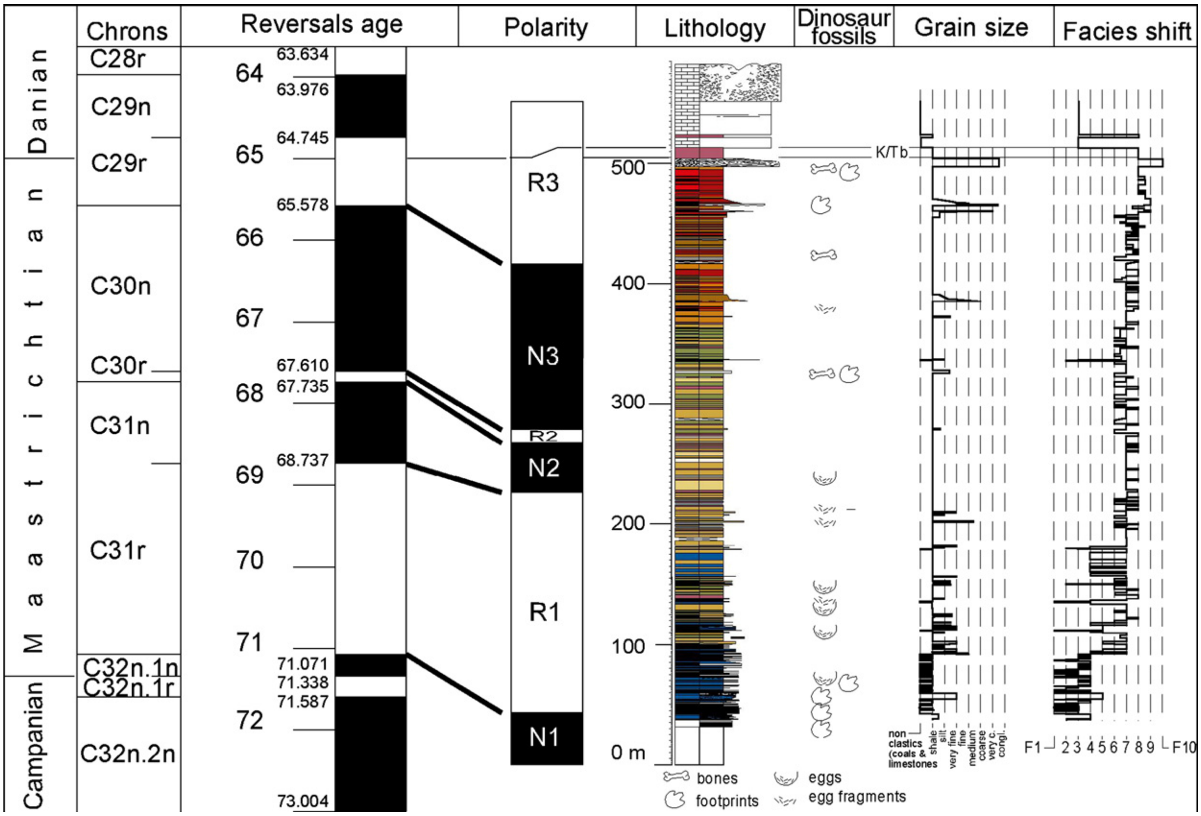

Fig. 8. Cretaceous interval of the composite Vallcebre section showing (from left to right): correlation to the standard Geomagnetic polarity time scale (Cande and Kent, 1995), correlation with polarity chrons, lithology, dinosaur content, and paleoenvironmental variations.

field strengths (general indicators of magnetic mineralogy) of particular lithologic facies and the paleoenvironment in which it was deposited. In the lagoonal blue facies (F4 and F5), high remanence is carried by several minerals, with important contribution of probable magnetite. In brown marginal lagoon and distal alluvial facies (F6 and F7), iron hydroxides are the main or the only carrier of magnetization. In continental settings (F8, F9 and upper Garumnian red beds), remanence is mainly carried by high temperature unblocking minerals, probably hematite.

The polarity zones observed in the Vallcebre section can be correlated with the GPTS according to the available biochronological data and polarity reversal pattern (Fig. 8). Five correlation criteria are considered. First, the occurrence of *Peckichara sertulata* (Médus et al., 1988, and other references) 1.5 m above the Reptile sandstone indicates a Maastrichtian age for the Lower Red Unit, whereas the charophytes found in the basal Vallcebre Limestone indicate a Tertiary age for uppermost part of the Vallcebre section. These fossil occurrences indicate that chron R3 is C29r (which hosts the K/T boundary). Second, the oospecies *M. siruguei* is present in most of the Campanian and in part of the Maastrichtian (C33 to C31, Fig. 5 in Garcia and Vianey-Liaud, 2001) and *M. mammillare* has a distribution range from C31 to C30n (Fig. 5 in Garcia and Vianey-Liaud, 2001). Therefore, the presence of the latter oospecies indicates that the R1 polarity interval (Fig. 4) is C31r (see Fig. 8 with GPTS by Cande and Kent, 1995). Third, the presence of the rudist *Hippurittes radiosus* in strata underlying the studied section indicate a terminal Campanian age for these deposits, confirming the correlation established above. Fourth, it is notable that dinosaur remains has been recovered in the strata encompassing the N1 to R3 polarity zones while they are absent in the continental succession comprising polarity zones R4 and R5, which suggests that at least part of R3 is Cretaceous in age. Fifth, if (in agreement with the four points above) we correlate the N1 polarity interval with C32n.1n and R3 with C29r, the relative length of the various polarity intervals of the Vallcebre section is very similar to that of the standard scale (Fig. 8) and implies a rather constant sediment accumulation rate throughout most of the section (about 77 m/Ma, see Fig. 9).

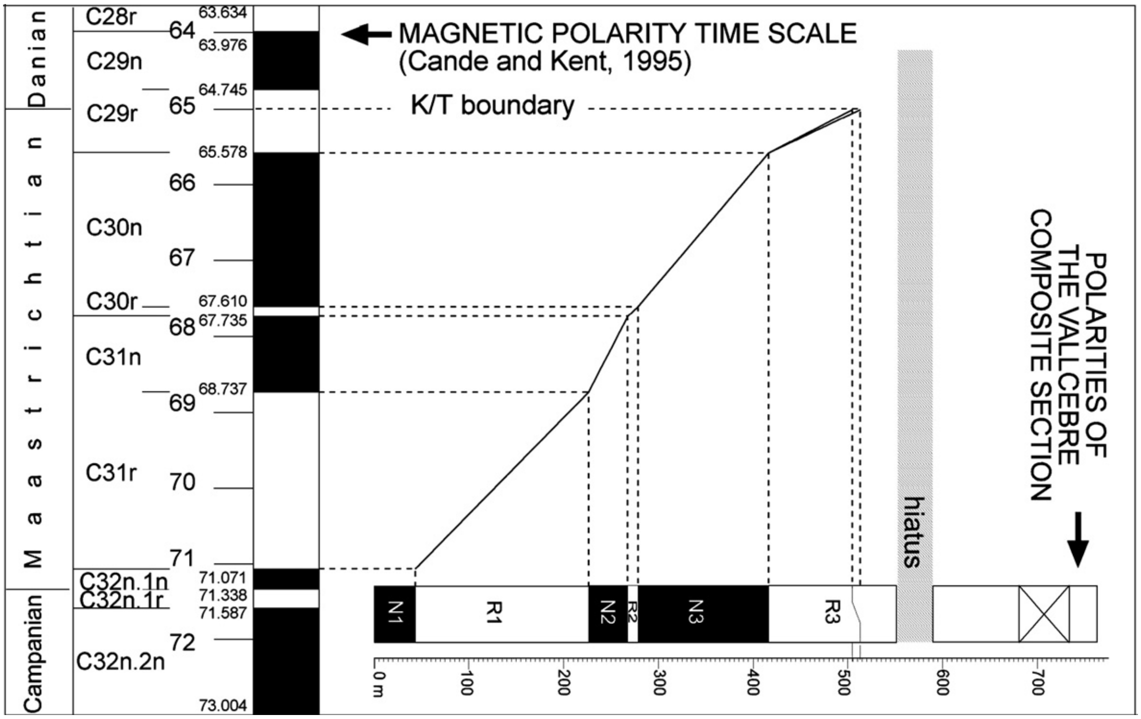

Fig. 9. Sediment accumulation curve throughout the Vallcebre composite section. Note a rather constant accumulation rate, with an average of 77 m/Ma (calculated between C32–C31 polarity reversal and the K/T boundary).

This correlation scheme indicates that the Vallcebre section records the entire Maastrichtian (maybe a short period from chron C32n.1n is not represented in chron N1) in parallic to continental facies. This interpretation refines the tentative Campanian–Maastrichtian age assignment of Vergés et al. (1994) to the Garumnian of the Pedraforca thrust sheet. More importantly, however, this correlation clearly indicates that the dinosaur extinction in southwestern Europe did not take place long before the K/T boundary (see Fig. 8, contra Galbrun, 1997) as dinosaur remains are found within the Reptile sandstone.

Over the 6 Ma of the Maastrichtian, steady, low-energy sedimentation took place in the Vallcebre Basin (fine grained lithologies) with a gradual marine regression leading to better drained environments (Fig. 8). Towards the end of this time interval, a maximum regression peak is recorded in the deposition of the Reptile sandstone that represents a period of high-energy flow in the basin (as seen in the granulometric curve on Fig. 8). This deposition event marks a landscape change from a previous muddy flood plain to a sandy braidplain (although in the last 15 metres above the Reptile sandstone, well-drained conditions are recorded again, after the sedimentation of F8 and F9). This scenario is consistent with the model for the dinosaur extinction proposed by Dingus and Rowe (1997), who suggested that a marine regression, in combination with latest Cretaceous igneous activity and the asteroid impact, caused the extinction (see a recent review in Fastovsky and Sheehan, 2005). Future work on dinosaur diversity of the Vallcebre basin will probably provide key information on this subject.

The paleomagnetic dating and petrological evidences strongly suggest that the Reptile sandstone can be correlated with the similar French Galante and Fleurie sandstone units (Westphal and Durand, 1990, and references therein). Despite some uncertainties for the French dataset, several sections indicate a position within a polarity chron correlatable with C29r (Westphal and Durand, 1990; Cojan et al., 2000). Sedimentological features are remarkably similar for all these units and in both cases provenance is from the south and southwest extant massifs of Sardinia (Westphal and Durand, 1990 and references therein) and Ebro (Masriera and Ullastre, 1982). These coarse-grained sediments would then reflect a major marine regression related to climatic change or to a major tectonic event. As of yet, no tectonic pulse has been described in the area (or even in the Pyrenees) near to the K/T boundary. Thus, our data suggest that a major landscape change occurred some time before the K/T boundary in the Vallcebre basin, by the transformation of muddy and quiet mud plains into sandy river plains, and was followed by a return to a muddy flood plain before the K–T boundary. This latter environmental shift could match the global cooling shift recorded near 65.6 Ma (see Wilf et al., 2003).

5. Conclusions

A thick and continuous stratigraphic record was obtained in the Garumnian facies of the Vallcebre syncline. These sediments record deposition during the Maastrichtian and into the Tertiary. This section is continuous and is probably among the thickest continental records of Maastrichtian age in the Old World. A robust magnetostratigraphic scheme is achieved, which can be unambiguously correlated to the standard GPTS in light of existing biochronological constraints (charophyte, marine invertebrates, eggshells and other dinosaur remains) preserved in the section.

Sedimentological observations reveal a regression during the Maastrichtian that achieved a maximum before the K/T boundary (85 metres above the base of C29r). The combined litho-and chronostratigraphic framework of the Vallcebre composite section permits a comparison with the stratigraphy from other Pyrenean localities, the Arc Basin and other French localities. In general, this regressive tendency seems to be common for other continental sections in south-western Europe.

We conclude that a maximum paleonvironmental change (regressive peak) affected the continental areas of SW Europe before the K/T boundary event. There are no tectonic evidences for the origin of this regression. This dramatic change of the landscape is evidenced by the transformation of quiet muddy floodplains into sandy braidplains deposited by high-energy currents. Overlying this event, a short stratigraphic interval recording sedimentary quiescence occurred before a Cenozoic flooding took place (lacustrine Vallcebre limestones).

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