Records of post–Cretaceous-Tertiary boundary millennial-scale cooling from the western Tethys: A smoking gun for the impact-winter hypothesis?

Simone Galeotti Istituto di Geologia and Centro di Geobiologia–Università di Urbino, Località Crocicchia, 61029 Urbino, Italy
Henk Brinkhuis Laboratory of Palaeobotany and Palynology, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, Netherlands
Matthew Huber Earth and Atmospheric Sciences Department, Purdue University, 1397 Civil Engineering Building, West Lafayette, Indiana 47906, USA

ABSTRACT

The record of both dinoflagellate cysts and benthic foraminifera across the Cretaceous-Tertiary boundary at El Kef, Tunisia, reveals a brief expansion of the Boreal bioprovince into the western Tethys, suggesting that an ~2 k.y. cooling occurred during the earliest Danian. We show that this prolonged cooling phase is consistent with the oceanographic response to an impact winter.

Keywords: K-T boundary, foraminifera, dinoflagellates, extraterrestrial impact, cooling.

INTRODUCTION

It is now widely appreciated that the Cretaceous-Tertiary (K-T) boundary coincides with an impact of a large extraterrestrial body, which apparently initiated a chain of events leading to global ecosystem collapse and extinctions (e.g., Alvarez et al., 1980; Smit and Hertogen, 1980). The possible primary and secondary global climatic and environmental effects of the Chicxulub impact event at the K-T boundary are, however, still subject to intense debate (see papers in Ryder et al., 1996; Koeberl and MacLeod, 2002). Numerical simulations predict an ~10 yr global surface cooling, the so-called impact winter, induced by reduction in incoming solar radiation caused by the sulfate aerosols generated by the bolide's impact (e.g., Pope et al., 1997). Constraining the existence and duration of the impact winter is crucial for discriminating between various K-T boundary scenarios and should shed light on our knowledge of the postimpact climate-system disruption and on subsequent feedback mechanisms. But many uncertainties hamper effective understanding of the impact's global effects, including the amount, residence time, and atmospheric effects of the different impact-generated gases and aerosols (e.g., Pierazzo et al., 2003). Even more important, the crucial data that constrain these models—e.g., variations in $\delta^{18}O$—are suspect (Magaritz et al., 1992), obstructing the assessment of climatic and oceanographic boundary conditions after the impact. In addition, the use of biota-based temperature proxies, such as calcareous plankton–based transfer functions, is obviously hampered across the K-T boundary because most Cretaceous species did not survive into the earliest Paleocene. Owing to these uncertainties and to the scarcity of high-resolution field data from the critical postimpact interval, the various proposed impact-induced sequences of global environmental change are still not resolved from the sedimentary and biotic records. Although no conclusive evidence is found in the geologic record of the earliest Danian, the vaporization of the massive evaporitic deposits forming 27% of the target rocks in the Yucatán platform (Dressler et al., 2003) might have induced a profound cooling phase, eventually leading to the K-T boundary mass extinction as proposed by Brett (1992). Here we present an integrated high-resolution study comparing quantitative records of two groups of organisms that were not pushed to extinction at the K-T boundary, i.e., organic-walled cyst-producing dinoflagellates (dinocysts) and benthic foraminifera. Moreover, we evaluate our results in the light of the modeled long-term (10^3 yr) effects of the climate forcing induced by the Chicxulub impactor.

MATERIAL AND METHODS

K-T boundary sections in the area of El Kef (northwest Tunisia) are among the most complete in marine settings (see Smit et al., 1997, and references therein). Previous studies indicate that benthic foraminifera (Keller, 1988; Speijer and Van der Zwaan, 1994; Coccioni and Galeotti, 1998) and dinocysts (Brinkhuis and Zachariasse, 1988; Brinkhuis et al., 1998) are abundant and well preserved in this section. The El Kef section thus offers a unique opportunity to evaluate the record of these groups across the boundary.

The studied interval, from a composite record of the El Kef I and El Kef II sections, spans 1 m below to 1 m above the K-T boundary. Most samples were taken from 1 cm intervals; others were taken from 3 to 10 cm intervals. For each sample, the mean distance from the K-T boundary is used in the plots. For location details, see Smit et al. (1997).

The data set presented in this paper is partly based on data from Brinkhuis et al. (1998) and Galeotti and Coccioni (2002) on dinocyst and benthic foraminiferal distribution, respectively. New supplementary results on the faunal composition of benthic foraminifera are provided here.

BIOTIC RECORD

Benthic foraminiferal and dinocyst assemblages from the outer-neritic or upper-bathyal El Kef show large fluctuations in abundance and composition across the K-T boundary (Brinkhuis and Zachariasse, 1988; Keller, 1988; Speijer and Van der Zwaan, 1994; Brinkhuis et al., 1998; Coccioni and Galeotti, 1998). Also, Galeotti and Coccioni (2002) reported an anomalous increase in the proportion of sinistrally coiled *Cibicidoides pseudoacutus* (Fig. 1), straddling the lowermost 6–8 cm of the boundary clay at El Kef and the lowermost 10 cm of the boundary clay in the nearby Elles section. In line with observations on modern foraminifera (Brummer and Kroon, 1988; Boltovskoy et al., 1991), this event can be interpreted to reflect either a temperature change or a bioprovincial reorganization in the earliest Danian.

Plotting abundances of typical Boreal species versus Tethyan and cosmopolitan species, Brinkhuis et al. (1998) recognized an earliest Danian invasion of Boreal (North Atlantic) forms in dinocyst assemblages, suggestive of a post–K-T boundary cooling event (Fig. 1; see also Brinkhuis et al., 1998).

Similar to what is observed in dinocyst assemblages, at least two benthic foraminiferal species (i.e., *Ammomarginulina aubertae* Gradstein and Kaminski and *Pseudouvigerina* sp. 1 Speijer) first appearing at the base of the boundary clay (Fig. 1) can be confidently considered as Boreal taxa migrating into the western Tethys. These two species are observed in Maastrichtian and Danian sequences of the North Atlantic (Gradstein and Kaminski, 1989; Speijer and Van der Zwaan,

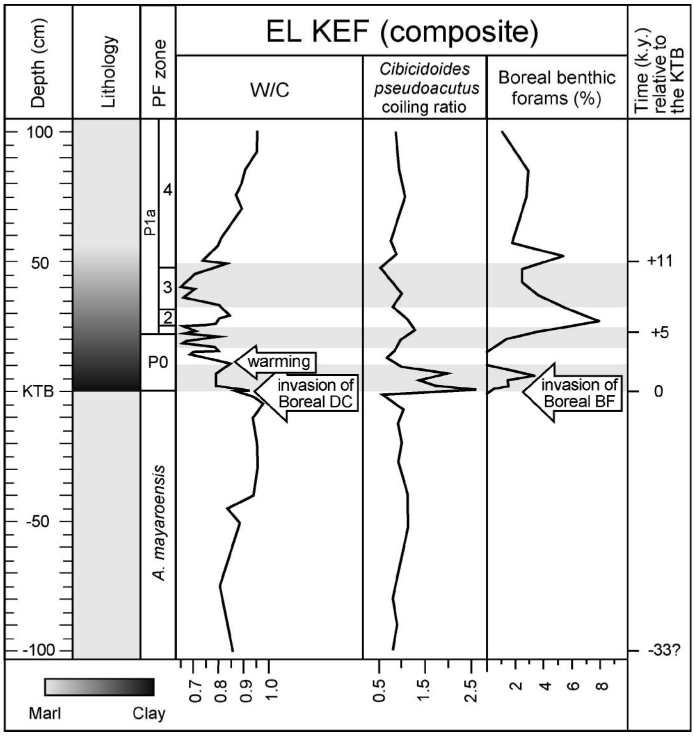

Figure 1. Dinoflagellate cyst (DC) and benthic foraminiferal (BF) records across Cretaceous-Tertiary boundary (KTB) of El Kef. W/C—warm/cold dinocyst ratio. Boreal benthic foraminiferal record corresponds to cumulative proportion of *A. aubertae* and *Pseudouvigerina* sp. 1. Shaded bands represent cooler intervals recognized in dinocyst assemblages by Brinkhuis et al. (1998). Planktic foraminiferal (PF) zonation after J. Smit *in* Brinkhuis et al. (1998). Shift in coiling ratio of benthic foraminifera *C. pseudoacutus*, which may indicate bioprovincial reorganization and/or temperature change, is also noticeable. Chronology is based on data reported by Mukhopadhyay et al. (2001) for Paleocene interval and Stüben et al. (2003) for uppermost Maastrichtian.

1994), but are not reported from any pre–K-T boundary Tethyan sequence. Their first appearances in the El Kef section can, therefore, be taken to indicate an expansion of the Boreal bioprovince into the western Tethys immediately following the K-T boundary event.

Above this interval, dinocyst assemblages from El Kef show an increase in the proportion of warmer (Tethyan) water species, and benthic foraminiferal assemblages record the temporary exit of Boreal taxa. Coinciding with the exit of the Boreal invaders, the coiling ratio of *C. pseudoacutus* reverted to pre–K-T boundary values (Galeotti and Coccioni, 2002), confirming a successive step of reorganization in the seafloor bioprovincialism and/or temperature.

OCEAN RESPONSE TO CLIMATE FORCING

Benthic foraminiferal and dinocyst assemblage records from the El Kef global stratotype section and point testify to a rapid expansion of the Boreal (North Atlantic) bioprovince into the western Tethys following the K-T boundary, providing evidence for a profound cooling of surface and intermediate waters induced by the Chicxulub impact event.

Model simulations predict a range of likely durations for substantial reductions in incoming solar radiation after the impact, ranging from 2 to 5 yr (Pierazzo et al., 2003), 9 yr (Gupta et al., 2001), to ≤12 yr (Pope et al., 1997), with a range of potential cooling amounts (5–31 °C). These models predict a brief but profound atmospheric cooling followed by a swift recovery of surface climate and terrestrial productivity (Lomax et al., 2001). The most recent estimate of the duration of planktic foraminiferal zone P0 is ~5 k.y. (Arenillas et al., 2002). According to Mukhopadhyay et al. (2001), the boundary clay of Ain Settara, which has a thickness approximately equal to that of El Kef, was deposited at a sedimentation rate of 4.4 cm/k.y. On this basis, the duration of the 23-cm-thick P0 at El Kef would be ~5 k.y., therefore confirming the suggestion by Arenillas et al. (2002). Hence, the combined benthic foraminiferal and dinocyst evidence would suggest that the cold impact winter (at this site at least) lasted ~2 k.y.—more prolonged than predicted by impact models. Consequently, our biota-based paleoenvironmental reconstruction appears to be consistent with a post-impact cooling but not the nearly immediate ($\ll$100 yr) recovery.

We note that in most of these modeling efforts, the effect that a global cooling might have had on the deep ocean is largely ignored, although Pope et al. (1997) suggested that its magnitude depends largely upon the rate of ocean mixing.

With a simple energy-balance calculation, we estimate the effect of substantial decreases in the solar constant due to an impact winter. Assuming that Earth cools at a rate governed by blackbody radiative cooling,

$$\frac{dE}{dt} = \varepsilon A \sigma T^4, \tag{1}$$

where E represents the total heat content of the ocean, ε is the emissivity (here assumed to be 1), A is the area of the ocean, σ is the Stefan-Boltzmann constant (5.67×10^{-8} W·m^{-2}·K^{-4}), T is a representative temperature, here assumed to represent a volume mean ocean temperature, and t is time. Combining equation 1 with the relationship defining the thermal inertia of the oceans and rearranging, we can arrive at the following relationship:

$$\frac{dT}{dt} = \frac{A\sigma}{V\rho_w c_p} T^4, \tag{2}$$

in which V refers to the ocean's volume, and ρ_w and c_p refer to the density of and specific heat of seawater, respectively. Equation 2 may, in turn, be integrated to calculate an approximate cooling time, t_{cooling}, given beginning and ending temperatures T_{initial} and T_{final},

$$t_{\text{cooling}} = \frac{D\rho_w c_p}{3\sigma}\left[\frac{1}{T^3_{\text{final}}} - \frac{1}{T^3_{\text{initial}}}\right], \tag{3}$$

where we have exchanged the ocean's V/A for D, the ocean's average depth (here we use 4000 m). A range of possible initial temperatures and the time required to reach specified final temperatures is shown in Figure 2. This is a crude estimate, involving many assumptions, the most important one being that Earth's cooling rate can be calculated from the ocean's volume-average temperature rather than from its surface temperature, but sensitivity studies show that the final result is not too sensitive to this assumption, and the assumption is reasonable if cooling lasts sufficiently long (>1 yr) to mix the ocean vigorously through convection. Furthermore, simulations with more sophisticated two-dimensional coupled ocean-atmosphere models, forced with large impact-induced radiative cooling lasting longer than 1 yr, unequivocally demonstrate that the deep ocean plays a critical role by buffering the upper ocean with its greater thermal inertia and in the process sequestering cool water (Bendtsen and Bjerrum, 2002) into the abyss. These more complete models produce estimates of cooling rates and ocean-temperature distributions that are the same as those shown here (see Fig. 2). As a further test, we performed a simulation with a fully coupled three-dimensional Community Climate System Model (CCSM of U.S. National Center for Atmospheric Research). Beginning from modern conditions (described in Huber and Sloan, 2001), the solar constant was decreased to nearly zero, and the model was integrated

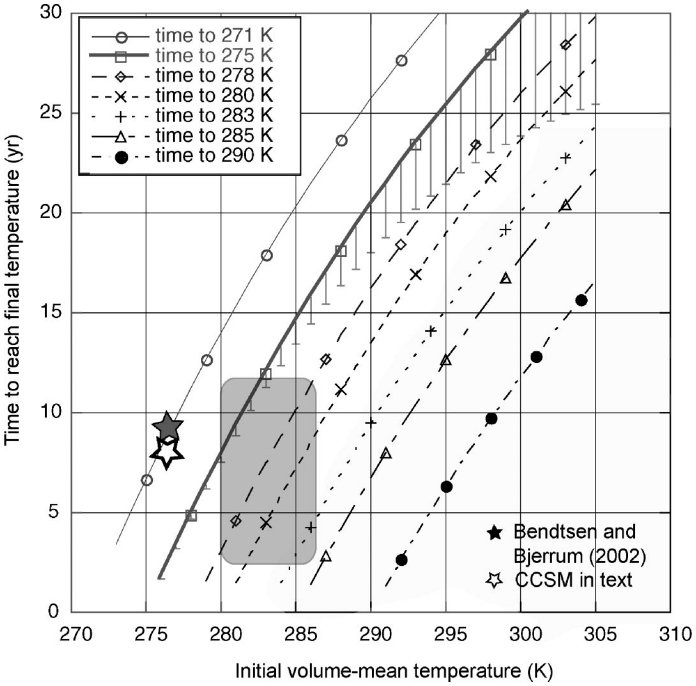

Figure 2. Contours of duration (in years) necessary to radiatively cool planet, from specified value of temperature T_{initial} to value T_{final}. Contours indicate different values of T_{final} as shown in key. To show relative robustness of results to assumptions, time to 275 K curve was recalculated by assuming constant cooling rate (determined by T_{initial}); these values are shown in error bars for 275 K curve. Gray box spans plausible range of impact-winter durations derived from Pope et al. (1997) and Pierazzo et al. (2003) vs. plausible range of initial Cretaceous ocean temperature taken from Wilf et al. (2003). From this plausible range, our best guess estimate of cooling on order of 5 °C is obtained. Stars show length of time explicitly predicted by two different numerical models (CCSM, Community Climate System Model), as indicated in lower-right key, to cool from modern conditions to global near-freezing conditions. Both compare favorably with predictions of energy balance described in text.

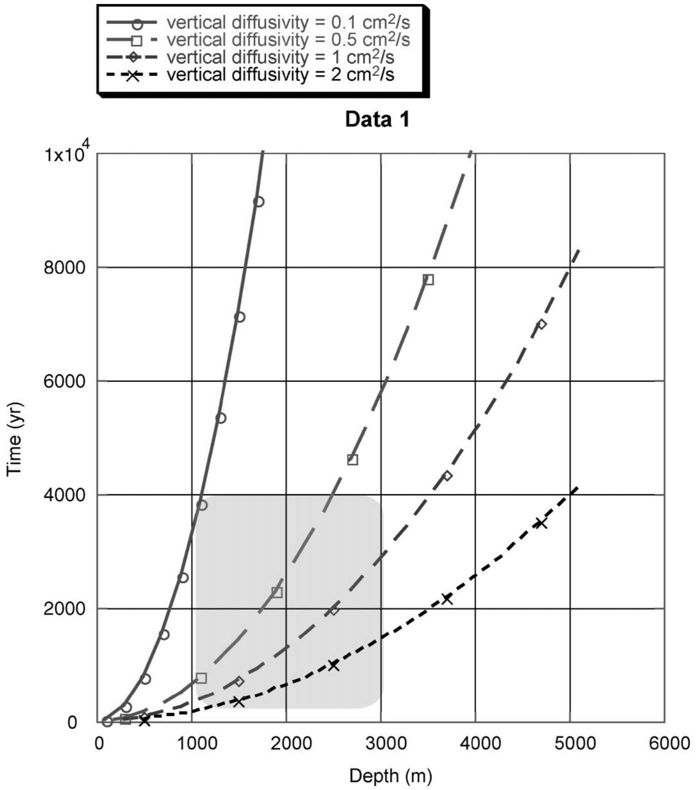

Figure 3. Time necessary to diffuse away a temperature anomaly over ocean thickness indicated by depth scale. Values are estimated from simple relation that time scale is proportional to square of depth divided by diffusivity (see Vallis, 2000). Contours represent different values of vertical-diffusion parameter in ocean, ranging from 0.1 cm^2/s (minimum value in ocean today in absence of any enhancements) to 2 cm^2/s (maximum value under assumption that vertical diffusion is strongly augmented by, e.g., wind-driven upwelling). Shaded zone indicates plausible range of depth to which impact-winter cooling is likely to have extended, based on impact winter of 3–5 yr duration and bounded by extreme ends of diffusivity contours. Most plausible estimates indicate duration of >2000 yr, but in world without wind-driven upwelling and without other vertical mixing enhancements, large, deep-ocean cold anomaly might persist for tens of thousands of years.

until a nearly global ice-covered state was achieved, ~8 yr, i.e., in agreement with the energy-balance considerations with the results of Bendtsen and Bjerrum (2002). The fact that theory and numerical results are in agreement demonstrates the robustness of the basic physical balances being invoked and suggests that the necessary assumptions in the theory do not weaken its predictive utility. It is easy to sketch a wide range of possible cooling scenarios, and for a range of initial temperatures characteristic of the Cretaceous, the global mean ocean temperatures were likely to have cooled by ~5 °C for a plausible range of impact-winter durations (as estimated from models herein), although the range of possible temperature changes is large (~2–12 °C) if the extremes of the plausible range of impact-induced cooling times and initial temperatures are used.

The response of the system to warming is asymmetric. Input of cold water to the deep ocean may have been rapid (<5 yr), but removal of this relatively dense, cold water likely took much longer, because of the density dependence of vertical mixing in the oceans. Return of normal insolation values led to a strong surface warming, perhaps bolstered by greenhouse gas increases, that occurred immediately after the impact winter. When coupled with the sudden emplacement of cold, dense deep water, it is likely that the stability of the water column throughout much of the world's oceans was increased, leading to a sharpening and strengthening of the main thermocline. Vertical mixing in the ocean is inhibited by strong static stability and is inversely proportional to static stability or even its square (e.g., Lyle, 1997); thus this anomalously cold bolus may have persisted for time scales on the order of thousands of years (Fig. 3), if the dominant means of removing the density anomaly was vertical diffusion. This result is in line with the duration of the cooling event recorded at El Kef. The dinocyst and benthic foraminiferal record suggests that, during this period, surface and intermediate waters, derived ultimately from cold or high-latitude regions, existed in the western Tethys for thousands of years following the K-T boundary impact. Coastal upwelling in regions such as El Kef—known both from data and models to have been sites of upwelling both before and after the K-T boundary (Huber and Sloan, 2000)—may have tapped and been cooled by volumetrically small amounts of water from the stably stratified deeper ocean, and this is the water mass that we hypothesize is sampled by the El Kef records. The duration of the cooling pulse and related changes in water circulation testified to by the micropaleontological record was ~2 k.y., and was therefore compatible with the model predictions of the long-term duration of climatic changes as predicted from theory and from coupled models (cf. Bendtsen and Bjerrum, 2002; Luder et al., 2002).

Changes in the ocean circulation may have induced a series of positive-feedback mechanisms that helped sustain the initial, impact-induced cooling pulse and are generally not considered in numerical-model simulations of the short-term changes. The sudden impact-induced cooling likely led to the vigorous production of cool-water masses in high-latitude regions. This effective deepening of the ''mixed layer'' in this region may have buffered high-latitude climate somewhat during the immediate ($\ll$100 yr) aftermath of the impact, but the heat lost to the atmosphere in this region should appear in the record as a cooling of the deep ocean. This cooler deep ocean may have been effectively insulated from postimpact solar heating and greenhouse gas–induced warming by the increase in the ocean's density stratification and associated decrease in vertical mixing. This increase is likely to have long-lasting consequences: (1) a decrease in the meridional overturning circulation and thereby (2) a decrease in the cycling of nutrient-rich waters from the deep ocean into the surface ocean. These consequences are likely to have slowed recovery to pre–K-T boundary temperatures and biological pump activity even after several to tens of thousands of years after the disappearance of a short-lived impact-derived darkness (depending on the assumed vertical diffusivity).

CONCLUDING REMARKS

The invasion of Boreal species in both benthic foraminiferal and dinocyst assemblages in the earliest Paleocene western Tethys suggests that profound changes in the ocean circulation occurred there in the immediate aftermath of the K-T boundary event. In line with the modeled initial results of the sulfate-aerosol–driven climate forcing induced by the Chicxulub impact, this phenomenon is here seen as a response to profound cooling of both surface and deeper waters immediately following the K-T boundary, which is likely to be a unique characteristic of the K-T boundary impact. The cooling phase and associated changes in ocean circulation testified to by the benthic foraminiferal and dinocyst record persisted for ~2 k.y. into the Tertiary. This estimate fits well with the modeled long-term effect of a large-sized impactor on the global climate system.

ACKNOWLEDGMENTS

This is Netherlands Research School in Sedimentary Geology contribution 2004.01.04 and Centro di Geobiologia contribution 6. We thank Kevin Pope and two anonymous reviewers for helpful comments.

REFERENCES CITED

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V., 1980, Extraterrestrial cause for the Cretaceous-Tertiary extinction: Science, v. 208, p. 1095–1108.

Arenillas, I., Alegret, L., Arz, J.A., Liesa, C., Meléndez, A., Molina, E., Soria, A.R., Cedillo-Pardo, E., Grajales-Nishimura, J.M., and Rosales-Domínguez, C., 2002, Cretaceous-Tertiary boundary planktic foraminiferal mass extinction and biochronology at La Ceiba and Bochil, Mexico, and El Kef, Tunisia, *in* Koeberl, C., and MacLeod, K.G., eds., Catastrophic events and mass extinctions: Impacts and beyond: Geological Society of America Special Paper 356, p. 253–264.

Bendtsen, J., and Bjerrum, C.J., 2002, Vulnerability of climate on Earth to sudden changes in insolation: Geophysical Research Letters, v. 29, no. 15, 1706, doi: 10.1029/2002GL014829.

Boltovskoy, E., Scott, D.B., and Medioli, F.S., 1991, Morphological variations of benthic foraminiferal tests in response to changes in ecological parameters: A review: Journal of Paleontology, v. 65, p. 175–185.

Brett, R., 1992, The Cretaceous-Tertiary extinction: A lethal mechanism involving anhydrite target rocks: Geochimica et Cosmochimica Acta, v. 56, p. 3603–3606.

Brinkhuis, H., and Zachariasse, W.J., 1988, Dinoflagellate cysts, sea level changes and planktonic foraminifers across the Cretaceous-Tertiary boundary at El Haria, northwest Tunisia: Marine Micropaleontology, v. 13, p. 153–191.

Brinkhuis, H., Bujak, J.P., Smit, J., Versteegh, G.J.M., and Visscher, H., 1998, Dinoflagellate-based sea surface temperature reconstructions across the Cretaceous-Tertiary boundary: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 141, p. 67–83.

Brummer, G.J.A., and Kroon, D., 1988, Genetically controlled planktonic foraminiferal coiling ratios as tracers of past ocean dynamics, *in* Brummer, G.J.A., and Kroon, D., eds., Planktonic foraminifera as tracers of ocean-climate history: Ontology, relationships and preservation of modern species and stable isotopes, phenotypes and assemblage distribution in different water masses: Amsterdam, Free University Press, p. 293–297.

Coccioni, R., and Galeotti, S., 1998, What happened to small benthic foraminifera at the K/T boundary?: Bulletin de la Société Géologique de France, v. 169, p. 271–279.

Dressler, B.O., Sharpton, V.L., Morgan, J., Buffler, R., Moran, D., Smit, J., Stöffler, D., and Urrutia, J., 2003, Investigating a 65-Ma old smoking gun: Deep drilling of the Chicxulub impact structure: Eos (Transactions, American Geophysical Union), v. 84, p. 125–130.

Galeotti, S., and Coccioni, R., 2002, Changes in coiling direction of *Cibicidoides pseudoacutus* across the Cretaceous/Tertiary boundary of Tunisia: Palaeoecological and biostratigraphic implications: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 177, p. 197–210.

Gradstein, F.M., and Kaminski, M.A., 1989, Taxonomy and biostratigraphy of new and emended species of Cenozoic deep-water agglutinated foraminifera from the Labrador and North Seas: Micropaleontology, v. 35, p. 72–92.

Gupta, S.C., Ahrens, T.J., and Yang, W., 2001, Shock-induced vaporization of anhydrite and global cooling from the K/T impact: Earth and Planetary Science Letters, v. 188, p. 399–412.

Huber, M., and Sloan, L.C., 2000, Climatic responses to tropical sea surface temperature changes on a ''greenhouse'' Earth: Paleoceanography, v. 15, p. 443–450.

Huber, M., and Sloan, L.C., 2001, Heat transport, deep waters, and thermal gradients: Coupled simulation of an Eocene ''greenhouse'' climate: Geophysical Research Letters, v. 28, p. 3481–3484.

Keller, G., 1988, Biotic turnover in benthic foraminifera across the Cretaceous-Tertiary boundary at El Kef, Tunisia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 66, p. 153–171.

Koeberl, C., and MacLeod, K., eds., 2002, Catastrophic events and mass extinctions: Impacts and beyond: Geological Society of America Special Paper 356, 749 p.

Lomax, B.H., Beerling, D.J., Upchurch, G.R., Jr., and Otto-Bliesner, B.L., 2001, Rapid (10-yr) recovery of terrestrial productivity in a simulation study of the terminal Cretaceous impact event: Earth and Planetary Science Letters, v. 192, p. 137–144.

Luder, T., Benz, W., and Stocker, T.F., 2002, Modeling long-term climatic effects of impacts: First results, *in* Koeberl, C., and MacLeod, K.G., eds., Catastrophic events and mass extinctions: Impacts and beyond: Geological Society of America Special Paper 356, p. 717–729.

Lyle, M., 1997, Could early Cenozoic thermohaline circulation have warmed the poles?: Paleoceanography, v. 12, p. 161–167.

Magaritz, M., Benjamini, C., Keller, G., and Moshkovitz, S., 1992, Early diagenetic isotopic signal at the Cretaceous/Tertiary boundary, Israel: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 91, p. 291–304.

Mukhopadhyay, S., Farley, K.A., and Montanari, A., 2001, A short duration of the Cretaceous-Tertiary boundary event: Evidence from extraterrestrial helium-3: Science, v. 291, p. 1952–1955.

Pierazzo, E., Hahmann, A.H., and Sloan, L.C., 2003, Chicxulub and climate: Radiative perturbations of impact-produced S-bearing gases: Astrobiology, v. 3, p. 99–118.

Pope, K.O., Baines, K.H., Ocampo, A.C., and Ivanov, B.A., 1997, Energy, volatile production, and climatic effects of the Chicxulub Cretaceous/Tertiary impact: Journal of Geophysical Research, v. 102, p. 21,645–21,664.

Ryder, G., Fastkovsky, D., and Gartner, S., eds., 1996, The Cretaceous-Tertiary event and other catastrophes in Earth history: Geological Society of America Special Paper 307, 560 p.

Smit, J., and Hertogen, J., 1980, An extraterrestrial event at the Cretaceous-Tertiary boundary: Nature, v. 285, p. 198–200.

Smit, J., Keller, G., Zargouni, F., Razgallah, S., Shimi, M., Ben Abdelkader, O., Ben Haj Ali, N., and Ben Salem, H., 1997, The El Kef sections and sampling procedures: Marine Micropaleontology, v. 29, p. 67–69.

Speijer, R.P., and Van der Zwaan, G.J., 1994, Extinction and survivorship patterns in southern Tethyan benthic foraminiferal assemblages across the Cretaceous/Paleogene boundary: Geologica Ultraiectina, v. 124, p. 19–64.

Stüben, D., Kramar, U., Berner, Z.A., Meudt, M., Keller, G., Abramovich, S., Adatte, T., Hambach, U., and Stinnesbeck, W., 2003, Late Maastrichtian paleoclimatic and paleoceanographic changes inferred from Sr/Ca ratio and stable isotopes: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 199, p. 107–127.

Vallis, G.K., 2000, Large-scale circulation and production of stratification: Effects of wind, geometry, and diffusion: Journal of Physical Oceanography, v. 30, p. 933–955.

Wilf, P., Johnson, K.R., and Huber, B.T., 2003, Correlated terrestrial and marine evidence for global climate changes before mass extinction at the Cretaceous-Paleogene boundary: National Academy of Sciences Proceedings, v. 100, p. 599–604.

Manuscript received 4 January 2004
Revised manuscript received 1 February 2004
Manuscript accepted 3 February 2004

Printed in USA