Geochemical and isotopic characterization of trace fossil in fillings: New insights on tracemaker activity after the K/Pg impact event

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Abstract

Geochemical and isotopic analyses of the Cretaceous–Paleogene (K/Pg) boundary deposits were conducted at the Caravaca section (External Subbeltic, southeast of Spain) in order to evaluate the recovery of the macrobenthic tracemaker community and the bioturbational disturbance. Samples from the infilling material of several lower Danian dark-colored trace fossils (Chondrites, Planolites, Thalassinoides and Zoophycos) located in the uppermost 8-cm of the upper Maastrichtian strata, as well as samples from the host sedimentary rock of these trace fossils, were analyzed and compared with data from the lower Danian deposits. The values of element ratios indicative of extraterrestrial contamination (Cr/Al, Co/Al and Ni/Al) are higher in the infilling trace fossil material than in the upper Maastrichtian and lower Danian deposits, which suggests a contribution of the ejecta layer. Regarding the isotope composition, the $\delta^{13}$C values are lower in the infilling material than in the Maastrichtian host sedimentary rocks surrounding the traces, while the $\delta^{18}$O are higher in the infilling material. The geochemical and isotopic compositions of the infilling material evidence the unconsolidated character of the sediment, including the red boundary layer. Softground conditions confirm a relatively rapid recovery by the macrobenthic tracemaker community, starting a few millimeters above the K/Pg boundary layer. The mixture of the infilling material of the trace fossils moreover reveals a significant macrobenthic tracemaker activity affecting K–Pg boundary transition sediments that may have significantly altered original signatures.

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1. Introduction

The Cretaceous–Paleogene (K/Pg) boundary, recently dated as $\approx 66.04$ Ma ago (Husson, Galbrun, Gardin, & Thibault, 2014; Vandenberghhe, Hilgen, & Speijer, 2012), is associated with the second most relevant mass extinction taking place during the Phanerzoic, with 40% of genus extinction (Bambach, 2006) and the disappearance of about 70% of the marine and continental species existing at this time (D’Hondt, 2005). Currently, the hypothesis of an extraterrestrial impact (Alvarez, Alvarez, Asaro, & Michel, 1980; Smit & Hertogen, 1980) causing the end-Cretaceous mass extinction is widely accepted (Molina, 2015; Schulte et al., 2010). The synchronicity of the Chicxulub impact and the mass extinction at the K/Pg boundary has also been widely demonstrated (e.g., Pälike, 2013; Renne et al., 2013 and references therein).

Over recent decades numerous literature on this topic has provided details about the impact site on the Yucatan peninsula in Mexico (Hildebrand et al., 1991); the size of the meteorite, around 10 ± 4 km in diameter (Donaldson & Hildebrand, 2001; Kyte & Wasson, 1982); its nature, of carbonaceous chondritic type CM or CO (Goderis et al., 2013; Kyte, 1998; Shukolyukov & Lugmair, 1998); and the amount and nature of debris ejected to the atmosphere that led to major environmental perturbations (Kring, 2007 and references therein).

The impact event also resulted in geochemical anomalies worldwide, recognized both in marine and continental depositional environments. The extraterrestrial effects are particularly evident in marine distal sections, located further than 7000 km from the Chicxulub crater (Smit, 1999). In these sections, trace metals of extraterrestrial origin show higher concentrations than in proximal and intermediate sections, wherein the extraterrestrial contribution is highly diluted by target rocks (Berndt, Deutsch, Schulte, & Mezger, 2011; Martínez-Ruiz et al., 2001).

Major environmental perturbations (i.e., nitric and sulfuric acid
rain, widespread dust and blackout, destruction of the stratospheric ozone layer, greenhouse effect, temperature increase), followed the K/Pg event (Alegret & Thomas, 2005; Peryt, Alegret, & Molina, 2002). Diverse geochemical redox proxies, commonly used to reconstruct paleo-oxygen conditions (e.g., Calvert & Pedersen, 2007; Tribovillard, Algeo, Lyons, & Ribouilleau, 2006), indicate anoxic conditions across the K/Pg boundary transition, mostly promoted by the enhanced contribution of metals to the basins (extraterrestrial contamination and terrestrial elements derived from increasing chemical alteration in emerged areas), as well as a higher input of both terrestrial and marine organic material. An abrupt spike in biomarkers such as dibenzofuran, biphenyl and cadalene evidences the increasing input of terrestrial organic material (Mizukami, Kaiho, & Oba, 2014).

The biotic response to the K/Pg impact event, including the post-event recovery, is still a matter of debate. Several contradictory hypotheses postulate the effects on planktonic vs. benthic organisms, K- vs. r-strategists, or deposit vs. suspension feeders (Labandeira et al., in press; Molina, 2015; Powell & MacGregor, 2011; Schulte et al., 2010). In the past decade, relevant information has been provided by ichnological data. The trace fossil analysis of K/Pg boundary sections reveals a minor impact of K/Pg environment changes on the deeper sea macrobenthic trace-maker community, as well as its rapid recovery (Monaco, Rodríguez-Tovar, & Uchman, 2015; Rodríguez Tovar, Martínez-Ruiz, & Bernasconi, 2004, 2006, 2011; Rodríguez-Tovar, 2005; Rodríguez-Tovar & Uchman, 2006, 2008). As pointed out by Sosa-Montes de Oca, Martínez-Ruiz, and Rodríguez-Tovar (2013), this unusual biotic recovery could be explained by a rapid response (some few hundred years) of bottom water oxygenation that reestablished shortly after the K/Pg event. Ichnological analyses furthermore revealed the importance of the bioturbational redistribution by trace-makers, which may have affected original signatures and therefore should be considered so as to prevent possible misinterpretations (Kędzierski, Rodríguez-Tovar, & Uchman, 2011; Rodríguez-Tovar, Uchman, Molina, & Monechi, 2010).

In order to evaluate and corroborate the hypothesis of the rapid recovery of the macrobenthic trace-maker community and the bioturbational disturbance, further analyses have been performed. In particular, geochemical and isotopic analyses of the K/Pg boundary deposits at the Caravaca section (southeast of Spain) included the infilling material of trace fossils as well as the upper Maastrichtian and lower Danian host rocks.

2. Geological setting and the study section

The K/Pg boundary section at Caravaca (38°04'36.39"N, 1°52'41.45"W) is located on the NW side of road C-336, in the Barranco del Gredero, about 4 km southwest of the town of Caravaca (Murcia, Spain) (Fig. 1). It belongs to the Jorquera Formation (lower Maastrichtian-lower Eocene), around 225 m-thick, which consists of intercalated marls, marly limestones and occasional beds, and of 0.8 cm kyr−1 calculated for the boundary clay layer (Kaiho et al., 1999), the studied transition would span a time interval of around 6330 years—from 2580 years prior to the K/Pg boundary to 3750 years afterward. Deposition of the ejecta layer at the K/Pg boundary can be considered instantaneous in the geological scale, roughly several weeks after the impact event (Artemieva & Morgan, 2009).

Geochemical and isotopic analyses were conducted on samples from the infilling material of several lower Danian dark-colored trace fossils located in the uppermost 8-cm of the light upper Maastrichtian strata (see Rodríguez-Tovar & Uchman, 2006 for detailed ichnological information), as well as on samples from the host sedimentary rocks of these trace fossils. Several specimens of dark-filled trace fossils were analyzed, belonging to Chondrites, Planolites, Thalassinoides and Zoophycos. Thalassinoides is commonly interpreted as having been passively filled (Bromley, 1996), as are some Planolites (Locklair & Savida, 1998), while the interpretation of Chondrites and Zoophycos is not yet definitive. Thus, we analyzed samples from i) large Chondrites (sample CA-93 Ch) and the corresponding host rock (CA-93 HS), at 1-cm below the K/Pg boundary, and ii) small Chondrites (samples CA-32 Ch, CA-135 Ch, CA-192 Ch), Planolites (samples CA-9 P1, CA-152 P1), Thalassinoides (samples CA-135 Th1, CA-135 Th2, CA-180 Th), and Zoophycos (samples CA-180 Z01, CA-180 Z02, CA-180 Z03), and the host sedimentary rock of each trace fossil (CA-9 HS, CA-32 HS, CA-132 HS, CA-135 HS, CA-180 HS, CA-192 HS), from 2 to 8 cm below the K/Pg boundary. Selected specimens were sampled using a Dremel tool fitted with a fine tip diamond studded drill bit, allowing sampling even the smaller burrows.

Moreover, isotopic analyses of δ13C and δ18O on samples from
Fig. 1. Caravaca outcrop. Location and close-up photographs of the Cretaceous–Paleogene (K/Pg) boundary section at Caravaca (Southeast Spain).
the lowermost Danian (CA+0.0 + 0.2, CA+0.6 + 0.8, CA+0.8 + 1.0, CA+0.9 + 1.2, CA+1.8 + 2.0, CA+2.8 + 3.0) were integrated with previous geochemical data from these samples (Sosa-Montes de Oca et al., 2013).

As proxies for extraterrestrial contribution we selected Cr, Co and Ni, which are typically enriched within the ejecta layer (Goderis et al., 2013). We used the Al-normalized concentrations of these elements (Cr/Al, Co/Al and Ni/Al) to avoid a lithological effect on trace element contents.

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) and Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS) were used for major and trace element analyses, and Mass Spectrometry (IRMS) for isotope analyses. All were performed at the Center for Scientific Instrumentation (CIC), University of Granada, Spain.

4. Results

4.1. Geochemical analysis

Geochemical data are presented in Table 1. The normalized concentrations of Cr, Co and Ni are plotted in Fig. 2, in which the diverse sedimentary intervals are marked: i) the ejecta layer (CA K–Pg) (data from Sosa-Montes de Oca et al., 2013), ii) the host rock from the lower Paleogene, at 2.8–3.0 cm above the K/Pg boundary (previous data from Sosa-Montes de Oca et al., 2013), iii) the infilling material of several trace fossils analyzed, and iv) the Cretaceous deposits hosting trace fossils (Fig. 2).

4.1.1. Lower Danian

To compare the Cr/Al, Co/Al and Ni/Al ratios in the diverse sedimentary materials, previous data from this section were considered (Sosa-Montes de Oca et al., 2013). According to the lithological differentiation of the dark boundary clay layer (Rodriguez-Tovar & Uchman, 2006), four selected samples (CA+0.0 + 0.2, CA+0.6 + 0.8, CA+0.8 + 1.0, CA+0.9 + 1.2, CA+1.8 + 2.0, CA+2.8 + 3.0) belong to the lower 14-mm-thick laminated unit and two (CA+1.8 + 2.0, CA+2.8 + 3.0) to the overlying 26-mm-thick bioturbated horizon. Samples from the laminated unit are in the range of (10−4) 18.26–22.78 (mean 19.98) for the Cr/Al ratio, 1.95–4.07 (mean 3.36) for the Co/Al ratio and 13.35–19.22 (mean 16.81) for the Ni/Al ratio. Samples from the overlying bioturbated interval show values of (10−4) 17.39–18.51 (mean 17.95) for the Cr/Al ratio, 3.45–3.65 (mean 3.55) for the Co/Al ratio and 15.29–16.87 (mean 16.08) for the Ni/Al ratio.

The ejecta layer (lowermost Danian) presents concentrations with values (10−4) of 132.16 for the Cr/Al ratio, 69.02 for the Co/Al ratio and 280.50 for the Ni/Al ratio (Table 1; Sosa-Montes de Oca et al., 2013).

| Sample | Distance (cm) | Age | Al | Ca | CaCO₃ | Cr | Co | Ni | Cr/Al | Co/Al | Ni/Al | δ¹³C | δ¹⁸O |
|--------|--------------|-----|----|----|------|----|----|----|-------|-------|-------|-------|------|------|
| CA-18 | > 2.8 + 3.0  | 3.0 | Early Danian host sediments | 5.25 | 18.94 | 47.34 | 91.23 | 18.11 | 80.23 | 17.39 | 3.45 | 15.29 | 0.45 | -2.48 |
| CA-1.8 + 2.0 | 2.0 | 8.37 | 6.99 | 17.49 | 154.99 | 30.54 | 141.26 | 18.51 | 3.65 | 16.87 | 0.07 | -2.78 |
| CA-1.0 + 1.2 | 1.2 | 7.56 | 8.51 | 21.28 | 151.09 | 29.17 | 145.22 | 19.99 | 3.86 | 19.22 | 0.12 | -4.00 |
| CA-0.8 + 1.0 | 1.0 | 7.69 | 8.01 | 20.02 | 142.74 | 30.77 | 137.63 | 18.88 | 4.07 | 18.20 | 0.13 | -3.53 |
| CA-0.6 + 0.8 | 0.8 | 7.44 | 6.78 | 16.95 | 169.46 | 14.49 | 99.32 | 22.78 | 1.95 | 13.35 | 0.02 | -3.73 |

Table 1: Element content (major and trace), elemental ratios and isotopic values. Al, Ca and CaCO₃ concentrations (%), Cr/Al, Co/Al, Ni/Al ratios (*10−4), and isotopic values (‰) measured across the Cretaceous–Cenozoic (K/Pg) boundary in the Cenozoic section i) in the ejecta layer, ii) in the host rock from the lower Paleogene, iii) in the traces fossils infillings, and iv) the host rock from the upper Maastrichtian nearby each trace fossil. The geochemical data from the ejecta layer (CA K–Pg) from lowermost Paleogene (CA-0.0 + 0.2, CA-0.6 + 0.8, CA-0.8 + 1.0, CA-1.0 + 1.2, CA-1.8 + 2.0, CA-2.8 + 3.0) were taken from Sosa-Montes de Oca et al. (2013). The isotopic data from the ejecta layer (CA K–Pg) were taken from Martínez-Ruz (1994).

4.1.2. Upper Maastrichtian

In the uppermost Maastrichtian, at 1.0 cm below the ejecta layer, the infilling of large Chondrites (sample CA-93 Ch) shows values (10−4) of 27.27 for the Cr/Al ratio, 11.35 for the Co/Al ratio and 49.14 for the Ni/Al ratio. The uppermost Maastrichtian host rocks nearby this trace layer (CA-93 HS) show values (10−4) of 12.15 for the Cr/Al ratio, 9.00 for the Co/Al ratio and 49.73 for the Ni/Al ratio (Fig. 2A).

The infilling of trace fossils and the corresponding upper Maastrichtian host rocks from between 2 and 8 cm below the ejecta layer give the following results:

- The three specimens of small Chondrites (samples CA-32 Ch, CA-135 Ch, and CA-192 Ch) present values for the infilling material in the range of (10−4) 17.25–18.17 (mean 17.75) for the Cr/Al ratio, 3.25–4.91 (mean 4.12) for the Co/Al ratio and 21.69–29.10 (mean 25.14) for the Ni/Al ratio (Fig. 2B).

- The host rocks close to these trace fossils (samples CA-135 HS, CA-192 HS, CA-32 HS) show values in the range of

Standard deviation obtained with NBS 19, NBS18 is ≤ 0.05% for δ¹³C and ≤ 0.08% for δ¹⁸O.
13.86–14.32 (mean 14.09) for the Cr/Al ratio, 2.25–2.77 (mean 2.49) for the Co/Al ratio and 15.51–19.59 (mean 17.91) for the Ni/Al ratio.

- The two specimens of *Planolites* (samples CA-9 Pl and CA-152 Pl) show values in the infilling material (\(10^{-4}\)) of 19.73–21.66 (mean 20.69) for the Cr/Al ratio, 4.58–7.61 (mean 6.09) for the Co/Al ratio and 23.88–24.84 (mean 24.36) for the Ni/Al ratio (Fig. 2C). The host upper Maastrichtian deposits near *Planolites* (samples CA-9 HS and CA-152 HS) present values (\(10^{-4}\)) of 13.63–13.83 (mean 13.73) for the Cr/Al ratio, 1.80–2.51 (mean 2.27) for the Co/Al ratio and 15.51–19.59 (mean 17.91) for the Ni/Al ratio.

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**Fig. 2.** Geochemical graphics. Compared the concentrations of Cr/Al, Co/Al and Ni/Al ratios (data from Table 1). i) In the ejecta layer. ii) In the host rock from the lower Paleogene. iii) In the trace fossils: at 1 cm below K–Pg boundary we found (A) large *Chondrites* (sample CA-93 Ch); between 2–4 cm below the K/Pg boundary, we found (B) *Chondrites* (samples CA-192 Ch, CA-32 Ch, CA-135 Ch), (C) *Planolites* (samples CA-9 Pl, CA-152 Pl), (D) *Thalassinoides* (samples CA-135 Th1, CA-135 Th2, CA-180 Th) and (E) *Zoophycos* (sample CA-180 Zo1, CA-180 Zo2, CA-180 Zo3). iv) And finally, in the host Cretaceous rock from nearby to each trace fossils. The data were taken from Table 1.
2.16) for the Co/Al and 15.29–18.05 (mean 16.67) for the Ni/Al ratio.

- Specimens of Thalassinoides (samples CA-135 Th1, CA-135 Th2, and CA-180 Th) register infilling material values (×10−4) in the range of 19.09–20.11 (mean 19.50) for the Cr/Al ratio, 5.98–9.16 (mean 7.82) for the Co/Al ratio and 25.81–33.76 (mean 28.29) for the Ni/Al ratio (Fig. 2D). The host rocks nearby these trace fossils (samples CA-135 HS, CA-180 HS) show values (×10−4) of 14.23–14.32 (mean 14.27) for the Cr/Al ratio, 2.77–3.25 (mean 3.01) for the Co/Al ratio and 18.63–19.58 (mean 19.10) for the Ni/Al ratio.

- Zoophycos (samples CA-180 Zo1, CA-180 Zo2, CA-180 Zo3) present values regarding the infilling material (×10−4) in the range of 18.25–20.24 (mean 19.03) for the Cr/Al ratio, 7.15–8.58 (mean 7.76) for the Co/Al ratio, and 29.24–36.79 (mean 33.75) for the Ni/Al ratio (Fig. 2E). The host rocks near the analyzed Zoophycos (sample CA-180 HS) present values (×10−4) of 14.23 for the Cr/Al ratio, 3.25 for the Co/Al ratio and 19.58 for the Ni/Al ratio.

4.2. Isotope composition

Isotopic data are presented in Fig. 3, Fig. 4 and Table 1. Moreover, the isotopic data from the K/Pg boundary layer were taken from Martínez-Ruiz (1994) in the case of δ18O.

4.2.1. Lower Danian

Isotopic data from the selected samples belonging to the lower 14-mm-thick laminated unit at the bottom of the dark boundary clay layer are in the range of −0.02%–0.13% for δ13C (mean of 0.06%) and from −4.00% to −3.53% for δ18O (mean −3.01%) (Fig. 3 and Table 1). Samples from the overlying bioturbated interval show values of 0.07%–0.45% for δ13C (mean 0.26%), and of −2.48% and −2.75% for δ18O (mean −2.61%).

The K/Pg boundary layer gives isotopic values of 1.14% for δ13C and of −2.43% for δ18O (Martínez-Ruiz, 1994). We cannot discard the possibility of a slightly altered isotopic value for δ13C, considering the global average value of −0.40% obtained by Ivany and Salawitch (1993).

4.2.2. Upper Maastrichtian

The infilling of large Chondrites located at 1.0-cm below the ejecta layer shows values of 1.86% for δ13C and −2.08% for δ18O, while data from the uppermost Maastrichtian deposits nearby this trace are 2.19% for δ13C and −1.92% for δ18O.

Infilling material of small Chondrites is in the range of 1.41%−1.92% for δ13C (mean 1.73%) and −1.88% to −2.97% for δ18O (mean −2.30%). The host rocks from the upper Maastrichtian near these small Chondrites are in the range of 2.02%–2.24% for δ13C (mean 2.11%) and −1.51% to −1.91% for δ18O (mean −1.75%).

Isotopic data pertaining to the infilling material of Planolites is 1.16%–1.25% for δ13C (mean 1.20%) and −2.05% and −2.55% for δ18O (mean −2.30%). The Upper Maastrichtian deposits hosting trace fossils present values of 1.99%–2.04% for δ13C (mean 2.01%) and −1.92% and −2.00% for δ18O (mean −1.96%).

Infilling material of Thalassinoides is in the range of 1.49%–1.67% for δ13C (mean 1.58%) and −2.01% to −2.30% for δ18O (mean −2.15%). The deposits hosting these trace fossils show values of 2.06%–2.12% for the δ13C (mean 2.09%) and of −1.82% and −1.97% for δ18O (mean −1.89%).

Isotopic values of the infilling material of Zoophycos are in the range of 1.19%–1.32% for δ13C (mean 1.25%) and −2.48% to −2.77% for δ18O (mean −2.63%). Isotopic values of the rocks hosting the analyzed Zoophycos are 2.12% for δ13C and −1.97% for δ18O (Fig. 4).

4.3. Comparative analysis

Comparative analysis of the obtained geochemical data reveals significant information:

- Infilling material of the studied trace fossils, with independence of the particular ichnotaxon, shows higher values that those corresponding to the hosting Maastrichtian deposits.
- Values of Cr/Al, Co/Al and Ni/Al ratios from the ejecta layer are significantly higher than those corresponding to the upper Maastrichtian and lower Danian deposits, and higher as well than the infilling material of any of the studied specimens.
- Values from the lower Danian rocks, both those corresponding to samples from the laminated unit and from the bioturbated interval, are lower than those from the infilling materials.
- Furthermore, the values of Cr/Al, Co/Al and Ni/Al ratios from the infilling trace fossils are higher than those from the upper Maastrichtian and lower Danian deposits, and significantly lower than those corresponding to the ejecta layer.

In terms of isotopic composition, regardless of the particular ichnotaxa, data for the δ13C are lower in the infilling material than in the corresponding Maastrichtian host rock surrounding the specimen. The opposite occurs regarding the δ18O values, consistently higher in the infilling material.

- Values of δ13C in the K/Pg boundary layer are lower than those from the upper Maastrichtian deposits and higher than those from the lower Danian.
- Values of δ18O in the K/Pg boundary layer are slightly lower than those from the upper Maastrichtian deposits higher than that from the lower Danian.
- The δ13C and δ18O values from the lower Danian rocks, both those corresponding to samples from the laminated unit and from the bioturbated interval, are lower than those corresponding to the infilling materials of trace fossils.

Thus, data for the δ13C from the lower Danian rocks and the K/Pg boundary layer are always lower than those registered in the infilling material of trace fossils, the latter in turn being lower than the values corresponding to the surrounding upper Maastrichtian deposits. In the case of δ18O, values from lower Danian deposits and the K/Pg boundary layer are consistently lower than those from the infilling material; the latter are likewise higher than the values corresponding to the upper Maastrichtian rocks hosting the traces.

5. Discussion

As previously indicated, numerous paleontological studies have been conducted on the K/Pg boundary at the Caravaca section in order to evaluate the effect of the K/Pg boundary event on the biota, in particular on the micropaleontological assemblages. Micropaleontological studies involving planktonic (i.e., Arenillas & Molina, 1997; Arz et al., 2000; Canudo et al., 1991; Kaiho & Lamolda, 1999; Molina, Arenillas, & Arz, 1998, 2001; Smit, 1990) and benthic foraminifera (Cocioni, Fabbucci, & Galeotti, 1993; Cocioni & Galeotti, 1994; Kaiho et al., 1999; Keller, 1992; Smit, 1990; Widmark & Speijer, 1997a, 1997b), together with calcareous nanofossils (i.e., Gardin & Monéchi, 1998; Molina, Arenillas, & Arz, 2001; Remein, 1977) shed some light on the effects of the K/Pg boundary perturbations on the micropaleontological community. The sudden decrease in diversity in coincidence with the K/Pg boundary event led to variable strategies of the biota, depending on the particular micropaleontological group. Similarly, the recovery
Fig. 3. Isotopic composition of Caravaca section. Isotopic composition of carbonate ($\delta^{13}$C, $\delta^{18}$O) for the Cretaceous–Paleogene (K–Pg) boundary at Caravaca section (Southeast Spain). The isotopic data ($\delta^{13}$C, $\delta^{18}$O) from the K–Pg boundary layer were taken from Martínez-Ruiz (1994).
shows different patterns and duration depending on the assemblage.

Early work on trace fossils in the K/Pg boundary at the Caravaca section was not very detailed, mainly indicating the presence of burrows filled with dark material from the overlying dark boundary clay layer (i.e., Arinobu et al., 1999; Molina et al., 2001; Smit, 2004; Smit & Ten Kate, 1982). Later on, more detailed ichnological analyses revealed a well-developed dark-colored trace fossil assemblage, bioturbating continuously from several horizons in the lowermost Danian dark boundary layer to the uppermost
Maastrichtian deposits, cross-cutting vertically and penetrating laterally the K/Pg boundary layer (Rodríguez-Tovar & Uchman, 2006, 2008). This fact was interpreted as revealing a minor incidence of the K/Pg boundary event on the trace-maker macroinfaunal community, as well as its relatively rapid recovery after the event. Moreover, these authors pointed out the possibility that Maastrichtian sediments could be contaminated with Danian microfossils due to bioturbation, and that the bioturbational disturbance of the rusty layer could induce erroneous interpretations (Rodríguez-Tovar & Uchman, 2006, 2008). The vertical displacement and taphonomical filtering of nanofossils due to bioturbation at the Caravaca K/Pg boundary was furthermore confirmed (Kędzierski et al., 2011).

5.1. Macrobenthic tracemakers after the K/Pg: recovery and bioturbational effects

The geochemical and isotopic information obtained in the present study is of special relevance in that it supports macrobenthic trace fossil activity after the K/Pg boundary event, including recovery and bioturbational effects. The infilling material of the trace fossils shows values of Cr/Al, Co/Al and Ni/Al ratios roughly midway between the higher values registered in the ejecta layer and the lower values obtained from the upper Maastrichtian and lower Danian deposits. This fact supports the mixture of the infilling material of the trace fossils, consisting not only of dark clay layer but also of ejecta layer material. However, neither red-colored particles nor spherules were observed in the infilling material. Rodríguez-Tovar (2005) registered Fe-oxide spheres in the infilling of Thalassinoides at the nearby Agost section (Alicante, Spain). This absence, especially of the red-colored particles from the ejecta layer, could be the consequence of a significant mixture of the material; an important redistribution would have caused the dilution of the comparatively scarce red boundary layer material into the dark upper Maastrichtian strata. Such a total mixture is more likely to occur when the sediment is still unconsolidated and softground conditions prevail. This context also suggests a relatively rapid recovery of tracemakers during the first phases of deposition of the dark boundary clay layer when the ejecta layer material is still unconsolidated. Softground conditions can be corroborated considering that the registered mixture is independent of the type of trace fossils—it involves the actively filled (i.e., Planolites), the passively filled (i.e., Thalassinoides), and the ones having a controversial origin (i.e., Chondrites and Zoophycos).

However, such a sediment mixture is not evidenced by the isotope composition, showing different patterns for the δ^13C and the δ^18O; δ^13C values are lower in the infilling material than in the corresponding Maastrichtian rock surrounding the specimen, while δ^18O values are consistently higher in the infilling material. A number of possibilities could be envisaged, for instance a mixture of the infilling material involving not only the lower Danian deposits and the K/Pg boundary layer material, but also the upper Maastrichtian host rock; or it may be that the analyzed trace fossils came from one or several horizons above the analyzed lower Danian deposits. In the first case, a mixture including the upper Maastrichtian host rocks is less likely when taking into account that both passively and actively filled trace fossils present a similar pattern. Hence, the second hypothesis is more plausible.

Isotopic data of the K–Pg boundary transition at the nearby Agost section, obtained from Danian dark-trace fossil filling as well as from upper Maastrichtian and lower Danian deposits, revealed a good correspondence between data from the filling material and the data corresponding to different levels of the lower Danian (Rodríguez Tovar et al., 2004, 2006). This correlation allows for a precise characterization of different horizons of colonization in the dark boundary clay layer. Such is not the case for the Caravaca section, where it is difficult to propose concrete horizon(s) of colonization based on the geochemical and isotopic data. Still, the horizon(s) of bioturbation must be close to the K/Pg boundary, taking into consideration the interpreted softground conditions for the ejecta layer. Accordingly, the first bioturbated horizon at 14 mm from the K/Pg boundary layer is the most plausible interval, confirming the rapid recovery proposed by Rodríguez-Tovar and Uchman (2006, 2008).

As interpreted from the geochemical and isotopic data, the macrobenthic tracemaker activity during the recovery is important, significantly affecting the K–Pg boundary transition sediments, including the ejecta layer. Trace fossil producers determine the bioturbational mixture of sediments, which conditions the geochemical and the isotope composition. This fact must be considered in order to arrive at a precise analysis of the K/Pg boundary materials and correct interpretations.

6. Conclusions

Geochemical and isotopic analyses conducted on the Cretaceous–Paleogene boundary transition at the Caravaca section have provided significant information on the macrobenthic tracemaker activity after the K/Pg boundary event. In particular, the Cr/Al, Co/Al and Ni/Al ratios from the infilling of trace fossils are higher than those of the upper Maastrichtian and lower Danian deposits, but lower than those corresponding to the ejecta layer, indicating a mixture of the sedimentary material due to biological activity across the boundary. Regarding the isotope composition, the δ^13C values are lower in the infilling material that in the corresponding Maastrichtian host rock surrounding the specimen, while the δ^18O values are higher in the infilling material.

These data support a significant mixture of the infilling material of trace fossils, with a dominance of dark lower Danian deposits and a scarce contribution of the ejecta layer material. The mixture occurred due to the unconsolidated character of the sediment, including the ejecta layer. Softground conditions associated with this unconsolidated sediment further support the relatively rapid recovery of the macrobenthic tracemaker community, within horizons a few millimeters above the K/Pg boundary event. The observed mixture of the infilling material in the different ichnotaxon also evidences a significant macrobenthic tracemaker activity across the K/Pg boundary deposits, which should be considered in order to interpret original signatures and to reconstruct paleoenvironmental conditions during the K–Pg transition.

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References


Alvarez, L. W., Alvarez, W., Asaro, F., & Michel, H. V. (1980). Extraterrestrial cause for...


