Reports

Impacts, Tsunamis, and the Haitian Cretaceous-Tertiary Boundary Layer

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The marker bed at the Cretaceous-Tertiary boundary of the Beloc Formation (southern Haiti) contains abundant coarse-grained microtektites and minor amounts of shocked quartz grains in the basal part. The upper part is composed of medium-grained marl with amalgamated microtektite lenses and finer-grained marl lenses disseminated throughout. Field and petrographic observations, and the distribution of planktonic foraminifera suggest that the bed formed from a complex sequence of events. A bolide impact nearby produced microtektites that settled to form a nearly pure layer at the base. Vaporized materials with anomalously high extraterrestrial components settled last, along with carbonate sediments. The entire bed became sparsely consolidated. Subsequently, another major disruptive event, perhaps a giant tsunami, partly reworked the initial deposit. Cohesive fragments of the original marker bed mixed with exotic materials were redeposited as lenticular bodies. This process also may have caused further mixing of Cretaceous and Tertiary microfossils, as observed at Beloc and elsewhere.

THE SERIES OF EVENTS THAT OCcurred at the Cretaceous-Tertiary (K-T) boundary interval have become a provocative topic since Alvarez and co-workers (*1*) presented geochemical evidence that they may be related to a catastrophic extraterrestrial bolide impact. Several lines of evidence have since been provided worldwide in support of this hypothesis (*2*), and recent data argue in favor of an impact site in the Caribbean area (*3–5*). A key piece of evidence in corroboration of a Caribbean impact is an extraordinary marker bed in the Beloc Formation (Fig. 1) of southern Haiti (*5–8*). The Beloc bed contains the thickest ejecta layer and has the largest microtektites (*3, 9*) known to date. In this report we summarize the lateral and vertical variations in lithology, sedimentary structures, and faunal content of the marker bed at Beloc, and discuss its origin.

In the field, the color and contrast of the marker horizon are distinct from those of the overlying and underlying rocks. Its color (*10*) varies between light olive gray (5Y 5/2) and light olive brown (5Y 5/6) when wet, but becomes significantly lighter and less conspicuous in the outcrops when dry. In contrast, the adjacent chalk and marlstone beds show various shades of gray and pale yellowish brown colors. The lower contact of the marker bed is sharp but shows little evidence of an erosional base. The upper contact is less sharp. The thickness of the bed varies from 40 to 72.5 cm at the stratotype (7) (Fig. 1), but is as thin as 10 cm at other outcrops within the Beloc area. At some of the sites imbrication caused by subsequent slumping has resulted in thickness in excess of 115 cm.

We recognize two levels in the marker bed. The lower part is a packed microtektite sandstone predominantly (80%) composed of clay spherules (altered microtektites) and interstitial smectite clay (*11, 12*) and minor carbonate. Its thickness is approximately 20 cm (Fig. 1), and shows a wavy gradational contact with the upper part. Carbonate becomes more abundant up section. The upper part consists of marl with medium-grained spherules, numerous intermingled lenses (up to 7 cm thick) of coarse clay spherules, and thin (4 to 10 mm thick) lenses of micrite and calcareous shale (Fig. 1). The number of spherules in the marl decreases toward the top of the bed. Both types of lenses may reach lengths exceeding 28 cm, and all lenses are parallel or subparallel to bedding. The topmost thin marl layer (2.5 cm maximum thickness), and similar lenses that occur in the upper part, contain high concentrations of Ir (*7, 13*). Gradation and cross-lamination occur within the upper part, which displays great lateral variations in geometry and lithology over short distances. However, the various outcrops reveal no consistent lateral or vertical size gradation such as those observed in ordinary turbidites (*14*).

Microscopically the matrix of the lower part is composed of angular glass completely altered into smectite. It also contains rare quartz grains, 1 to 2 mm across with multiple intersecting straight (planar) lamellae thought to be caused by shock deformation (*9*). The matrix in the upper part consists primarily of microspar aggregates, and less than 1% distinguishable nannoplanktons, most of which are dislocated and poorly preserved (*6, 7*). Argillaceous components of the matrix are microcrystalline and display a finely isotropic fabric parallel to bedding. Similarly, allochems show a distinct preferential orientation of long axes parallel or subparallel to bedding.

Spherules are greatly variable in size (they range up to 8 mm across) and morphology (*3, 9, 15*). Spherical and ellipsoidal shapes

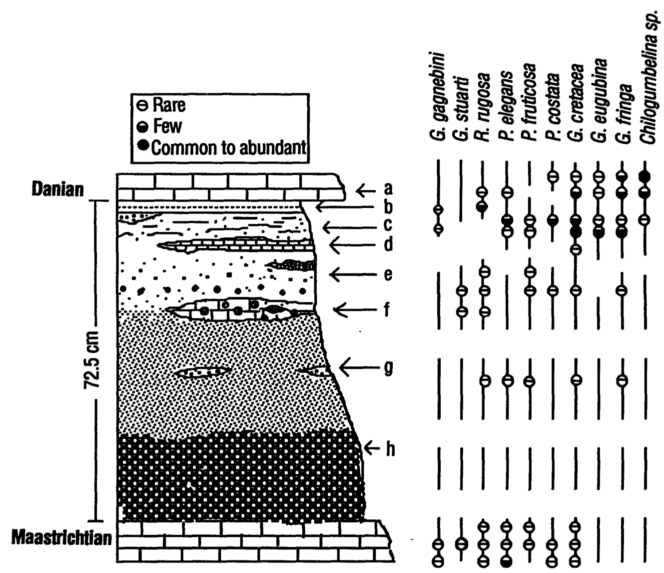

Fig. 1. Sketch of the measured stratotype section of the K-T boundary layer at Beloc: a, limestone; b, fine clay (2 cm thick) layer that also has the greatest concentration of Ir (*8*); c, laminated sandy marl (7.5 cm thick) with small lenses of coarse spherules; d, white chalk lens (4 cm thick); e, graded sandy marl with small lenses of micrite; f, coarse spherule-bearing marl lens with included small lenses of micrite; g, fine spherules in a sandy marl (this layer also contains lenses of coarse spherules); h, coarse, brown-colored, spherule-rich smectite layer (ejecta layer). 'Rare' means 2 to 4 specimens, 'few' means 5 to 10, and 'common to abundant' means >10 per cubic centimeter of dry bulk sediment.

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are prevalent, but teardrop- and dumbbell-shaped spherules are fairly common. In several spherules, the outermost 0.1 mm or so is concentrically layered, whereas the inner parts are free of any structure. Most of these spherules are completely altered to a brown smectite, and have a translucent shiny appearance. The large spherules generally contain smaller spherules within them.

The spherules from the lower part of the boundary bed are too altered to yield reliable original composition of the glass, but electron microprobe data (Table 1) of their alteration product or clay allow some overall constraints to be placed on the composition of the original silicate glass. The relatively high MgO and FeO contents preclude an original rhyolitic glass, whereas the SiO_2 content is too high for the original material to be ultramafic. These values may imply that the impact site contained some mafic or andesitic rocks; in either case, some CaO was probably lost during diagenesis and crystallization of interstitial calcite.

Approximately 10% of the spherules from the middle and upper parts of the boundary bed contain unaltered glass cores (*9, 15*). These spherules occur where carbonate is most abundant in the matrix (*16*). In several spherules the glass is completely surrounded by massive calcite, which appears to have effectively prevented access of ground water to the core of these spherules. Most (90%) of the clay spherules are, however, hollow, and their cores are either empty or lined with drusy calcite. The color of the glass varies from deep brown to (rarely) deep yellow. Individual glass fragments are fairly homogeneous in composition, and are consistently free of any crystals or microlites (*17*). This characteristic and the morphology of the glass spherules (Fig. 2) clearly indicate that they are tektites. Empty or calcite-lined vesicles occur in both yellow and brown glass, and vesicle abundance is not related to the glass color (*18*). As noted by other workers (*9, 15*), the glasses typically have a cratered surface with sharp ridges (Fig. 2).

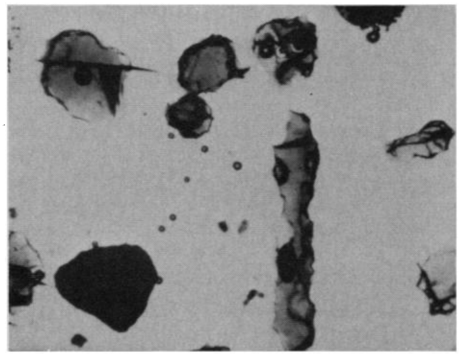

Fig. 2. Photomicrograph showing some of the glass fragments recovered from the cores of spherules. The long fragment in the center was recovered from a dumbbell-shaped spherule.

The high silica content (63 to 67%) and abundance of other major and minor elements in the glasses with various shades of brown (Table 1) is also similar to that of andesites or graywackes but it is not yet clear whether the altered spherules from the lower part were originally similar in composition to the fresh glassy spherules of the upper part of the marker bed. The average upper continental granitic crust has a much higher K_2O content than the high-silica tektite glasses. A significant amount of K_2O is unlikely to have been preferentially lost through vaporization during tektite formation because Na_2O, another equally volatile oxide, is comparably high in the tektite glasses. Therefore, a granitic continental crust as parent rock can be ruled out.

The rare yellow-colored tektite glasses that we analyzed contain about 25% CaO; values as high as 30% have been reported (*15*). Such high CaO content provides further support for a tektite origin of the spherules because no terrestrial volcanic rock with such a composition has been found (*9, 15*). Our data support the inference that these glasses were produced by fusion of a mixture of siliceous and carbonate rocks (*15*). However, common shale, granite, and the mean upper continental crust, or mixtures of these with calcite, cannot be fused to produce glasses with MgO contents similar to those of the high Ca glass (Fig. 3) (*19*). Such composition is better explained if platform carbonates rich in dolomite rather than calcite are used as one of the end members. Thus, we surmise that the impact site was a mixture of rocks of mainly andesitic composition and dolomitic rocks.

Microfossils occur primarily in the upper part of the bed. Both Cretaceous taxa, such as *Rugoglobigerina rugosa*, *Pseudotextularia elegans*, *Pseudogumbelina costatata*, *Racemigumbelina fruticosa*, and *Gumbelitria cretacea*, and Tertiary species (for example, *Globigerina inconstans*, *G. fringa*, *G. eugubina*) are found. The different species are found primarily in calcareous lenses and toward the top of the sequence (*6, 7*). The relative abundances of planktonic foraminiferal taxa (Fig. 1) verify earlier observations in the Caribbean region (*7, 20*) and elsewhere (*21*) that the Cretaceous and Tertiary microfossils are mixed at the boundary (*22*). We infer that coeval occurrences of the two series of taxa imply that either an event caused mechanical mixing after the occurrence of the Tertiary taxa, or that the Cretaceous and Tertiary species overlapped within the conventional upper limit of the Maastrichtian (*23, 24*). The data at hand suggest a combination, because of the distinct record of extensive bottom reworking, discussed below.

Key features for understanding the origin of the boundary layer at Beloc (not in order

Table 1. Microprobe analyses of altered spherules and glassy tektites in the Haitian layer and comparison with some crustal rocks. A 10-μm-diameter beam was used to analyze clay spherules. For glass analysis a 2-μm beam diameter was used. All elements were analyzed by wavelength dispersive spectrometry using the ARL SEMQ microprobe at Florida International University. Na and K were always analyzed first. Natural andesitic and basaltic glasses were used as standards. Andesites are analyses of Cretaceous rocks in the Greater Antilles. Other crustal rocks are mean compositions. All iron reported as FeO.

Oxides (wt%)	Clay spherule	Yellow glass	Brown glass	Continental crust*	Ocean crust*	Antilles andesites† 1	Antilles andesites† 2	Platform carbonate*	Grey-wackes*
SiO_2	47.08	49.06	63 to 67	65.91	59.67	60.48	64.2	8.2	66.7
TiO_2	0.80	0.64	0.5 to 0.68	0.59	0.87	0.52	0.48		0.6
Al_2O_3	13.18	13.19	15.7 to 16.9	15.63	15.85	15.73	15.7	2.2	13.5
FeO	5.35	5.14	4.5 to 5.2	4.82	6.77	4.44	4.8	1.57	4.94
MnO	0.15	0.16	0.07 to 0.13	0.10	0.17	0.11		0.07	0.01
MgO	5.70	4.09	2.4 to 2.7	2.28	4.02	2.56	3.1	7.7	2.1
CaO	2.32	24.54	5.8 to 7.7	4.10	7.24	5.66	2.7	40.5	2.5
Na_2O	0.15	2.10	2.8 to 3.05	3.15	2.98	4.83	3.8		2.9
K_2O	0.14	0.63	1.7 to 1.8	3.39	2.42	3.60	1.5		2.0
Total	74.87	99.56		100.00	100.00	97.93	96.28	60.24	95.24

*From (*35*) †From (*36*).

of importance) are: (i) the thickness of this layer varies tremendously in a lateral direction although its overall petrographic compositions remain relatively constant; for example, there is no lateral grain size gradation as is seen in turbidites; (ii) microtektites (clay spherules) occur in a nearly pure smectic matrix in the lowermost part; (iii) the bed contains the largest spherules in any K-T boundary bed; (iv) the contacts with the enclosing rocks are sharp; (v) the lithic character changes to a carbonate-rich upper part; (vi) thin elongated lenses of micritic materials occur intermingled with larger lenses of coarse-sized spherules; such lenses have not been found at other K-T boundary layers.

The simultaneous occurrence of shocked quartz, microtektites (commonly as altered clay spherules), and the Ir anomaly within the marker bed at Beloc (*7, 13*) is strong evidence that this bed represents deposits produced by the impact of an extraterrestrial bolide (*1, 2, 9, 15*). Even though significant volcanism occurred at the onset of the Maastrichtian (*25*), there is no compelling evidence at hand to support a volcanic origin for the marker bed at Beloc (*26*). Furthermore, the large size and abundance of the ejecta materials imply that the impact occurred nearby (*3–5*).

The amalgamation of coarse- and finer-sized particles, together with lenses of coherent marls, is an intriguing aspect of the boundary layer at Beloc (Fig. 1). This feature seems to be peculiar to the Beloc and Brazos River, Texas, sections (*27*). Such structures are known to occur in subaqueous debris flow or incoherent slump processes

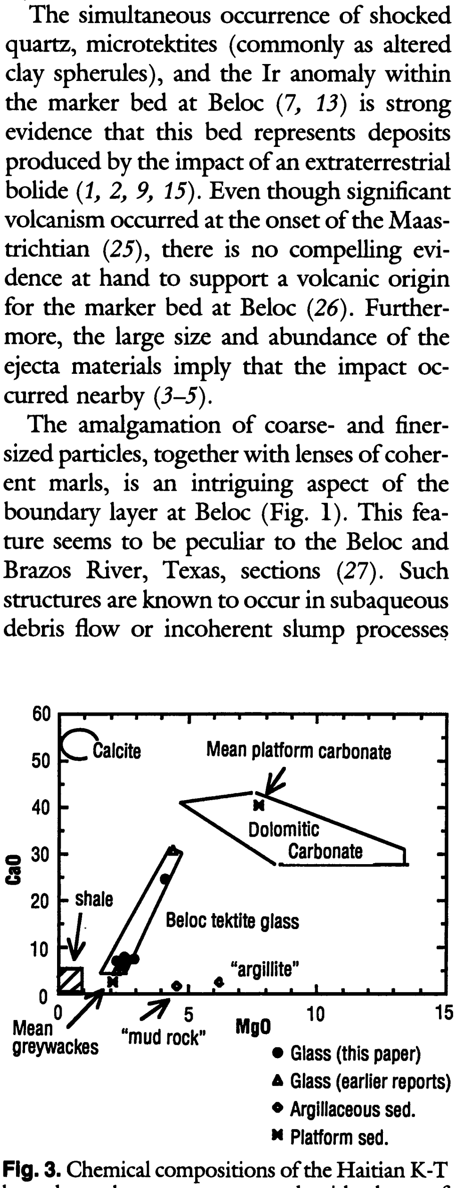

Fig. 3. Chemical compositions of the Haitian K-T boundary glasses are compared with those of other rock types. The field marked "Beloc tektite glasses" includes data obtained in the present study as well as those given by Izett *et al.* (*9*) and Sigurdsson *et al.* (*15*). 'Argillite' and 'mudrock' compositions are from Sigurdsson *et al.* (*15*). The fields for the sedimentary rocks and calcite are from Carmichael (*35*).

(*14*) in which the original stratification is destroyed and the material becomes a chaotic mixture of water and particles of various sizes. By analogy, the structures in the marker bed at Beloc thus suggest that significant subaqueous flow processes recurred over a protracted period (perhaps several thousand years) after initial deposition of the bed. Additional evidence in support of this interpretation is that the topmost Ir-rich layer (Fig. 1), which accumulated last from the impact fallout, became compacted enough to become dislocated and redeposited, in part, as coherent lenses. The widespread and random occurrence of discontinuous lenses of reworked microspherules implies that these lenses became amalgamated within a finer matrix of fine micrite and microspherules due to varying energy conditions. The complex faunal distribution in the marl lenses also points to the unusual reworking process at Beloc, a phenomenon commonly observed in the ocean basins at that time (*7, 20, 21, 23, 24, 27, 28*). Based on these data, we interpret the upper part of the Beloc marker bed as the result of gigantic subaqueous flow processes that occurred after the initial effects of the bolide impact. The presence of eupelagic sediments in the marker bed and faunal characteristics indicating a water depth in excess of 2 km (*6, 7, 29*), also suggests that 2 km is the minimum depth affected by the process that caused the reworking. In ordinary tsunamis vertical movement of fluid particles is negligible compared with the horizontal movement; in wind-generated storms the energy quickly dissipates with depth; thus, such processes could not have caused the structures at Beloc.

Ahrens and O'Keefe (*30*) calculated that an oceanic impact with a 10-km bolide (*1*) would result in impulsive-like giant tsunamis with initial amplitudes of about 4 km, the solitary water-wave stability limit in the deep ocean. The structures observed in the marker bed at Beloc are compatible with such a hypothesis, because they require a process violent enough to generate large waves of translation (*14*) that could cause significant physical disturbances in the ocean bottoms (*20, 21, 28*). We infer that it is this process that caused the initial mixing of the ocean bottoms as observed worldwide at the K-T boundary event (*20, 21, 28*). The exact expression of sediment mixing in the ocean basins would have depended not only on local physiographic factors and proximity to the collapsing impacted edifice, but also on paleobiogeography of that time. Because of the random effects of mixing, the stratigraphy in sections formerly believed to be continuous is now controversial (*23*). In this regard the magnitude of the structures observed in Haiti (*7, 31*), Cuba (*32*), and at Brazos, Texas (*27*), but not elsewhere (for example, Gubbio), are compatible with an impact site in the Caribbean area (*3, 5*). Thus, the composition, textures, and structures observed in the lower part of the boundary bed at Beloc, Haiti, can be explained as related to the initial disruptive effects of the Caribbean impact. The melt ejecta materials travelled a relatively short distance and represent the original fallout that is mixed with a small component of volcanic glass. Likewise, the structures observed in the upper part of the bed apparently resulted from another major disruptive event nearby. The geologic record left in rocks deposited at great depth in the Caribbean basin area of that time (*7, 27, 31, 32*) implies that the intensity of water displacement during this later reworking event was perhaps as much as in the initial impact event (*1*).

We conclude that a second generation of tsunamis may have been responsible for further mixing that has led to a confusing biostratigraphic record of oceanic sediments. Furthermore, this chain of events may have caused thorough oceanic mixing with long-lasting effects on ocean water chemistry and biotic productivity for as much as 500,000 years (*33*). This time is sufficient to have allowed partial lithification of the original ejecta materials redeposited in the upper part of the Beloc boundary bed. The triggering mechanism of such second-generation tsunamis of unusual magnitude is unclear. It is conceivable that they are related to subsequent tectonic or volcanic events (*34*) in the Caribbean, as crustal rebound and dislocation continued through time. However, if the energy released by such phenomena was insufficient to affect the oceans over a large region, perhaps multiple and closely spaced impacts may have occurred. High-resolution biostratigraphy coupled with isotopic data at selected key sites worldwide should shed significant light on the role of the individual factors outlined above.

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8 January 1991; accepted 28 March 1991

Identification of Widespread Pollution in the Southern Hemisphere Deduced from Satellite Analyses

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Vertical profiles of ozone obtained from ozonesondes in Brazzaville, Congo (4°S, 15°E), and Ascension Island (8°S, 15°W) show that large quantities of tropospheric ozone are present over southern Africa and the adjacent eastern tropical South Atlantic Ocean. The origin of this pollution is widespread biomass burning in Africa. These measurements support satellite-derived tropospheric ozone data that demonstrate that ozone originating from this region is transported throughout most of the Southern Hemisphere. Seasonally high levels of carbon monoxide and methane observed at middle- and high-latitude stations in Africa, Australia, and Antarctica likely reflect the effects of this distant biomass burning. These data suggest that even the most remote regions on this planet may be significantly more polluted than previously believed.

WIDESPREAD AIR POLLUTION HAS generally been regarded as an anthropogenic phenomenon identifiable with industrialized nations, primarily in the Northern Hemisphere. Recent satellite measurements of ozone (O_3) in the troposphere (*1*) define distinct plumes emanating from North America, Asia, and Europe. When these data are compared with available ozonesonde measurements at sites with enough data to derive a climatology of free tropospheric O_3, the differences in agreement between the satellite analysis and the ozonesonde measurements are generally smaller than 15% (*1*). The satellite measurements also indicate that a large amount of O_3 pollution comes from tropical southern Africa and that this source is most pronounced during the dry season from August to October. In addition, elevated concentrations of carbon monoxide (CO) and meth-

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