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A multi-proxy approach to decode the end-Cretaceous mass extinction

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ABSTRACT

Mass extinctions generally involve a complex array of interrelated causes and are best evaluated by a multi-proxy approach as applied here for the end-Cretaceous mass extinction. This study documents and compares the planktic foraminiferal records, carbonate dissolution effects, stable isotopes, and magnetic susceptibility in France (Bidart), Austria (Gamsbach) and Tunisia (Elles) in order to explore the environmental conditions during the uppermost Maastrichtian *Plummerita hantkeninoides* zone CF1 leading up to the mass extinction. Planktic foraminiferal assemblages at Bidart and Gamsbach appear to be more diverse than those at Elles, with unusually high abundance (20–30%) and diversity (~15 species) of globotruncanids in the two deep-water sections but lower abundance (<10%) and diversity (<10 species) at the middle shelf Elles section. Oxygen isotopes in zone CF1 of Elles record rapid climate warming followed by cooling and a possible return to rapid warming prior to the mass extinction.

The onset of high stress conditions for planktic foraminifera is observed ~50–60 cm below the KTB at Bidart and Gamsbach, and ~4.5 m below the KTB at Elles due to much higher sediment accumulation rates. These intervals at Bidart and Gamsbach record low magnetic susceptibility and high planktic foraminiferal fragmentation index (FI) at Elles, Bidart and Gamsbach. An increased abundance of species with dissolution-resistant morphologies is also observed at Gamsbach. The correlative interval in India records significantly stronger carbonate dissolution effects in intertrappean sediments between the longest lava flows, ending with the mass extinction. Based on current evidence, this widespread dissolution event stratigraphically coincides with the climate cooling that follows the Late Maatrichtian global warming and may be linked to ocean acidification due to Deccan volcanism. The estimated 12,000–28,000 Gigatons (Gt) of CO_2 and 5200–13,600 Gt of SO_2 introduced into the atmosphere likely triggered the carbonate crisis in the oceans resulting in severe stress for marine calcifiers leading to mass extinction.

1. Introduction

One of the best-known European Cretaceous–Tertiary boundary (KTB) sections, also known as Cretaceous–Paleogene (KPB or KPg) sections, is exposed at a beach near Bidart in the Basque–Cantabrian basin of southwestern France (Figs. 1, 2B, Seyve, 1990; Haslett, 1994). At this locality, about 8 m of uppermost Maastrichtian and ~4 m of basal Danian sediments are exposed including the boundary clay, an Iridium (Ir) anomaly and negative $\delta^{13}C$ excursion that indicate a relatively complete KTB transition (Fig. 2A, C; Renard et al., 1982; Bonté et al., 1984; Apellaniz et al., 1997; Font et al., 2014). Nevertheless, the Bidart section remained in limbo for nearly two decades because of uncertain age control, particularly the reported absence of the latest Maastrichtian nannofossil *Micula prinsii* zone and absence of the planktic foraminiferal zones CF1 (*Plummerita hantkeninoides*) and CF2, which together are correlative with paleomagnetic chron C29r. This led to the assumption that the latest Maastrichtian is missing (Gallala et al., 2009). Subsequent paleomagnetic and microfossil studies revealed that the ~8 m of uppermost Maastrichtichtian sediments below the KTB were deposited during the *Micula prinsii* zone (Galbrun and Gardin, 2004) and the recent finding of *P. hantkeninoides* zone CF1 (Font et al., 2014) further confirms deposition in paleomagnetic chron C29r below the KTB boundary and hence a substantially complete KTB transition.

Restudy of the Bidart section is particularly important because of the potential connection between the high-stress interval spanning the last 50-cm of the Maastrichtian and Deccan volcanism in India (Font et al., 2011, 2014). As early as in the 1990s, Apellaniz et al. (1997) reported a drop in carbonate content and increased planktic foraminiferal test dissolution particularly in the KTB clay and the underlying 28-cm of uppermost Maastrichtian sediments. This interval depleted in carbonate content is also featured by a loss of iron oxides (biogenic and detrital magnetite), interpreted to be the result of acidification linked to Deccan acid rains (Font and Abrajevitch, 2014; Font et al., 2014). The possible

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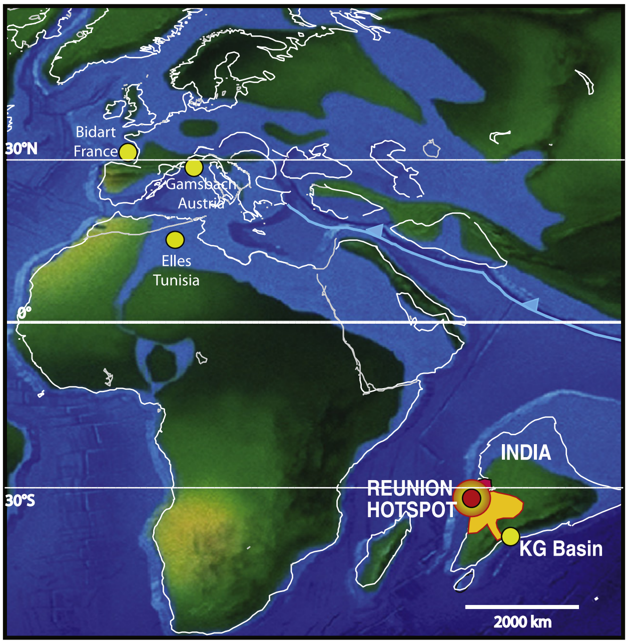

Fig. 1. Palaegeographic map of 66 Ma showing the study sections Bidart (France) and Gamsbach (Austria) and the reference section Elles (Tunisia, GSSP) relative to the location of the Reunion hotspot (focal point of Deccan volcanism). Modified after ©2000 C R Scotese PALEOMAP Project.

link between this dissolution interval and ocean acidification related to Deccan volcanism appears to be more than coincidental and warrants a fresh investigation of associated changes in planktic foraminiferal assemblages. Bidart therefore provides a unique opportunity to analyze this critical time interval in Earth history to understand the environmental changes in the northern mid-latitude Atlantic Ocean that may be related to the global effects of Deccan volcanism.

Preliminary faunal analysis of the Bidart section reveals a planktic foraminiferal assemblage remarkably different from those reported for El Kef (GSSP) and Elles, Tunisia, and other continental shelf locations (Abramovich and Keller, 2002; Font et al., 2014). To evaluate whether this is due to different depositional settings (open ocean bathyal depths for Bidart versus shelf depth for Tunisia), we chose a second bathyal section, Gamsbach, Austria, as a control site. Gamsbach is located in the Eastern Alps with a palaeogeographic setting and depositional history similar to Bidart (Figs. 1, 3B; Grachev et al., 2005). Gamsbach contains planktic foraminiferal assemblages similar to those at Bidart, including a pre-KTB dissolution interval that supports the choice of Gamsbach as a complementary site.

Although numerous studies have explored the KTB transition at Bidart and Gamsbach over the past three decades (see sections 1 and 2, supplementary material), the published microfossil records are generally not quantitative and at very low sample resolution yielding little or no information for the critical pre-extinction interval. We present comprehensive biostratigraphic, assemblage and stable isotope, geochemical and mineralogical data that focus on the rapid climatic and biotic events of zone CF1, which globally record the crises that led up to the KTB mass extinction. The primary objective of this study is to test the hypothesis that Deccan volcanism may have caused global climate changes and ocean acidification that directly resulted in the KTB mass extinction recorded in planktic foraminifera.

We test this hypothesis based on: (1) High-resolution quantitative planktic foraminiferal species abundances through the uppermost Maastrichtian zones CF1–CF2 at Bidart and Gamsbach; (2) high-resolution biostratigraphic analysis with special emphasis on the presence/absence of index species (e.g., *Gansserina gansseri* and *Plummerita hantkeninoides*) to re-evaluate the conflicting published reports (reviewed below); (3) evaluation of the palaeoclimatic and the paleoenvironmental conditions recorded in stable isotopes, geochemical proxies, and associated biotic events; (4) evaluation of carbonate and iron oxide dissolution events based on the quality of foraminiferal test preservation (fragmentation index FI) and magnetic susceptibility, respectively; (5) determination of the chronologic sequence of biotic, climatic and geochemical events through zone CF1 at Bidart and Gamsbach, as well as their regional and global oceanographic significance in the context of environmental perturbations related to Deccan volcanism; and (6) comparison with shelf sequences at Elles and El Kef, Tunisia, to assess the nature of environmental changes in shallow vs. deep-water environments.

2. Background

2.1. Bidart and Gamsbach

Previous studies of the Bidart and Gamsbach sections report sedimentologic, geochemical, paleomagnetic and microfossil biostratigraphic data. A brief summary is presented here (see supplementary material for details).

2.1.1. Bidart

Planktic foraminifera and nannofossils record a rapid decline at the KTB in Bidart (Gorostidi and Lamolda, 1995; Apellaniz et al., 1997; Thibault et al., 2004; Gallala et al., 2009), whereas benthic foraminifera switch from infaunal to epifaunal dominance across the KTB (Alegret et al., 2004). An Iridium anomaly of 6.3 ± 1.1 ppb, enrichment of Co, Cr, Ni, As, Sb, and Se, and depletion of rare earth elements (REE) are reported in the Bidart KTB red clay layer (Delacotte, 1982; Smit and Ten Kate, 1982; Bonté et al., 1984). Some studies report the presence of microtektites, microspherules and Ni-rich crystals in the KTB red layer in the Basque sections but provide no supporting data (Apellaniz et al., 1997; Arz and Arenillas, 1998; Arenillas et al., 2004).

2.1.2. Gamsbach

Previous studies on Gamsbach show the KTB clay enriched in Ir (6 ppb), iron hydroxides, Co, Ni, Cr and siderophile elements and sporadic occurrence of pure Ni crystals, awaruite (Fe_3Ni), Ni–Fe, Ni–Fe–Mo and Ni–Fe–Co alloys, cosmic dust and spherules of varied geochemical affinities (Grachev et al., 2005, 2008; Pechersky et al., 2006; Egger et al., 2009). Micropaleontological and biostratigraphic studies are limited due to poor carbonate preservation throughout the KTB transition (Egger et al., 2004, Summesberger et al., 2009, Korchagin and Kollmann in Grachev, 2009). Summesberger et al. (2009) reported on the cephalopod, nannofossil and planktic foraminiferal biostratigraphy at Gamsbach but provided no quantitative documentation.

2.2. Deccan volcanism

Deccan eruptions resulted in an estimated 1.5 million km^3 of lava flooding the Indian sub-continent (Raja Rao et al., 1999). Three main phases of eruptions are recognized: the initial phase-1 (∼6% of the total volume) in the early late Maastrichtian recently dated by $^{40}Ar/^{39}Ar$ at 67.12 ± 0.44 Ma at the chron C30n/C29r transition (Schöbel et al., 2014); the main phase-2 (∼80% of the total lava pile) in chron C29r (Subbarao et al., 2000; Chenet et al., 2007, 2008; Jay and Widdowson, 2008; Schoene et al., 2014) culminating in the KTB mass extinction (Keller et al., 2011a, 2012); and the final phase-3 (∼14% of the total volume) in the early Danian chron C29n. The environmental effects of the three Deccan phases are determined by the tempo and magnitude of eruptions and the amounts of SO_2, CO_2, Cl and other gases released into the atmosphere (Self et al., 2008). A global review of the planktic foraminiferal events contemporaneous with Deccan phase-2 and phase-3 can be found in Punekar et al. (2014a).