Ichnological analysis of the Bidart and Sopelana Cretaceous/Paleogene (K/Pg) boundary sections (Basque Basin, W Pyrenees): Refining eco-sedimentary environment

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1. Introduction

The Cretaceous–Paleogene (K/Pg) boundary event is one of the most spectacular phenomenon in the Phanerzoic history of the Earth causing a global major extinction. In pelagic environments it is recorded in the so-called boundary layer, which is a thin, usually 5–10 cm thick, dark and calcium carbonate depleted claystone or marlstone. Commonly, the base of the boundary layer is defined by a millimeter-thick rusty layer which contains the iridium and other geochemical anomalies related with the extraterrestrial bolide impact at the northern Yucatan peninsula (Schulte et al., 2010; Smit, 1999) which defined the formal position of the K/Pg boundary (Molina et al., 2006). Publications showing the presence of trace fossils at the K/Pg boundary interval are scarce (see Rodríguez-Tovar and Uchman, 2008 for a review), especially those including a detailed ichnological characterization (e.g., Ekdale and Bromley, 1984; Ekdale and Stinnesbeck, 1998). However, in the last years ichnological analyses conducted in several K/Pg sections, reveal that the boundary layer is bioturbated, containing diverse trace fossils, which help to refine several aspects in the interpretation of the palaeoenvironmental conditions that prevailed during sedimentation of the K/Pg boundary event interval (Rodríguez-Tovar, 2005; Rodríguez-Tovar and Uchman, 2004a,b, 2006, 2008; Rodríguez-Tovar et al., 2002, 2004, 2006).

In the Basque Basin (western Pyrenees) several outcrops of deep marine (hemi)pelagic facies have been studied, revealing the well developed, expanded and relatively complete K–Pg boundary interval (see Apellaniz et al., 1997; Pujalte et al., 1998). These favourable features determined the numerous studies conducted in the uppermost Maastrichtian–lowermost Danian sediments of this area, involving sequence stratigraphic, mineralogical, isotopic, geochemical, magnetostratigraphical and biostratigraphical analyses (see Alegret, 2007 for a recent review). In this exhaustive research, however, detailed ichnological analysis has been only recently initiated (Rodríguez-Tovar et al., 2010). In this paper we present the ichnological analysis of two of the best-preserved K/Pg boundary sections, Bidart, in SW France, and Sopelana, in N Spain (Figs. 1 and 2). Their ichnological features have been investigated in...
order to show some biogenic and sedimentary phenomena through the K/Pg boundary interval, and to define the similarities and differences between these two sections. The latter aspect is of special interest, because in deep basins that presumably record homogeneous hemipelagic sediment supply, ichnological features may become a powerful tool to recognize subtle lateral changes in the sedimentation regime and the palaeoenvironmental conditions at the sea floor.

2. Location and setting

The late Cretaceous and Paleogene in the Pyrenees are represented by a wide variety of sedimentary rocks, including continental alluvial clastics, shallow marine carbonates and deep-water hemipelagites and turbidites accumulated in a broad E–W elongated embayment opened into the Bay of Biscay and the North Atlantic (Baceta, 1996; Baceta et al., 2004; Plaziat, 1981; Pujalte et al., 1998). Basinal
Hemipelagites and turbidites were deposited in the central part of the embayment, the so-called Basque Basin (Pujalte et al., 1998), at depths ranging from 1000 to 1500 m (Fig. 1).

The late Maastrichtian–earliest Ypresian was a phase of relative tectonic quiescence, during which turbidite deposition was reduced and the Basque Basin became dominated by regular alternations of hemipelagic limestones and marls, usually grouped in bedding couplets and bundles as representative of precession and short-eccentricity climatic cycles (Dinarès-Turell et al., 2003, 2007).

The best known K/Pg boundary sections being of the Basque Basin are located in coastal cliffs between the north of Bilbao and the south of Baiona. Up to twelve of these K/Pg sections can be identified, the Zumaia section being the reference for all of them (see Apellaniz et al., 1997 for a synthesis). Bidart and Sopelana, the two K/Pg sections selected for ichnological analysis, are 100 km apart (see Fig. 1 for correlation with the Zumaia section according the most significant correlation levels a to e). The Bidart section is located in southwestern France, in a long beach few kilometres to the north of the Zumaia section. The Sopelana section is located in the Basque Country, between the north of Bilbao and the south of Baiona.

Fig. 2. Lithological columns of the Sopelana B and Bidart sections with sample locations and range of trace fossils.
Bidart town (43º27′N and 1º35′E), within an upper Cretaceous–Eocene succession that dips 15–35º to the north. The Sopelana section is located north of Bilbao, in northern limb of the Cretaceous–Paleogene Byscay Sinclinorium (Fig. 1, 43º23′N and 2º59′W). The upper Cretaceous–Paleocene basinal succession of the Sopelana section is affected by reverse and strike-slip faults, which cause stratigraphic repetitions and the existence of three different K/Pg boundary outcrops. Two of these sections have been analysed: Sopelana A (Sopelana Beach) and Sopelana B (above the cliff) sections, which in previous papers were labelled, respectively, as Sopelana III (Apellaniz, 1998) and Sopelana I (Orue-Etxebarria, 1983, 1984, 1985).

3. Lithostratigraphy and biostratigraphy of the K/Pg boundary in the Basque Basin

3.1. Bidart and Sopelana sections

A profuse research has been conducted in the last decades in the Bidart section (see Gallala et al., 2009 for a review). Recently, the K/Pg boundary transition at Bidart section was studied, focusing on the trace fossil assemblage (Rodríguez-Tovar et al., 2010; Figs. 2 and 3). The upper 4 m of the Maastrichtian contain grey and pinkish marls and marly limestones. The rusty layer marking the K/Pg boundary is well preserved and about 2 mm thick. Above it, the first Danian deposits occur in an about 15 cm thick dark clay layer, overlain by nearly 23 cm thick reddish to greenish marls and marly limestones. Above them, a 93 cm thick interval of partly parallel laminated white to reddish limestones is present, followed by a 1–1.5 m thick pebbly mudstone bed made up of roundish clasts of hemipelagic limestones embedded in a marl-lime matrix. This clastic deposit is interpreted as reflecting an episode of erosion and redeposition by submarine debris flows. The upper part of the studied section consists of white and reddish bioturbated limestones with thin (2–3 cm) marlstone interbeds.

The Bidart section can be considered, together with the classical Zumaia section (Fig. 1), as one of the most complete land-based K/Pg boundary sections exposed in the eastern margin of the Atlantic Ocean (Apellaniz et al., 1997; Haslett, 1994; Seyve, 1990), as recently corroborated by magnetostratigraphic, calcareous nannofossils and planktic foraminifera analyses (Galbrun and Gardin, 2004; Gallala et al., 2009). These works reveal a continuous sedimentation across the K/Pg boundary transition, without any biostratigraphically significant hiatus. The planktic foraminifera biozonation (Gallala et al., 2009), is as follow: a) at the Upper Maastrichtian, the Abathomphalus mayaroensis Zone is differentiated, b) the Guembelitria cretacea Zone that marks the base of the Lower Danian, around 15 cm thick in the Bidart section, and subdivided into the Hedbergella holmdelensis and Parvularugoglobigerina longiapertura subzones, and c) the P. eugubina Zone, around 100 cm thick in the Bidart section, that is subdivided into the P. sabina and Eoglobigerina simplicissima subzones.

The K/Pg boundary transition at the Sopelana section (A and B) has been comparatively less studied than that at Bidart. Descriptions of the Sopelana A section can be found in Lamolda et al. (1983) and Orue-Etxebarria (1985). Especially interesting is the complex iridium distribution, with two iridium spikes, the first coeval with the final Cretaceous planktonic foraminiferal extinction, and the second in coincidence with the nannoplankton crisis (Rocchia et al., 1988). Detailed analysis of the Sopelana section (A and B) corroborates similar facies composition as in the Bidart section, but different thicknesses (Figs. 2 and 4). The upper 7 m of the Maastrichtian consists of grey and pinkish marls of changing endurance. Above them, a 90 cm thick interval of white and reddish bioturbated limestones with thin (2–3 cm) marlstone interbeds.

Fig. 3. Outcrop of the K/Pg boundary layer at Bidart. A) General view showing top of the Maastrichtian marlstones, the boundary layer and the Danian limestones and marlstones. Stars pointed by arrows indicate debris flow calciruditic beds; note their convex up upper bedding planes. B) Detail of A. C) Boundary layer. D) Debris flow calciruditic beds in the Danian (indicated by stars); compare to A.
limestones which includes a level with some evidence of soft-sediment synsedimentary deformation, in the form of irregular folding and fracturation with differentiation of isolated limestone clasts. Biostratigraphic analysis based on planktonic foraminifera and calcareous nannoplankton revealed that the first occurrence of the Tertiary planktonic foraminifera *Globigerina (E.) eugubina* is a few centimetres (8–10 cm) above the extinction of Upper Cretaceous planktonic foraminifera (Lamolda et al., 1983). Thus, the lowermost part of the Paleogene corresponding to the *Guembelitria cretacea* Zone was not identified (Lamolda et al., 1983; Mary et al., 1991). This zone could be represented in the 2–3 cm just above the contact with the Maastrichtian, but the relative scarcity and poor preservation of planktonic foraminifera above the rusty layer avoid a conclusive interpretation (Canudo, 1994). The incompleteness of the Sopelana A...
section was also revealed based on the graphic correlation analysis; the 2 cm separating the red layer from the FAD of P. eugubina imply the absence of the Zone P0 estimated in 50,000 yr in duration (MacLeod and Keller, 1991; MacLeod et al., 1997). The K/Pg boundary interval in the Sopelana B section situated 60 m from the former above the seafiffs, is more complete and significantly better preserved. According to Apellaniz et al. (1997) and Apellaniz (1998) the boundary layer marking the boundary is 7 cm thick and contains a planktic foraminifer assemblage characteristic of the Guembelitria cretacea Zone. The overlying marl-marlstones that are 28 cm thick are also well preserved. Their lower 22–23 cm corresponds to the Parvularugoglobigerina longiapertura Zone.

4. Trace fossil analysis

Only occasionally trace fossils or bioturbational structures have been mentioned in the K/Pg boundary section at Bidart (Gorostidi and Lamolda, 1995; Haslett, 1994; Smit and Ten Kate, 1982), while in the Sopelana section, Lamolda et al. (1983) refer to “a distinct burrowed surface” at the top of the purple marls corresponding to the latest Maastrichtian. Recently, Rodríguez-Tovar et al. (2010), present a preliminary ichnological analysis of the K/Pg boundary transition at the Bidart section, focusing on the effects of different tracemakers on the redistribution of calcareous nannofossils throughout the K/Pg boundary. The section shows a relatively abundant and conspicuous dark-coloured trace fossil assemblage with Chondrites, Planolites, Thalassinoides, Trichichnus and Zoophycos, and less abundant light-coloured ichnofossils including Planolites and Thalassinoides. Calcareous nannofossils are re-distributed in fillings of some ichnotaxa in the Bidart section, with danian calcareous nannofossil assemblages present in Maastrichtian samples, evidenced by abundant Paleogene calcareous nannofossils just below the K/Pg boundary (Rodríguez-Tovar et al., 2010).

The sections were analyzed layer by layer. Selected samples were collected continuously at the K/Pg boundary transition, and more sparsely in the rest of the succession, and then cut and polished in the laboratory. The cut and polished surfaces were wetted in order to obtain better contrast for photographs.

4.1. Synopsis of trace fossils

The trace fossil assemblage identified in the K/Pg sections of Bidart and Sopelana is low diverse, with 5 common ichnogenera (Chondrites, Planolites, Thalassinoides, Trichichnus and Zoophycos), together with ? Phycosiphon only registered in the Sopelana section.

Chondrites isp. (Figs. 4C–D, F–G, 5A, 6A, D–G, 8B–C) is observed (1) on parting surfaces as branched burrow system composed of compressed straight or curved equidimensional cylindrical, unlined elements (Figs. 4D, 6A, D), or in (2) cross section as patches of circular to elliptical spots and short bars, some of them branched (Figs. 4C, E–G); they are cross sections of a branched tubular burrow system. The branches are under acute angle. The filling is darker (Fig. 4D–G), rarely lighter than the host rock (Fig. 4C). Larger forms (Fig. 4C–G), 1.2–2.2 mm in diameter, and smaller forms, 0.3–0.9 mm diameter (Fig. 4E), can be distinguished. At least some of the larger forms belong to Chondrites targionii (Brongniart, 1828) and at least some of the smaller forms belong to Chondrites intricus (Brongniart, 1823) but limited observations along the tunnels preclude accurate determinations. The smaller form can be found in the fillings of some Thalassinoides or Planolites, and the larger forms in Thalassinoides.

Chondrites von Sternberg, 1833 is a feeding system of unknown tracemakers (e.g., Osgood, 1970) which, according to Kotake (1991a), are surface ingestors, packing their faecal pellets inside burrows. According to Seilacher (1990) and Fu (1991), the tracemaker may be able to live at the aerobic-anoxic interface as a chemosymbiotic organism.

Fig. 5. Ichnofabrics and trace fossils of the pre-event Maastrichtian marlstones at Bidart. A) Thalassinoides isp. (Th) cross cut by Chondrites isp. (Ch), Planolites isp. (Pl), all in the totally bioturbated background; polished slab; sample Bd2. B) Zoophycos isp. (Zo) in the totally bioturbated background. Polished slab, sample Bd11. C) Trichichnus isp. (Tr) on a rough surface, sample Bd8.
in diameter, with swellings up to 35 mm wide. At Bidart, smaller forms commonly penetrate along fillings of older generation, larger *Thalassinoides*; and both are filled with dark sediment (Fig. 6B). The prevailing Y-shaped branches and swellings suggest assignation to *Thalassinoides suevicus* Rieth, 1932.

*Thalassinoides* Ehrenberg, 1944 is a domichnial and fodinichnial structure produced by crustaceans, mostly decapods (Frey et al., 1984). For further discussion of this ichnogenus and its ichnotaxonomic problems see Fürsich (1973), Ekdale (1992) and Schlirf (2000).

*Trichichnus* isp. (Figs. 4G, 5C) is a winding or straight, differently oriented, rarely branched, 0.2–0.3 mm thick (rarely up to 0.7 mm), thread-like cylinder filled with ferruginous substance, with a yellowish halo around the cylinder. *Trichichnus* Frey, 1970 is a eurybathic marine trace fossil, which is common in fine-grained
Fig. 7. Ichnological and sedimentological features of the lowest Danian sediments in the Sopelana B section. A) Bioturbational structures with Thalassinoides isp. (Th) in the K-Pg boundary layer, horizontal section, sample So-86. B) As in A but with ?Thalassinoides isp. (?Th). C, D) Laminated sediments of the K-Pg boundary layer, vertical sections, sample So-89. E) Debris flow calcilutites above the boundary layer, vertical section, sample So-91. F) Partly bioturbated top of the bed represented by sample So-89, Thalassinoides (Th), horizontal section.

Fig. 8. Ichnofabrics and trace fossils of the Danian limestones and marlstones. A) Totally bioturbated marly limestones with Zoophycos isp. (Zo); vertical section, polished slab; sample 22. B, C) Thalassinoides isp. (Th), Chondrites isp. (Ch) and Planolites isp. (Pl) in totally bioturbated background; weathering surface. D) Zoophycos isp. cross cut by Planolites isp. (Pl), weathering surface.
seds. Trichichnus is regarded as the domiciial burrows of marine meiofaunal deposit feeders (Frey, 1970). Possibly, the producer of Trichichnus was a chemosymbiont (Uchman, 1995), as in the case of the Chondrites producer (Fu, 1991; Seilacher, 1990). McBride and Picard (1991) suggest that Trichichnus had a more opportunistic character than Chondrites because it occurs more deeply in very poorly oxygenated sediments. For taxonomic discussion see Uchman (1999).

Zoophycos isp. (Figs. 4H–I, 5B, 6C, 8A–D) occurs on parting surfaces as horizontal or oblique lobes and tongues, up to 40 cm wide, filled with spreite laminae encircled by a thin marginal tunnel. In cross section it is seen as straight or curved stacked stripes, 1.5–4 mm thick, 7–28 mm apart, which can be massive or filled with spreite manifested on the surface as menisci-like structures. They are a part of a helical burrow system.

Zoophycos s.l. is generally considered a structure produced by some yet undiscovered deposit-feeder, which is referred to sipunculids (Wetzel and Wern, 1981), polychaete annelids, arthropods (Ekdale and Lewis, 1991), or echinurans (Kotake, 1989). Kotake (1989, 1991b) reported that Zoophycos is produced by surface ingestors of organic detritus. However, the precise ethological interpretation of Zoophycos remains still controversial. Bromley and Hanken (2003) suggested that the upper helical part of a large Pliocene Zoophycos from Rhodes, Greece, is a deposit-feeding structure, and lateral lobes developing from its lower part are sulphide wells for chemosymbiotic bacteria. The same interpretation refers to a similar but smaller Zoophycos from the Miocene of Austria, which displays very steep lobes in its lowermost part (Pervesler and Uchman, 2004).

4.2. Ichnological features

4.2.1. Abundance of trace fossils, and size of Thalassinoides

The trace fossil abundance (number of specimens and visual density estimations), and size of Thalassinoides, varies significantly between the Bidart and Sopelana sections (Sopelana A and B sections considered together). Thalassinoides is distinctly more abundant and larger at Bidart (mean diameter of 35 specimens = 10.1 mm, maximal width 30 mm) than at Sopelana (mean diameter of 28 specimens = 6.4 mm, maximal width 14 mm). The larger Chondrites is around two times more abundant in the K/Pg boundary at Bidart than at Sopelana. Reverse tendency is clear for the smaller Chondrites and very distinctly (by more or less four times) for Trichichnus. Zoophycos is comparatively more abundant at Bidart than at Sopelana. Phycosiphon has been only recognized at Sopelana.

4.2.2. Feeding behaviour

The trace fossil assemblage reveals different feeding behaviour. They belong to domiciia/fodinichnia (Thalassinoides), chemichnia (Chondrites, Trichichnus), pascichnia (Planolites) and fodinichnia (Zoophycos, Phycosiphon). All of them indicate that the trace makers obtained food from sediment.

4.2.3. Depth of penetration

The dark filling of some trace fossils located in the uppermost Maastrichtian sediments clearly derives from the dark sediments of the K/Pg boundary layer (black-filled trace fossil ranges in Fig. 9). Detailed microfossil analyses at Sopelana, especially in section B, reveals the presence of numerous dark-filled trace fossils coming down from the dark-boundary layer into the light upper Maastrichtian sediments. Dark-filled Chondrites and Zoophycos are present from several centimetres above to below the K/Pg boundary. Zoophycos and Chondrites are the deeper trace fossils. In the Bidart section, large dark-coloured Zoophycos isp. is the deepest trace, in some cases penetrating up to −45 cm (45 cm below the K/Pg boundary layer) in the marlstones underlying the K/Pg boundary surface. In the Sopelana B section it occurs at depths of −22 cm below the boundary.

Chondrites penetrates up to −25 cm at Bidart, −40 cm at Sopelana B and −22 cm at Sopelana A. Thalassinoides was found up to −32 cm at Bidart and −40 cm at Sopelana B, and −20 cm at Sopelana A. Planolites is still present at −40 cm at Bidart, −30 cm at Sopelana B; dark-filled Planolites was not found at Sopelana A.

The values are minimal because the burrows can be filled from different levels above the boundary rusty layer, corresponding to 38 cm thick (15 cm thick dark clay layer + 23 cm thick reddish to greenish marls) at Bidart, and at least 22 cm thick at Sopelana A and at least 25 cm thick at Sopelana B of green-grey marls. Data from the Sopelana A section are not fully representative because of limited number of samples obtained by digging due to outcrop constraints. These data should be rather treated as complementary to the Sopelana B section.

Trichichnus is filled with pyritized sediment and Phycosiphon with light material. Therefore, depth of penetration of these ichnotaxa cannot be measured in respect to the boundary layer. However, it is known that Phycosiphon belongs to shallow and moderate deep tiers and Trichichnus is a deep-tier burrow (e.g., Uchman, 1999).

4.2.4. Trace fossil distribution through the K/Pg boundary interval

The boundary layer at Bidart contains the rusty layer at the base, just above 1–2 cm thick, grey, thin, totally bioturbated marly mudstone (Fig. 9). The rusty layer is only partly bioturbated. Above, the boundary layer is totally bioturbated, except for two laminated intervals, which are crossed only by some trace fossils (Fig. 6F). At Sopelana (Fig. 4A–B), the boundary layer is disturbed by tectonic sliding, therefore its primary internal structure is partly obliterated. In the Sopelana A section, the boundary layer is totally bioturbated, with two rusty laminae in the lower part (Fig. 9). In the Sopelana B section, the boundary layer is totally bioturbated (Fig. 7A–B) except for its uppermost laminated few centimetres (Fig. 7C–D). The trace fossils content of the boundary layer is almost the same as the dark-filled trace fossil assemblage.

In the lowest 2 m of Danian above the boundary layer at Bidart, trace fossils are poorly recorded (Fig. 9); partly by diagenetic obliteration in the lower part and by the presence of the debris flow calcritudite beds (Fig. 3D) in the upper part. The top of the first calcriduate layer is bioturbated and contains Thalassinoides. The beds of the first metres are at least partly bioturbated, but no discrete trace fossils was recognized. Above, well preserved Chondrites, Planolites, Thalassinoides and Zoophycos, are well visible on bioturbated background (Fig. 8A–D).

At Sopelana, the first metre of sediments above the boundary layer is totally bioturbated (Fig. 9) except for the debris flow deposits (Fig. 7E–F). In the bioturbated parts, trace fossils are poorly visible, probably due to poor colour contrast and diagenetic obliteration.

5. Discussion

5.1. Trace fossil assemblage, abundance of trace fossils, size of Thalassinoides and depositional environment

The trace fossil assemblage is low diverse. All the ichnotaxa identified are rather common in fine-grained, low-energy open-marine sediments of the Mesozoic and Cenozoic. Their low diversity and the presence of Zoophycos suggest the Zoophycos ichnofacies, which typically occurs down the offshore but beyond the areas of turbiditic sedimentation (e.g., Frey and Seilacher, 1980). The total bioturbation of the fine-grained calcareous sediments that characterized the two K/Pg boundary sections studied, and the general lack of storm or turbiditic beds agrees with this general interpretation. Thus, ichnological data point to upper bathyal zone, with no significant differences between the depositional settings corresponding to both sections. This interpretation accords partly with previous data based on microfossil assemblages. The dominance of calcareous taxa in the
Upper Maastrichtian and lower Danian benthic foraminiferal assemblages from the Bidart section are interpreted as indicating upper-middle bathyal depths between 500 and 700 m (Alegret et al., 2004). Kuhnt and Kaminski (1993) assigned middle bathyal water depth to the Maastrichtian–Paleocene of the Zumaia section, comparable with the Sopelana section, based on agglutinated foraminiferal assemblages, with absolute values at about 1.000 m depth suggested by Herm (1965).

According to sequence stratigraphic analyses (Fig. 1), the K/Pg boundary transition is included in a transgressive system tract (TST) belonging to a 3rd order depositional sequence (Apellaniz et al., 1997; Baceta, 1996; Pujalte et al., 1998). The top of this sequence is related to an erosive event, resulting from a sea-level drop, reflected by breccias well developed at the Bidart section. This interpretation accords with that from Peybernès et al. (1996), interpreting that the breccias were deposited under conditions of low sea level, and the underlying limestones under high sea-level conditions. Other possibility is that they could be interpreted as a slump triggered by local tectonics during the early Danian (Alegret et al., 2004). For Seyve (1984), the Bidart section can be interpreted as located close to a palaeoslope. Alegret et al. (2004) interpreted that the dominance of calcareous benthic foraminifera through the Bidart section may be indicative of a small supply of terrigenous sediment at Bidart as compared to the coeval Sopelana section (Kuhnt and Kaminski, 1993), where agglutinated foraminifera are dominant.

The higher abundance of Thalassinoides and its larger size, higher abundance of Zoophycos and larger Chondrites, lower abundance of Trichichnus and small Chondrites at Bidart than at Sopelana can be related to palaeogeographic position and the distance of the basin margin. The Sopelana section occupied a more basal position than the Bidart section during the Maastrichtian and Paleocene. This can result in a slightly greater depth, as confirmed by the foraminiferal data, and lesser food supply at Sopelana than at Bidart. Environmental stress related to decrease in food can result in decrease in abundance of larger trace fossils (Thalassinoides, larger Chondrites, and Zoophycos) and thus a dominance of smaller forms (small Chondrites, and Trichichus). This is in accordance to the decrease of both macrobenthic biomass (Rowe, 1983) and number of macrofaunal organisms with increasing depth, especially rapid in the first 2 km (Rowe, 1983; Rowe et al., 1982), and the decrease of biomass with distance to the shore (if not disturbed by upwellings and other currents) (Gage and Tyler, 1991, and references therein). Also the size of the animals decreases generally with increasing depth (e.g., Gage and Tyler, 1991; Thiel, 1975). Thus, the variability within the Zoophycos ichnofacies can be a proxy of food availability related in simple cases to the distance from the shore and water depth. Smaller size of ichnotaxa and decrease in abundance of larger trace fossils can point to more distant and deeper settings.

5.2. Feeding behaviour, nutrients availability and oxygenation of sediments

The presence of chemichnia and trace fossils which trace makers sequestered sediments from the sea floor in deep burrows (Zoophy- cOS) suggest at least periodical food deficiency pressing animals to more sophisticated searching for food.

Variations between oligotrophic and mesotrophic conditions have been alluded to interpret marked quantitative changes in benthic community structure through the K/Pg boundary transition in both sections (Alegret et al., 2004; Kuhnt and Kaminski, 1993). In the Sopelana sections, major change in the quantitative composition of deep-sea agglutinated foraminiferal community structure is related, probably, to a dramatic drop of productivity in surface waters, nearly instantaneously with the terminal Cretaceous event, that determined the collapse of the food web for benthic communities (Kuhnt and Kaminski, 1993). At the lower part of the boundary clay, just after the K/Pg boundary, they record the predominance of low-oxygen tolerant and infaunal agglutinated foraminiferal assemblages, in relation to oligotrophic surface conditions. Coarsely agglutinated forms are common, indicating the increase in detrital supply to the deep sea,
which Kuhnt and Kaminski (1993) interpret in terms of a short-lived regressive event. Although not present in Sopelana, cm-thick silicilastic or mixed carbonate-silicilastic turbidites occur overlying or within the K/Pg clay in several basinal sections in the area between Sopelana and Bidart (e.g., Zumaia, Urrutxua, Herrera or Monte Urko; Baceta, 1996; Apellanz, 1998). Thus, the relative abundance of coarsely agglutinated foraminifers could be explained rather by the presence of discrete levels rich in reworked detrital grains.

In the Bidart section, benthic assemblage shows a similar pattern (Alegret et al., 2004). Upper Maastrichtian benthic foraminiferal assemblages are diverse and heterogeneous, with infaunal and epifaunal forms, revealing mesotrophic conditions. At the K/Pg boundary, a drastic decrease in diversity and heterogeneity is recorded, which is coeval with a major diminution in the percentage of infaunal taxa. This drastic change is related to a significant decrease in the food supply from surface waters to the sea floor, oligotrophic conditions, due to the collapse of the food web accompanying the mass extinction of primary producers (during very limited food supply to the sea floor, food particles were consumed at the sediment surface by epifaunal species, whereas the percentage of infaunal species decreased due to the lack of organic matter in the underlying sediment). In the early Danian, the low diversity of the assemblages, together with the low percentage of infaunal forms, suggests that primary productivity had not completely recovered for more than 200 ky after the K/Pg boundary event. However, even if benthic foraminifera indicate oligotrophic conditions just after the K/Pg boundary, blooms of dinoflagellates have been documented in the dark clay layer (Peybénés et al., 1996), which would have provided large amounts of food that reached the sea floor. For Alegret et al. (2004), primary productivity during the early Danian was dominated by blooms of non-calcareous primary producers; such a change in phytoplankton composition induced a stressful environment for the benthic fauna. These authors indicated that it was not only the drastic decrease in primary productivity, but also the changes in phytoplankton type (from calcareous to organic-walled phytoplankton) just after the K/Pg boundary that caused the low diversity, high-dominance benthic foraminiferal assemblages from the lower part of the dark clay layer (Alegret et al., 2004). It seems, however, that the changes did not influenced tracemakers.

Total bioturbation of sediments (except for some interval of the boundary layer and the debris flow sediments in the Danian) suggest generally good oxygenation below sediment–water interface. Data from benthic microfossils do not reveal a significant incidence of low oxygenation in microbenthic environment (Alegret et al., 2004; Kuhnt and Kaminski, 1993); only, as previously indicated, just after the K/Pg boundary at the Sopelana section, low-oxygen tolerant and infaunal agglutinated foraminiferal assemblages are dominant, but mainly related to oligotrophic conditions (Kuhnt and Kaminski, 1993).

5.3. Depth of penetration and rate of sedimentation

The penetration depth of the dark-filled trace fossils can be treated as frozen tiering pattern of burrows (Bromley, 1996). At Bidart the deepest trace fossil is Zoophycos, similarly to the Caravaca section in the Betic Cordillera (Rodríguez-Tovar and Uchman, 2006). Zoophycos tracemaker probably preferred the partly stiff or partly firm substrate of the Maastrichtian marls, which were dewatered during the slowly accumulating Danian dark-boundary layer. The increased cohesion may have prevented the Chondrites tracemaker to get deeper penetration. Commonly, Chondrites, is the deepest tier burrow in the Cretaceous marls (Ekdale and Bromley, 1991). Such a situation is met at Sopelana, however Thalassinoides penetrates almost to the same depth. Zoophycos is distinctly rarer here than at Bidart, what suggests it was approaching to its environmental limit. In such a situation, the Zoophycos tracemaker could penetrate to smaller depth than in its optimal environment. A comparatively higher cohesion for the Maastrichtian sediments at the Bidart section could be related with a higher rate of sedimentation; a 40 mm/ky sedimentation rate for the Maastrichtian is calculated for the Bidart section (Nelson et al., 1991) against 25 mm/ky for the Sopelana section (Mary et al., 1991).

5.4. The Cretaceous–Paleogene (K–Pg) event incidence

The trace fossil assemblage can be considered with respect to the K–Pg event. The content of pre-event latest Maastrichtian ichnoassemblage, characterized by light-filled trace fossils is nearly the same as the lowest Danian ichnoassemblage characterized by dark filling deriving from the boundary layer (Figs. 4D–I, 6A–D). Light-filled Zoophycos has not been observed in the uppermost 7 m of Maastrichtian at Sopelana, but it is present below. Trichichnus was not detected at above the boundary layer at Bidart and at Sopelana. Thus, according to trace fossil assemblages, the K/Pg boundary event reveals a minor incidence on macrobenthic environment. Previous trace fossil analyses in other K/Pg boundary sections have revealed that changes in environmental parameters at the seafloor during the deposition of the K/Pg boundary sediments did not significantly affect colonization by macrobenthic tracemakers, showing a relatively rapid colonization, specially by organisms with a high independence with respect to substrate features (i.e., Chondrites and Zoophycos tracemakers; Rodríguez-Tovar and Uchman, 2004a, 2006, 2008; Rodríguez-Tovar, 2005; Rodríguez-Tovar and Martín-Peinado, 2009). This comparatively minor incidence in sections here studied, accord with that interpreted for the benthic environment based on microfossils data. Benthic foraminifera assemblage reveals similar response through the K/Pg boundary transition in the Sopelana (Kuhnt and Kaminski, 1993) and Bidart (Alegret et al., 2004) sections. As is generally recognized at the K/Pg boundary, benthic foraminifers did not experienced significant extinction (only three species disappears in Bidart; Alegret et al., 2004) in any of both sections, comparing with the well known mass extinction of planktic organisms which is interpreted as revealing a weak benthopelagic coupling at that time (Alegret et al., 2004 and references therein). However, marked quantitative changes in their community structure (percentage of particular morphogroups, diversity, etc.), are evident and mainly related to changes in productivity at the K/Pg boundary (see above: Kuhnt and Kaminski, 1993; Alegret et al., 2004). In the Sopelana section, benthic foraminiferal populations show a slow recovery that took at least 50 ky following the K/Pg boundary event (Kuhnt and Kaminski, 1993).

The planktic foraminiferal extinction pattern in the Bidart section suggest a sudden catastrophic extinction at the K/Pg boundary, at the base of the 2 mm thick rusty layer, affecting, at least 53 species out of the 72 species registered at the uppermost Maastrichtian (Gallala et al., 2009).

5.5. Bioturbational redistribution of sediment components through the K/Pg boundary event

One especially important aspect to be taken into consideration is the possible bioturbational disturbance of the K/Pg boundary, a fact which is usually underestimated. Detailed ichnological analysis in the Caravaca section (SE Spain), revealed that trace fossils range continuously from the lowermost Danian to the uppermost Maastrichtian sediments, with the rusty layer being cross cut by Zoophycos and Chondrites, and also penetrated laterally by Chondrites (Rodríguez-Tovar and Uchman, 2008). Thus, the authors claimed on the possible redistribution of the components related to the K/Pg boundary impact due to the tracemakers activity. Recently, the effects of different tracemakers on the redistribution of calcareous nanofossils throughout the K/Pg boundary at the Bidart section have been revealed (Rodríguez-Tovar et al., 2010). Bloom of the Paleogene calcareous nanofossil appearances just below the K/Pg boundary are related to
infiltration into dark trace fossil infillings proceeding from the earliest Paleogene, in the Sopelana sections a complex iridium distribution is recognized, with two iridium spikes registered in the dark-boundary layer (the first coeval with the final Cretaceous planktonic foraminiferan extinction, and the second in coincidence with the nannoplankton crisis; plate B in Rocchia et al., 1988). As previously indicated, distribution of dark-trace fossil in the Sopelana sections (Fig. 9) reveals that the boundary layer is totally bioturbated, with a continuous record of Chondrites from the entire dark-boundary layer, except for its uppermost laminated few centimetres, to the uppermost Maastrichtian sediments. Moreover, Planolites and Thalassinoides range from the lower part of the dark-boundary layer to the uppermost Maastrichtian sediments, except for Zoophycos registered only in the dark-boundary layer. Thus the interval of the dark-boundary layer recording the two iridium spikes is affected by an important significant bioturbation. Therefore, a redistribution by trace-makers activity affecting iridium concentration in the dark-boundary layer is possible in the Sopelana sections, but a more detailed analysis, out of the focus of this research, is necessary for confirmation, even more taking into account that recently, the relatively mobile behaviour of iridium within the sediments in depth has been demonstrated (Martin-Peinado and Rodríguez-Tovar, 2010; Miller et al., 2010; Racki et al., in press).

5.6. Continuity at the K/Pg boundary transition

As previously commented, the Bidart section can be considered as one of the most complete K/Pg boundary sections exposed in the eastern margin of the Atlantic Ocean (Apellaniz et al., 1997; Haslett, 1994; Seyye, 1990). Recent magnetostratigraphic, calcareous nannofossil and planktic foraminifera analyses reveal a continuous sedimentation across the K/Pg boundary transition, without any biostratigraphically significant hiatus (Galbrun and Gardin, 2004; Gallala et al., 2009). However at the Sopelana section, the lowermost part of the Paleogene (Guemebeltia cretacea Zone) was not identified (Lamolda et al., 1983; Mary et al., 1991), and graphic correlation analysis indicated the incompleteness of the Sopelana section with the absence of the Zone P0 estimated in 50,000 yr in duration (MacLeod and Keller, 1991; MacLeod et al., 1997). The distribution of trace fossils in the Sopelana section does not reveal any evident disruption of ichnological features, but a continuous and similar record from the dark-boundary layer to the upper Maastrichtian sediments. Macrobenthic colonization of the dark-boundary layer could be conducted 50,000 yr after the K/Pg boundary, according to the estimation of the duration of the absent Zone P0 (MacLeod and Keller, 1991; MacLeod et al., 1997). However, during this time changes in substrate features (i.e., substrate consistency) around the K/Pg boundary must be envisaged, determining variations in the ichnological features which were no registered. Thus, the absence of sediments corresponding to an estimated duration of 50,000 yr is not confirmed by ichnological analysis.

6. Concluding remarks

Ichnological analysis at the K/Pg boundary transition in the Bidart (SE France) and Sopelana (N Spain) sections reveals a low diverse trace fossil assemblage, with five common ichnogenera (Chondrites, Planolites, Thalassinoides, Trichichnus and Zoophycos), together with ? Phycosiphon registered only in the Sopelana section. This assemblage suggests the Zoophycos ichnofacies, which typically occurs down the offshore but beyond the areas of turbiditic sedimentation. Minor differences in the earliest Danian ichnoassemblage (dark-filled trace fossils) between sections are related to palaeogeographic position within the upper bathyal zone and to the distance to the basin margin. The higher abundance of large Thalassinoides, Zoophycos and larger Chondrites, and lower abundance of Trichichnus and small Chondrites, at Bidart than at Sopelana, is in agreement with a more distal position of Sopelana relative to Bidart, with a slightly higher depth and smaller food supply.

Feeding strategies showing the presence of chemichnia and trace fossils which trace-makers sequestered sediments from the sea floor in deep burrows (Zoophycos) denotes some intervals of periodical food deficiency pressing animals to more sophisticated searching for food. A generalized total bioturbation of sediments point to good oxygenation below sediment–water interface. The similarity between the pre-event (light-filled trace fossils) and the post-event (dark-filled trace fossils) trace fossil assemblage reveals a minor incidence of the K/Pg boundary event on the macrobenthic environment. The near continuous record of dark-filled trace fossils through the K/Pg boundary interval, from the upper part of the dark-boundary layer, especially in the Sopelana section, to the uppermost Maastrichtian sediments prevent on a possible redistribution of the biotic and abiotic components.

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References


Frey, R.W., 1970. Trace fossils of Fort Hays Limestone Member of Niobrara Chalk (Upper Cretaceous), West-Central Kansas. The University Kansas Paleontological Contributions, 53, 1–147.


Lethaia 24, 379–316.

Lethaia 25, 311–316.

Lethaia 24, 379–316.

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