The Cretaceous-Tertiary boundary cocktail: Chicxulub impact triggers margin collapse and extensive sediment gravity flows

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ABSTRACT

A distinctive mixture of reworked microfossils, impact-derived materials, and lithic fragments occurs in sediments at the Cretaceous-Tertiary boundary in the basinal Gulf of Mexico and Caribbean. We have named this mixture the Cretaceous-Tertiary boundary "cocktail." Lithologic and paleontologic evidence suggests that the cocktail was deposited by giant sediment gravity flows, apparently triggered by the collapse of continental margins around the Gulf of Mexico as a result of the Chicxulub impact. As most microfossils in the gravity-flow units are reworked, biostratigraphy provides only maximum ages. Recognition of the cocktail is a reliable way to identify Cretaceous-Tertiary boundary deposits in the basinal Gulf of Mexico and Caribbean.

INTRODUCTION

The high-energy bolide impact at Chicxulub left a distinct mark in Cretaceous-Tertiary (K-T) boundary sediments in the Gulf of Mexico and Caribbean region. For example, 900-m-thick impact breccia deposits are present 100 km from the crater (e.g., Sharpton et al., 1996). Tsunami deposits containing decimeter-size rip-up clasts are found along continental shelves in Texas and northern Mexico (e.g., Bourgeois et al., 1988). Gravity-flow deposits occur at the K-T boundary in Cuba (Iturralde-Vinent, 1992), Chiapas (Montanari et al., 1994), and Belize (O'Campo et al., 1996). Disturbed K-T boundary units are also reported in Haiti (Maurrasse and Sen, 1991) and in Deep Sea Drilling Project (DSDP) sites at the base of the Campeche Escarpment (Alvarez et al., 1992).

The age of proposed K-T boundary deposits on the shelf and in the basin of the Gulf of Mexico, however, has been disputed. Biostratigraphic interpretations yielding Cretaceous ages for spherule-bearing shelf sequences have caused some (e.g., Keller et al., 1997) to question the association of these deposits, and thus of the Chicxulub event itself, with the profound changes in the Earth's environment that occurred at the K-T boundary (e.g., Hildebrand et al., 1991). In addition, Keller et al. (1993) concluded that the K-T boundary is unconformable throughout the basinal Gulf of Mexico and Caribbean, whereas Alvarez et al. (1992) correlated coarse-grained basinal deposits to the K-T boundary Chicxulub event.

Here we describe a distinctive mixture of reworked microfossils, impact-derived materials, and lithic fragments found in K-T boundary strata in the basinal Gulf of Mexico and Caribbean. Lithologic and paleontologic evidence suggests that this mixture of particles was deposited by sediment gravity flows, probably triggered by the Chicxulub impact. As a result of the pervasive reworking, biostratigraphy provides maximum ages for the components that comprise K-T boundary strata, but not necessarily the age of deposition.

METHODS AND RESULTS

We have investigated the K-T boundary interval at 11 Gulf of Mexico and Caribbean DSDP and Ocean Drilling Program (ODP) sites, and one land section (Beloc, Haiti) (Fig. 1). The sites include K-T boundary sections that appear to be stratigraphically complete as well as those that contain unconformities, and they range from slope settings near the Yucatan to basinal locations from the proximal Gulf of Mexico and distal Caribbean Sea (Fig. 2). Most of the sections drilled during DSDP Legs 10 and 15 (Sites 86–152) were incompletely cored.

Calcareous nannofossil biostratigraphy is based upon high-resolution sampling (1–5 cm) across the K-T boundary interval.[1] Nannofossils were identified using a light microscope. Planktic and benthic foraminifers and other coarse silt- and sand-sized particles were observed in a few key samples from Sites 536, 537, 538, and 540. These particles were separated by washing the sediment over a 44 µm sieve, then examined using binocular and scanning electron microscopes (SEM). Mineralogies of key samples were determined using transmitted light microscopy and SEM-energy dispersive spectrometry.

The original nannofossil biostratigraphy of Sites 86–152 was conducted before taxonomies and zonations were well established (e.g., Sissingh, 1977); thus this study has resulted in significant revisions (Fig. 2). Elsewhere the biostratigraphy is similar to published accounts (Watkins and Bowdler, 1984; Sigurdsson et al., 1991).

The K-T boundary level is identified by the lowest occurrence of Paleocene microfossils; however, a suite of facies and considerable thicknesses of sediments directly below this horizon in several sites (Fig. 2) may be related to the impact event. A combination of nannofossil biostratigraphy and diagnostic materials (including spherules, shocked quartz, and Ir anomalies) is used to identify units associated with the impact

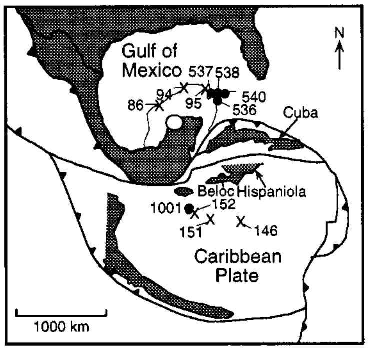

Figure 1. Paleogeographic reconstruction of Caribbean (after Pindell and Barrett, 1990) showing location of depositional (black circles) and erosional (crosses) Cretaceous-Tertiary boundary sequences investigated. Numbers refer to DSDP and ODP sites. Chicxulub impact site is indicated by large white circle.

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[1] GSA Data Repository item 9838, biostratigraphic and sedimentologic data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

Data Repository item 9838 contains additional material related to this article.

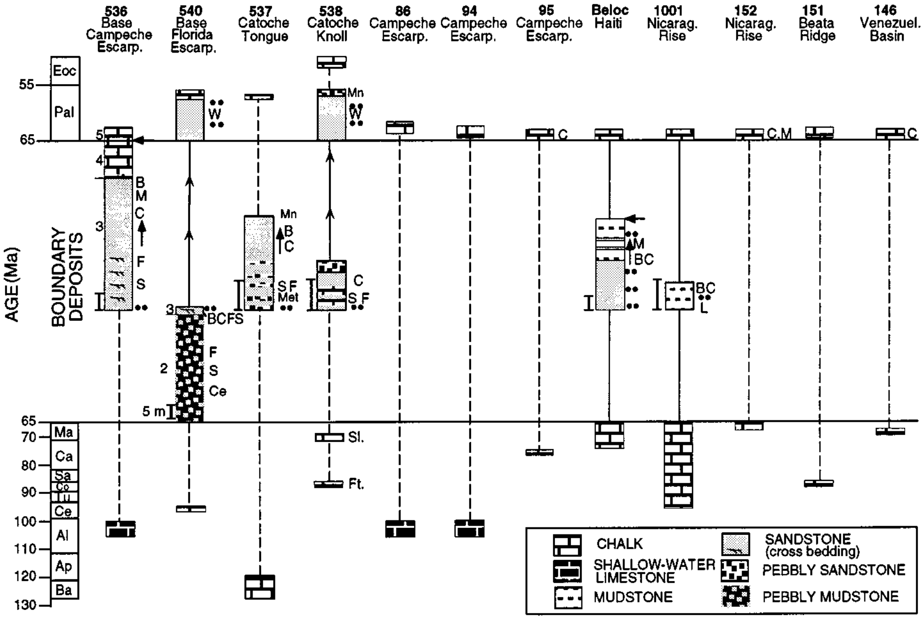

Figure 2. Stratigraphy and sedimentology of Cretaceous-Tertiary (K-T) boundary sections (see footnote 1). Dashed lines indicate unconformities; solid lines indicate continuous deposition. Timing of K-T boundary sediment deposition assumes that spherule-bearing sediments are isochronous and that combined Site 536 and 540 sequence is complete. Reworked nannofossils: B = Barremian to early Aptian, Ce = Cenomanian, C = late Campanian to early Maastrichtian, M = late Maastrichtian; F = reworked shallow-water benthic foraminifers (after Sliter and Premoli Silva, 1984); Mn = Fe-Mn oxide coating; S = shallow-water carbonate fragments, L = limestone (undifferentiated) fragments, Met = metamorphic and igneous rock fragments; vertical black arrow = fining-upward sequence; horizontal arrow shows location of Ir anomaly; double black circles show locations of spherules; vertical scale bar by boundary deposits shows 5 m at Site 540, 10 cm at other sites; Sl. = slumped; Ft. = faulted; W = winnowing. Age of winnowed cocktail deposits at Sites 538 and 540 are best estimates. Numbers shown along Sites 536 and 540 columns refer to Alvarez et al. (1992) lithologic units. Information on K-T boundary characteristics was taken from Alvarez et al. (1992) for Sites 536 and 540; from Sigurdsson et al. (1997) for Site 1001; and from Maurrasse and Sen (1991) for Beloc.

and to characterize the K-T boundary interval as being either erosional or depositional (Fig. 2). Spherule horizons at Sites 537 (Catoche Tongue), 538 (Catoche Knoll), and 540 (base of the Florida Escarpment) are described for the first time.

MICROFOSSIL REWORKING AND ITS STRATIGRAPHIC IMPLICATIONS

Age-diagnostic nannofossils of multiple ages occur in deposits directly below the K-T boundary level at basinal Gulf of Mexico and Caribbean sites where there is no obvious unconformity (Fig. 2). This mixture is indicative of reworking. Reworked assemblages contain markers that are diagnostic of the late Campanian to early Maastrichtian (*Aspidolithus parcus* subsp. *parcus, A. parcus* subsp. *constrictus*, *Eiffellithus eximius*, *Quadrum gothicum*, *Q. trifidum*, *Reinhardtites anthophorus*, *R. levis*, *Lithastrinus grillii*, and *Tranolithus orionatus*), and Barremian to earliest Aptian (*Nannoconus steinmannii*, *N. elongatus*, *N. minutus*, and *Hayesites radiatus*).

At Sites 536, 540, and 1001, and Beloc, older reworked nannofossils are found mixed with late Maastrichtian species (e.g., *Micula murus* and *Lithraphidites quadratus*). Rare specimens of *Micula prinsii* were observed in uppermost Maastrichtian sediments from Site 536 (samples 536-9-5, 130–131 cm and 536-9-6, 22–23 cm). The proportion of nannofossils that are diagnostic of Barremian to early Aptian age is estimated to be <5%, and the proportion of age-diagnostic late Campanian to early Maastrichtian species may exceed 25%. Most taxa have long stratigraphic ranges that extend through the Late Cretaceous. Species restricted to the late Maastrichtian are unusually rare, indicating that most, if not all, nannofossils are reworked. Abundances of reworked nannofossil specimens decreases in the lowermost 5 cm of the Paleocene in all sections.

The origin of sediments near the K-T boundary at Sites 536 and 540 in the basinal Gulf of Mexico (Fig. 1) has been debated. Alvarez et al. (1992) proposed that these sediments were redeposited as a consequence of the Chicxulub impact based in part on the distribution of spherules, shocked quartz, glass fragments, and an Ir peak that corresponds to the paleontological K-T boundary (Fig. 2). Keller et al. (1993) assigned these same sediments to an early or early late Maastrichtian age on the basis of the absence, or extreme rarity, of latest Maastrichtian planktic foraminifers, and thus questioned the relation of these deposits to the K-T boundary impact.

In the sequence at Site 536, we found rare late Maastrichtian planktic foraminifers (*Abathomphalus mayaroensis* [Fig. 3], *Planoglobulina multicamerata, Racemiguembelina powelli, R. fructicosa*, and *Rugoglobigerina scotti*) mixed with late Campanian to early Maastrichtian taxa. Nannofossil and planktic foraminiferal assemblages are consistent with a depositional age of late Maastrichtian or younger, supporting the association of these units with the K-T boundary (Alvarez et al., 1992).

Extensive redeposition in Gulf of Mexico and Caribbean sections complicate the use of biostratigraphic data, which commonly only provide maximum ages, in establishing the sequence of events around the K-T boundary. Clearly, other approaches are required.

THE K-T BOUNDARY COCKTAIL

K-T boundary strata from proximal basinal sites adjacent to the Campeche margin to the more distal central Caribbean contain a mixture of reworked microfossils (nannofossils, and planktic and benthic foraminifers), lithic fragments, and impact-derived materials. We term the distinctive mixture of components the K-T boundary "cocktail." In some sites, cocktail units are separated from underlying Cretaceous and overlying Paleocene strata by unconformities (Fig. 2). The relative abundance of components in the cocktail differs between sites as do the durations of the hiatuses between cocktail units and Cretaceous and Paleocene strata.

The sandy and pebbly chalk cocktail deposits at Sites 537 and 538 contain glass fragments (10–50 µm diameter), quartz and sanidine grains, granule-sized fragments of schist, gneiss, granite, and shallow-water limestone, fish teeth, echinoid spines, and reworked nannofossils and mid-Cretaceous neritic benthic foraminifers (Fig. 2). Many of the grains at the top of the cocktail units are coated by Fe-Mn oxides. Smectite spherules (largely hollow, spherical in shape, and 20–200 µm diameter) are common at Site 537 (sample 537-3-2, 42 cm) (Fig. 3); smectite spherules are rarer at Site 538 (samples 538A-21-1, 61 and 66 cm). Smectite spherules are commonly formed by alteration of impact-derived glass tektites (e.g., Izett, 1991).

Sandstone and chalk cocktail deposits at Sites 536 and 540 (units 3 and 4 of Alvarez et al. [1992]) contain spherules, shocked quartz, and glass fragments (Alvarez et al., 1992). In addition, we found fragments of shallow-water limestone and chalk, fish teeth, echinoid spines, and reworked nannofossils, planktic foraminifers, and mid-Cretaceous neritic benthic foraminifers (see also Sliter and Premoli Silva, 1984). Distal cocktail deposits from Beloc contain glass, shocked quartz, spherules (Sigurdsson et al., 1991; Maurrasse and Sen, 1991), and reworked nannofossils; distal deposits from Site 1001 contain shocked quartz, spherules, fragments of limestone and claystone (Sigurdsson et al., 1997), and reworked nannofossils (Fig. 2).

The K-T boundary cocktail is derived from multiple sources so that microfossil biostratigraphy typically provides ages of its components, but not necessarily the timing of their final deposition. Latest Cretaceous marker species are exceptionally rare due to dilution by other cocktail components and/or longer ranging taxa. Thus, the recognition of the cocktail itself provides a reliable way of identifying K-T boundary units at basinal Gulf of Mexico and Caribbean sites.

EVIDENCE FOR GRAVITY FLOWS DURING THE K-T BOUNDARY EVENT

K-T boundary sediments at the basinal Gulf of Mexico sites show lithologic evidence for deposition by sediment gravity flows. Sequences of coarse-grained deposits at Sites 536 and 540 originally described by Alvarez et al. (1992) consist of poorly sorted pebbly mudstone containing chalk, mudstone, and bioclastic limestone clasts (unit 2) and cross-bedded sandstone containing angular chalk and bioclastic limestone clasts (unit 3) that grades up into chalk (unit 4) (Fig. 2). Alvarez et al. (1992) proposed that units 3 and 4 were reworked by waves and currents triggered by the Chicxulub impact. We interpret these units as turbidites because of their fining-upward grain size and paleodepths well below wave base.

The age of pebbly mudstone unit 2 at Site 540 was originally interpreted as extending from early to late Cenomanian (Premoli Silva and McNulty, 1984; Watkins and Bowdler, 1984). Our observations suggest that the entire unit is late Cenomanian or younger on the basis of rare occurrences of the nannofossil *Lithraphidites acutum* in the matrix. The mudstone contains angular clasts of Albian chalk and mudstone and is mixed with decimeter-size clasts of Albian shallow-water limestone (Premoli Silva and McNulty, 1984). Mudstone-supported clasts suggest redeposition by mud flows (e.g., Lowe, 1982). Large clast size indicates that unit 2 was derived from proximal strata, suggesting that no microfossils are of pelagic origin. Even though the age of the pebbly mudstone is not precisely established, we tentatively associate this unit with the K-T boundary events on the basis of its position beneath other redeposited K-T boundary strata (Fig. 2).

Fining-upward, sandy and pebbly chalk cocktail deposits around the K-T boundary at Sites 537 (section 537-3-2, 11 to 45 cm), 538 (section 538A-21-1, 57 to 75 cm), and 540 (sections 540-30-2 and 540-30-CC, above the interval studied by Alvarez et al. [1992]) are interpreted to be turbidite deposits. Microfossil biostratigraphy indicates that the depositional age of sediments at Site 537 is late Campanian or younger. In Sites 538 and 540, reworked Cretaceous nannofossils are mixed with early to late Paleocene nannofossils and planktic foraminifera. Abundance of Paleocene microfossils increases upward, suggesting extensive winnowing after deposition.

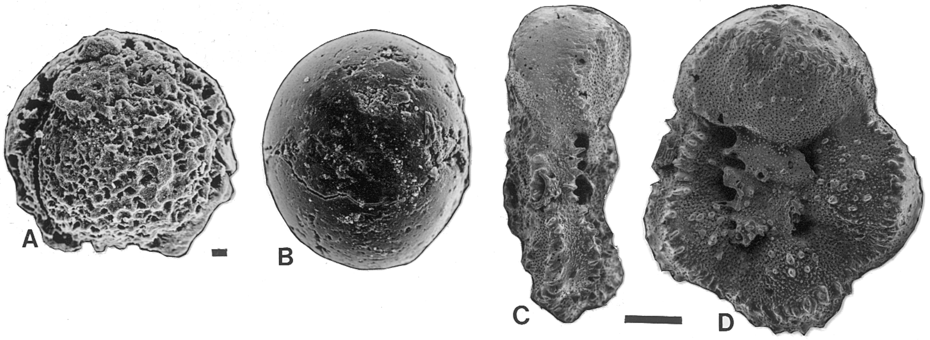

Figure 3. A, B. Smectite spherules (scale bar = 10 µm): A: Sample 537-3-2, 42–43 cm. B: Sample 538A-21-1, 66 cm. C, D. *Abathomphalus mayaroensis* Sample 540-31-1, 26–27 cm (scale bar = 100 µm). C is edge view; D is umbilical view.

RELATIONSHIP OF THE K-T BOUNDARY COCKTAIL TO THE CHICXULUB IMPACT

The K-T boundary cocktail contains a mixture of impact-derived materials that may have settled through the water column, and redeposited materials laid down by gravity flows. Only the deposits at Beloc and Sites 536, 540, and 1001 have previously been attributed to the Chicxulub event (e.g., Sigurdsson et al., 1991, 1997; Alvarez et al., 1992). However, identical reworked nannofossil assemblages in most K-T boundary deposits suggest a similar origin. The biostratigraphy of K-T boundary deposits at some proximal locations (Sites 536, 537, units 2–3 of Alvarez et al. [1992] at Site 540) provides maximum ages ranging from Cenomanian to latest Maastrichtian that are consistent with a K-T boundary origin, whereas in others (Sites 538 and 540 [sections 540-30-2 and 540-30-CC]) some impact-derived materials are winnowed into upper Paleocene sediments (Fig. 2).

Impact-generated gravity flows appear to have caused erosion at sites throughout the basinal Gulf of Mexico and Caribbean. Duration of hiatuses (or coring gaps) in the sections studied range from less than a nannofossil zone (Site 152) to about 60 m.y. (Site 537) (Fig. 2). In several sites (e.g., Sites 86, 94, 95, 146, 151, and 152), sediment overlying the unconformity is earliest Paleocene in age (nannofossil zones CP1 and CP2), suggesting that pelagic sedimentation resumed shortly (mostly <~0.5 m.y.) after erosion of the missing Upper Cretaceous section during the K-T boundary event. At Sites 95, 146, and 152, reworked late Campanian to early Maastrichtian and late Maastrichtian nannofossil species are identified in sediments 1–2 cm above the K-T boundary unconformity (Fig. 2) but are absent in overlying Paleocene horizons. The same reworked nannofossils found in K-T boundary deposits elsewhere indicates that the gravity flows reached large areas of the basinal Gulf of Mexico and the Caribbean Sea.

SOURCE(S) AND EXTENT OF THE SEDIMENT GRAVITY FLOWS

The K-T boundary cocktail can be used to trace the origin and path of gravity flows in the basinal Gulf of Mexico and Caribbean. Several components in K-T boundary deposits match sediments found directly below the K-T boundary unconformity on the Yucatan continental margin, suggesting that this location was a source of the gravity flows. The sedimentary rocks directly below the K-T boundary unconformity at Sites 95 (Campeche Escarpment) and 538 (Catoche Knoll) are late Campanian to early Maastrichtian in age. These units are the same age as angular chalk clasts in the sandstone (unit 3) at Site 540 and a dominant component in the reworked nannofossil assemblage (Fig. 2). Sedimentary rocks directly below the K-T boundary unconformity at Site 537 (Catoche Tongue) are Barremian to early Aptian in age, which matches reworked nannofossil assemblages found at other downslope sites. In Sites 537 and 538, K-T boundary deposits also contain fragments of metamorphic rocks that were probably derived by erosion of nearby basement. Rocks recovered beneath the unconformity at Sites 86 and 94 (Campeche Escarpment) are mid-Cretaceous shallow-water carbonates, similar to fragments and redeposited neritic benthic foraminifers found in K-T boundary deposits at Sites 536 (base of Campeche Escarpment), 537, 538, and 540 (Sliter and Premoli Silva, 1984). The western Florida continental margin is another possible gravity-flow source.

The K-T boundary gravity flows were aerially and vertically extensive. Reconstructions (Fig. 1) show the Caribbean sites to be as much as 1000 km from a potential gravity-flow source. The presence of the K-T boundary cocktail at Sites 537 and 538 located on Cretaceous topographic highs (Schlager et al., 1984) illustrates that the gravity flows engulfed a significant part of the lower water column. Given the distribution of redeposited sediments, and the proximity of possible sediment sources on continental margins

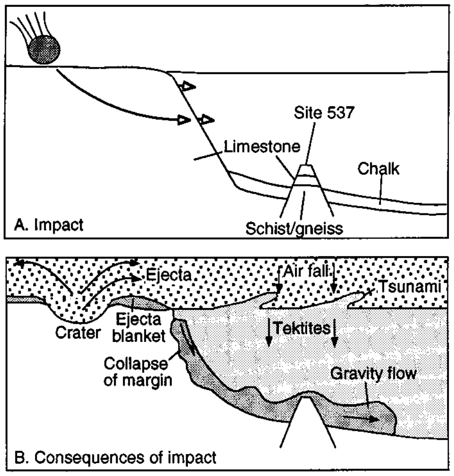

Figure 4. Effect of Chicxulub impact on Yucatan continental margin and proposed origin of the Cretaceous-Tertiary boundary cocktail and gravity flows.

surrounding the Gulf of Mexico, Caribbean, and western Atlantic, the volume of K-T boundary gravity-flow deposits may have been enormous.

TRIGGER AND TIMING OF K-T BOUNDARY SEDIMENT GRAVITY FLOWS

The Chicxulub impact may have dramatically altered sedimentation in the Gulf of Mexico. The kinetic energy derived by the impact is estimated at $\sim 5 \times 10^{30}$ ergs, which is equivalent to 10^8 Mt of TNT or a Richter-magnitude 13 earthquake (Covey et al., 1994). Gravity data are consistent with an oblique, south to north bolide trajectory (Schultz and D'Hondt, 1996). We postulate that sufficient energy was transmitted to the Yucatan and surrounding continental margins to cause massive slope failure (Fig. 4). The collapse of continental margins around the Gulf of Mexico may have generated the large tsunami waves that affected shelf sedimentation (e.g., Bourgeois et al., 1988).

Submarine landslides probably were triggered by the Chicxulub impact, and further erosion occurred during the subsequent passage of high-energy gravity flows across the basinal Gulf of Mexico and Caribbean. Deposition of gravity-flow–borne material, which in cases includes spherules, through the Gulf of Mexico and Caribbean may have occurred in several phases, but much of this material would have accumulated within hours to days of the impact. At paleodepths <2000 m, deposition of the entire K-T boundary unit requires several years at most, the time it would take for clay-bound Ir to reach the bottom (e.g., Ledbetter and Sparks, 1979).

CONCLUSIONS

Cretaceous-Tertiary boundary sediments in the basinal Gulf of Mexico and Caribbean are composed of variable proportions of reworked microfossils, lithic fragments, and impact-derived materials. This distinctive mixture, termed the K-T boundary cocktail, provides a reliable way of recognizing boundary units. Lithologic and paleontologic evidence suggests that the cocktail was deposited by geologically instantaneous gravity flows generated by the collapse of surrounding continental margins, presumably as a result of the Chicxulub impact. The gravity flows eroded large areas and acquired sedimentary components from a variety of sources.

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