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Spatial and Temporal variations of the Haitian K/T Boundary record: implications concerning the event or events

Variaciones espaciales y temporales del registro del límite K/T en Haiti: implicaciones acerca del evento o eventos

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Abstract

Evidence of physical disruptions caused by the postulated bolide impact at the close of the Maastrichtian is clearly defined in the record of the K/T boundary (KTB) layer from different sites in the Southern Peninsula of Haiti. Lithologic and biostratigraphic record of the KTB layer from the different sites also show varying degrees of mixing, yielding faunal components within a time range consistent with bioevents characteristic of the traditional boundary zone equivalent to the uppermost part of the *Abathomphalus mayaroensis* Zone, part of the *Guembelitria cretacea* Zone, and the *Parvularugoglobigerina eugubina* Zone, respectively. The calcareous nannofloras also show transitional taxa that concur with the foraminiferal data, and are indicative of the *Micula murus* and *M. prinsii* Subzones as well as the CP1a, *Cruciplacolithus primus* Subzone, of the Early Paleocene. The Boundary layer shows variation in thickness with a maximum of 75cm at the Beloc stratotype, and the topmost part of the main tektite layer is coincident with an iridium peak. Geochemical analyses and radiometric dating have also demonstrated that the spherules are tektites (Premo and Izett, 1991) that can be chronologically related to the impact event recorded at Chicxulub, Yucatan, Mexico, 65 million years ago. Most importantly faint primary sedimentary structures within the boundary layer are constant at all outcrops, but discrete spatial differences exist even within short distances. In addition, in the areas adjacent to the stratotype (Platon Piton and Madame Toussaint) a volcanogenic layer occurs below the main tektite layer assigned to the Chicxulub event, and it also shows conspicuous, as well as cryptic, cross-lamination indicative of complex, multiphase, subaqueous flow processes that affected sedimentation of the layers similar to the KTB layer.

Such structures are known to characterize oscillatory wave processes that affect cohesionless sediments. Water motion associated with seiche is the only known modern analog of a subaqueous flow that provides a plausible mechanism to explain how various levels of the water column in a large basin can oscillate to develop the structures observed. Because of the magnitude of the bolide impact, "megaseiches" must have developed in the oceans worldwide, and subsequently more localized "megaseiches" developed during major crustal readjustment. These phenomena may thus explain the heterogeneity of patterns and faunal discrepancies observed at KTB sites of different water depths worldwide. The structures represent a record of water movement and resuspension of sediment at different times. As observed in smaller-scale modern seiche, various oscillatory modes controlled the duration and attenuation of the water movement, the magnitude of bottom traction and resuspension that led to complex sedimentary structures and reworking of the microfossils.

Keywords: mixing, tektites, impact, boundary layer, volcanogenic layer, structures, seiche, megaseiche, resuspension.

Resumen

El registro en la capa del límite K/T (KTB), en diferentes localidades de la Península Meridional de Haití, muestra claras evidencias de disrupciones físicas causadas por el impacto postulado de un bólico al final del Maastrichtiense. Tanto el registro bioestratigráfico como el litológico de la capa KTB, en diferentes localidades, muestra también diversos grados de mezcla, con componentes faunísticos de edades congruentes con los bioeventos característicos de la transición del límite, equivalentes a la parte terminal de la Zona de *Abathomphalus mayaroensis* y partes de las Zonas de *Guembelitria cretacea* y de *Parvularugoglobigerina eugubina*. La nanoflora calcárea también muestra taxones de la transición, concurrentes con los datos de foraminíferos, e indicativos de las Subzonas de *Micula murus* y *Micula prinsii*, así como de la Subzona de *Cruciplacolithus primus* (CP1a), del Paleoceno basal. La capa del límite tiene variaciones en su potencia, con un máximo de 75cm en el estratotipo de la Formación Beloc, y a techo de la capa principal tectítica hay un máximo de iridio. Los análisis geoquímicos y la datación radiométrica han demostrado también que las esférulas son tectitas (Premo e Izett, 1991) que pueden estar relacionadas cronológicamente con el evento de impacto registrado en Chicxulub, Yucatán, México, hace 65 Ma. Aún más, las delicadas estructuras sedimentarias primarias en la capa del límite son constantes en todos los afloramientos, aunque hay diferencias espaciales incluso a corta distancia. Además, en las áreas adyacentes al estratotipo (Platon Piton y Madame Toussaint) se encuentra una capa volcanogénica, bajo el nivel tectítico principal relacionado con el evento de Chicxulub, que muestra una laminación cruzada, tanto conspicua como críptica, indicativa de procesos de flujo complejos, multifásicos y subacuáticos que afectaron a la sedimentación de forma parecida a la del lecho KTB.

Se conocen tales estructuras como características de la acción de ondas oscilantes sobre la cohesión de los sedimentos. El movimiento de las aguas asociado con un seiche es el único análogo actual conocido de un flujo subacuático que proporcione un mecanismo plausible para explicar el que varios niveles de la columna de agua, en una gran cuenca, pueden oscilar para desarrollar las estructuras observadas. Dada la magnitud del impacto del bólido, debieron desarrollarse 'megaseiches' en los océanos a escala mundial y, subsecuéntemente, se producirían otros 'megaseiches' más localizados durante los reajustes principales de la corteza. Esos fenómenos pueden así explicar la heterogeneidad de pautas y discrepancias faunísticas observadas en varias localidades del KTB, de distinta profundidad de depósito, en el mundo. Las estructuras representan un registro de los movimientos del agua y de la resuspensión de los sedimentos en momentos diferentes. Tal como se ha observado en seiches modernos a pequeña escala, la duración y atenuación de los movimientos del agua y la magnitud de la tracción y resuspensión estuvieron controlados por diversos modos oscilatorios que dieron lugar a complejas estructuras sedimentarias y al retrabajamiento de los microfósiles.

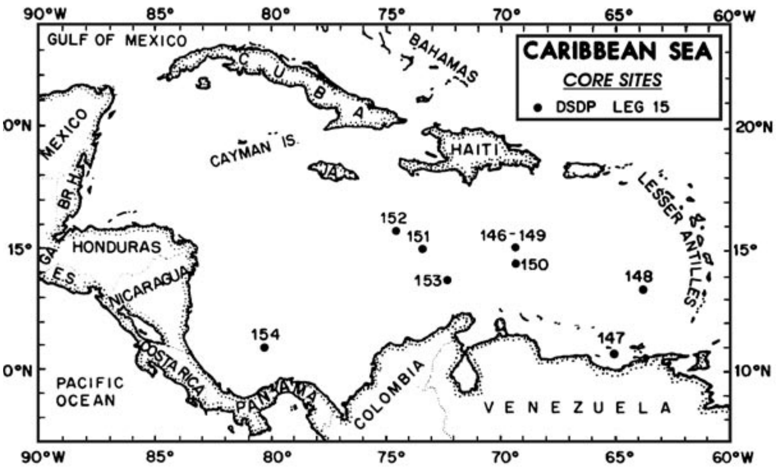
Palabras clave: mezcla, tectitas, impactos, capa del límite, capa volcánica, estructuras, seiche, megaseiche, resuspensión.

1. Introduction

The lithologic record of cores recovered during Deep Sea Drilling Project Leg 15 (Edgar *et al*., 1973) at Sites 151, 152, and 153 (Fig. 1) showed physical evidence of a major disruptive event that affected the Caribbean Sea area toward the close of the Maastrichtian. Worldwide implication of these observations (Edgar *et al*., 1973; Premoli-Silva and Bolli, 1973; Maurrasse, 1973) only became evident later, because of the postulation of a global catastrophic hypothesis caused by a bolide impact (Alvarez *et al*., 1980). When Alvarez *et al*., (1980) published their provocative paper on the Cretaceous/Tertiary boundary of Gubbio, Italy, their key evidence was based on an Iridium spike that formed the basis for their bolide impact hypothesis. Such impact implied a major disruptive global effect, thereby providing a unifying catastrophic mechanism to explain evidence in the stratigraphic record that suggested a worldwide physical event occurred at the close of the Maastrichtian.

Alvarez work gave the impetus to KTB research, and since 1980 a voluminous literature has developed on the subject, as the boundary has been positively identified at sites worldwide, and a compatible impact site has been located at Chicxulub in northern Yucatan, Mexico (Hildebrand and Boynton, 1990; Hildebrand *et al*., 1995). In addition to the previously well-reported dramatic biotic turnover, or mass extinction (Molina *et al*., 1998), its distinct characteristics have been found to include a combination of all, or some of the following: presence of microtektites, shocked quartz (Izett, 1991), an iridium spike, sudden increase in clay with geochemical signatures of an origin associated with carbonaceous chondrites (Alvarez and Asaro, 1990; Luck and Turekian, 1983; Shykolyukov and Langmuir, 1998; and others). The general consensus is that the global record of the impact that produced the tektites appears to be synchronous (Hall and York, 1991; Swischer *et al*., 1992), but the complexity of its characteristic signals includes serious micropaleontological inconsistencies with mixed biotic assemblages that perpetuate divergence of interpretations, and raise doubts on the timing and real causal mechanisms of the biotic turnover that characterizes the boundary. Indeed, often the biostratigraphic signals are difficult to resolve because of a hiatus in deposition, or sediments are highly reworked, and distinct taxonomic successions are not clearly defined.

Such characteristics are well represented in the boundary layer of the Beloc Formation (Fig. 2) from diverse locations in the Southern Peninsula of Haiti (Maurrasse,



Site	Coordinates	Depth (m)	Location
146	15°06’ N 69°22’W	3,949	Venezuela Basin
147	10°42’ N 65°10’W	892	Cariaco Trench
148	13°25’ N 63°43’W	1,232	Aves Ridge
149	15°06’ N 69°21’W	3,972	Venezuela Basin
150	14°30’ N 69°21’W	4,545	Venezuela Basin
151	15°01’ N 73°24’W	2,029	Beata Ridge
152	15°52’ N 74°36’W	3,899	Nicaragua Rise
153	13°58’ N 72°26’W	3,932	Aruba Gap
154	1°05’ N 80°22W	3,338	Colombian Basin

Fig. 1.- Caribbean Deep-Sea Drilling Project Leg 15, drill sites.
Fig. 1.- Estación 15 del DSDP, Caribe

1982b; Maurrasse *et al.*, 1979/1985; Izett *et al.*, 1990; Hildebrand and Boynton, 1990; Maurrasse and Sen, 1991a; 1991 b; Sigurdsson *et al.*, 1991b; Lamolda *et al.*, 1997b, and others).

The standard initial outcrop of the K/T record at Beloc (Fig. 3) characterized by the tektite layer and an iridium anomaly (Fig. 4) has been discussed in numerous published studies listed in the references, and its coevality with the Chicxulub event has also been established with Argon-40/Argon-39 dating (Izett *et al.*, 1991; Swisher *et al.*, 1992; Dalrymple, *et al.*,1993) with respective ages of 64.5 to 64.2 MA for tektites from Haiti and the Northwest U.S, and 65.0 MA for the Chicxulub tektites (Swisher *et al.*, 1992). These concurrent ages thus support the singularity of the event that gave rise to the boundary layer marking the end of the Cretaceous Period.

Since documented KTB record in the published literature clearly implies that vigorous disruption of the water column reached from the shelf to abyssal depths of the ocean basins (Bourgeois, *et al.*, 1988; Maurrasse and Sen, 1991b; Alvarez *et al.*, 1991b; Smit *et al.*, 1992 and others), this point is critical to unravel the type of water movement or hydrodynamics of the basins that led to mixing, a problem which fuels further controversies concerning the biostratigraphic reliability of the event marker (Glen, 1994), and its duration (Kent, 1977). Different mechanisms have been invoked to explain the inconsistencies, including volcanism (Graup *et al.* 1989) and the possibility of multiple events (Maurrasse and Sen 1991a; Izett, 1991; Smit *et al.*, 1992; Albertao *et al.*, 1994; Lopez-Oliva and Keller, 1996; Bruns *et al.*, 1997; Molina *et al.*, 1998, and others). One of the problems impeding adequate understanding of the KTB reworking dilemma, however, is a lack of historical records that could be used as proxies to explain the genesis of amalgamation that so often characterizes the boundary level. Based on modern sedimentary records, none of the well-known types of deposits from large-scale turbulent flow processes such as tsunamis and turbidites (Ericson *et al.*, 1961; Dott, 1963; Bouma and Brower, 1964; Horn *et al.*, 1969; 1971; 1972) provides a satisfactory counterpart to explain the mechanism for the complex KTB layer. Taken account of all the facts in support of a major event that caused extraordinary disruptions at the end of the Cretaceous, there is not yet a unifying mechanism to explain the sedimentological and

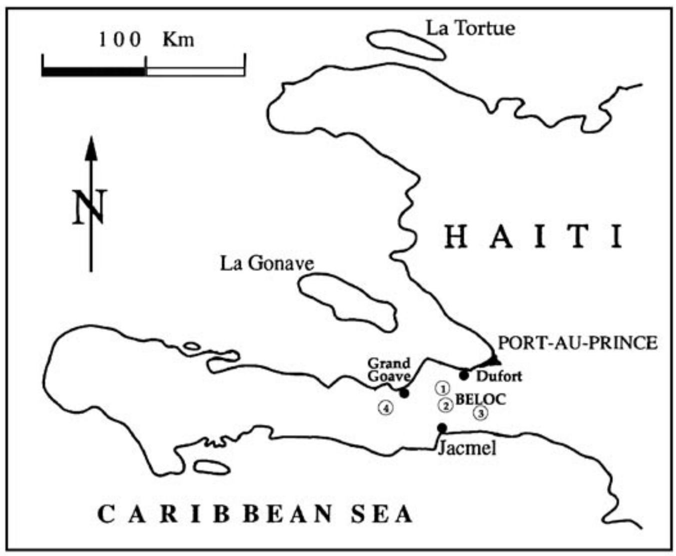


Fig. 2.- Sites of the Beloc Formation with outcrops of the Cretaceous/Tertiary boundary layer.1, Beloc outcrop adjacent to the Village; 2, Beloc stratotype and Platon Piton; 3, Beloc outcrop at Riviere Gosseline; 4, outcrop at Mme Toussaint, near Grand Goave.
Fig. 2.- Localidades con afloramientos de la capa del límite Cretácico/Terciario, Formación Beloc. 1: afloramientos adjacentes a la aldea de Beloc; 2: Estratotipo de la Fm. Beloc y Platón Pitón; 3: Afloramientos de la Fm. Beloc en el río Gosseline; 4: afloramientos en Mme. Toussaint, cerca de Grand Goave.

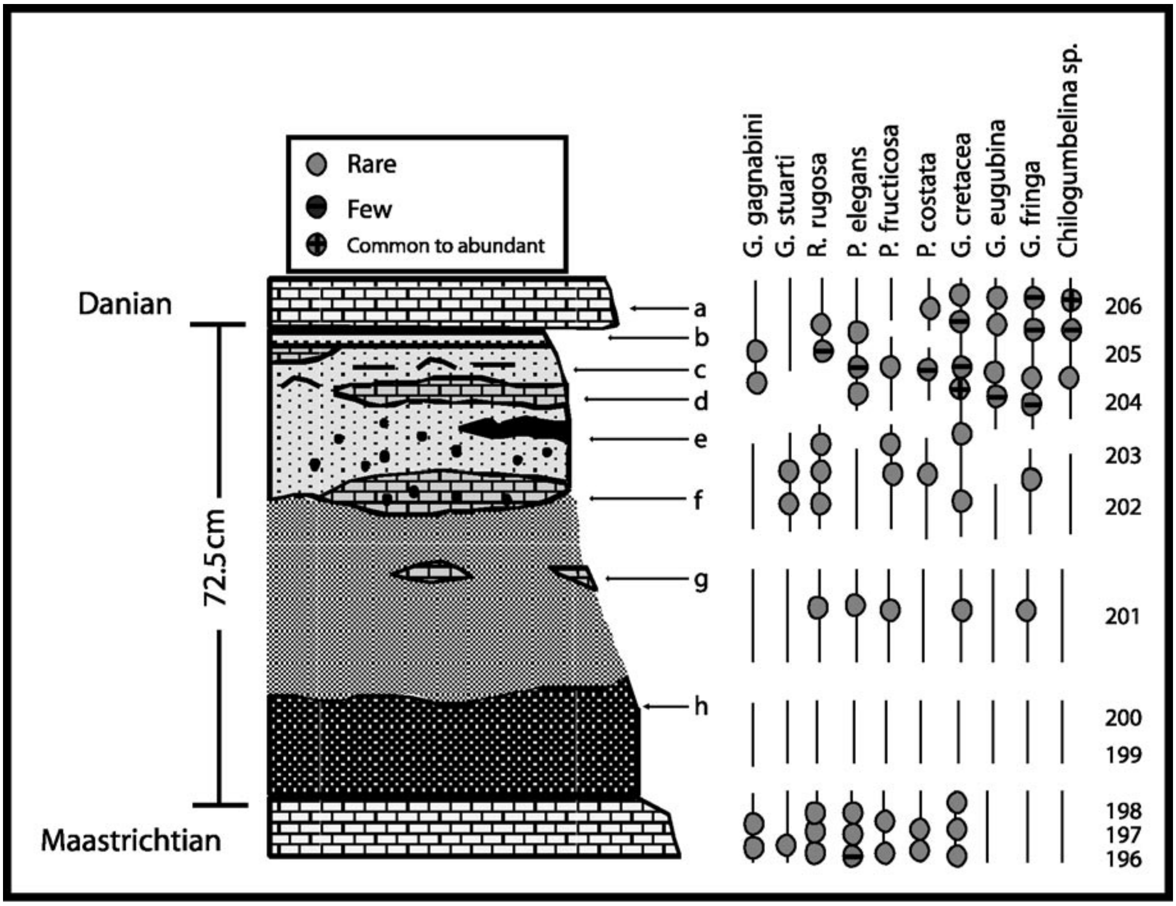


Fig. 3.- Sketch of the boundary layer measured at the Beloc stratotype section: a, Danian limestone; b, fine, 2-cm-thick clay-rich layer with the highest iridium values (see Fig. 4); c, laminated sandy marl; d. white chalk lens; e, graded sandy marl; f, coarse tektite-bearing marl lens, may also contain fresh glass at center of some tektites only altered at periphery; g, fine tektites in a sandy marl; h, coarse, brown-colored tektites altered into smectite. (Adapted from Maurrasse and Sen, Science, 1991a).

Fig. 3.- Esquema de la capa del límite medida en la sección estratotipo de la Fm. Beloc: a, calizas danienses; b, capa fina rica en arcilla, 2cm de espesor, con altos contenidos en iridio (ver Fig. 4); c, margas arenosas laminadas; d, creta blanca lenticular; e, margas arenosas gradadas; f, lechos lenticulares de margas con tectitas gruesas, en la parte central de algunas tectitas puede haber vidrio inalterado, mientras la periferia está alterada; g, marga arenosa con tectitas pequeñas; h, tectitas gruesas oscuras alteradas a esmectita. (Adaptado de Maurrasse y Sen, Science, 1991a).

biostratigraphic evidence of sites worldwide that have yielded different degrees of pervasive reworking. In view of this fact, the question remains as to how the Chicxulub impact event could have induced basin-wide physical disruptions worldwide, and why the actual record of the event can be different at different sites?

Here we further discuss the characteristics of the boundary layer at Beloc (Figs. 2, 3, 5 - 7) in relation to the global event and we propose "megaseiche" as large-scale mixing processes to explain the KTB discrepancies. We also report the presence in the Beloc Formation of an important volcanogenic layer that displays primary flow structures similar to those of the superjacent KTB layer. Conformity of appearance of the flow structures associated with the two distinct layers further supports the conclusion that the basin was capable to enter in oscillation in response to a major physical disturbance, in this case a volcanic eruption in the Caribbean area. The volcanogenic layer thus provides additional evidence to further our understanding of the complex dynamic aqueous processes of megaseiches in the ocean basins that are affected by major physical events, such as the impact at the close of the Mesozoic, and subsequent effects to the beginning of the Tertiary.

2. Methods

Studies were carried out on four different outcrop areas (Fig. 2) in the Southern Peninsula of Haiti that show variation in the physical make up of the KTB layer. Rock colors were given following the standard color chart of the Geological Society of America (Anonymous, 1979). Samples collected were treated in the laboratory for either standard (38 micrometer-sieve mesh) microfossil preparations of soft sediments, or for standard thin sections in indurated rocks. Washed residues were examined under high-magnification binocular microscopes and SEM, and thin sections were examined under the polarized light microscope. Some acid-etched thin sections were also analyzed with the help of a SEM JSM-5900-LV for semi-quantitative chemical composition. Carbonate analyses were carried out with a Leco CR-412 analyzer. The taxonomy used for radiolarian taxa is after Pessagno (1963; 1976); and Foreman (1968; 1975).

3. Lithostratigraphy

Rocks in the Southern Peninsula where the KTB layer occurs are part of the Beloc Formation (Maurrasse, 1982a), which overlies a suite of complex igneous and sedimentary sequences of the Dumisseau Formation (Maurrasse *et al.*, 1979) that consists primarily of tholeithic basalts (Sen and Maurrasse, 1988).

The lithologic sequence of the Beloc Formation occurs over a wide area of the Southern Peninsula of Haiti (Fig. 2), where at the field scale it displays a distinct physical break or "marker bed" of variable thickness, between 10 and 75 cm. At the type locality, the Beloc Formation includes a monogenic conglomerate, 1 to 2 meters thick that overlies and intergrades with weathered rocks of the Dumisseau Formation. While the lithologic sequence as a whole varies little in color, between very pale orange (10YR 8/2) and grayish orange (10YR7/4), the marker bed or boundary layer is clearly distinct with darker shades of olive gray (5Y4/2), depending on the humidity conditions of the outcrops (Maurrasse, 1982b). Beds in the lower part of the sequence vary from about 3cm to 100 cm in thickness, but become more even, from about 10cm to 20cm, toward the upper part. Outcrops of the KTB layer occur along the main road to the city of Jacmel, and on the steep mountain slopes in the vicinity of the village of Beloc. They are discontinuous due to intense thrust faulting that cause significant vertical displacement and repetition of units that are not readily apparent because of the homogeneity of facies. The sequence consists of sparse foraminiferal nannoplankton limestones of variable indurations. The Cretaceous portion also contains variable amount of radiolarians, and intermittent dark brownish gray chert stringers. At the field scale, the boundary layer is easily distinguished from the enclosing limestones and close observation reveals extensive heterogeneity (Maurrasse and Sen, 1991a), which are best observed on undisturbed older exposed surfaces. The KTB layer shows sharp contrast in color, particularly in the lower part that is composed of pure weathered microtektites, whereas the upper part is lighter

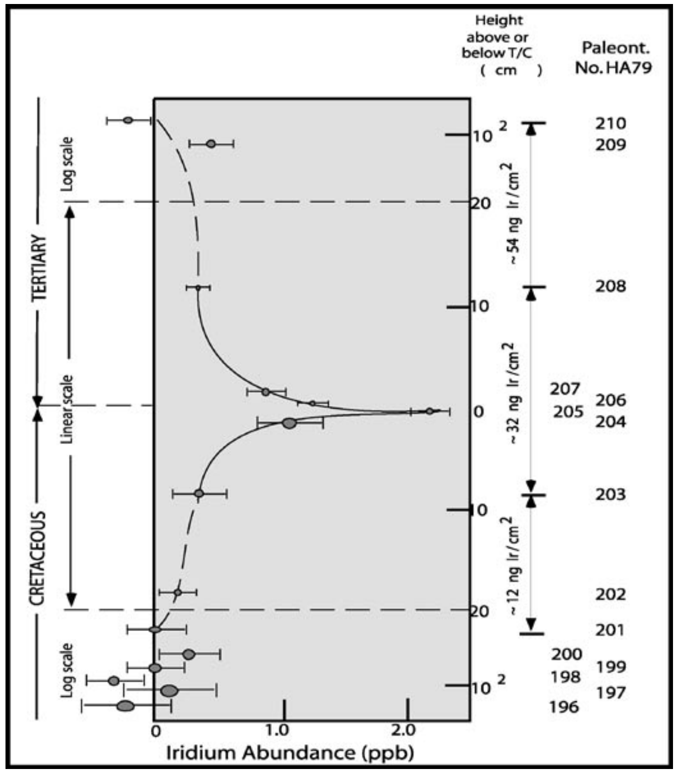


Fig. 4.- Iridium anomaly at the K/T boundary layer stratotype section. Samples are same as those shown in Fig. 3. Data from Frank Asaro.

Fig. 4.- Anomalía de iridio en la capa del límite K/T en la sección del estratotipo. Las muestras son las mismas que se muestran en la Fig. 3. Datos de Frank Asaro.

due to increasing carbonate content. Coarse components consist essentially of planktonic foraminifers, and fewer radiolarians (Fig. 8), and the relative abundance and preservation of the foraminifers is consistent with similar sediments deposited between middle and lower bathyal depths of modern ocean basins. The maximum thickness of the KTB layer at the locality called Beloc Classic (Fig. 2) consists predominately of altered microtektites, which may occasionally have well-preserved glass (Hildebrand and Boynton, 1990; Maurrasse and Sen, 1991a; Sigurdsson *et al.*, 1991b; Lamolda *et al.*, 1997a, and others). Argon-40 /Argon-39 dating (Izett *et al.*, 1991) on fresh glasses shows respective ages of 64.5 +/-0.1 MA to 64.2 MA for tektites from Haiti and the Northwest U.S, and 65.2 +/-0.4 MA for the Chicxulub tektites (Swisher *et al.*, 1992). Similar dating on feldspar from the Hell Creek site in Montana also yielded a date of 64.6 +/-0.2 MA (Hall and York, 1991). Concurrence of these ages thus supports the singularity of the event (Alvarez *et al.*, 1980) that gave rise to the marker bed or boundary layer from distant localities.

Although primary sedimentary structures in the boundary zone are not always easily conspicuous, and therefore

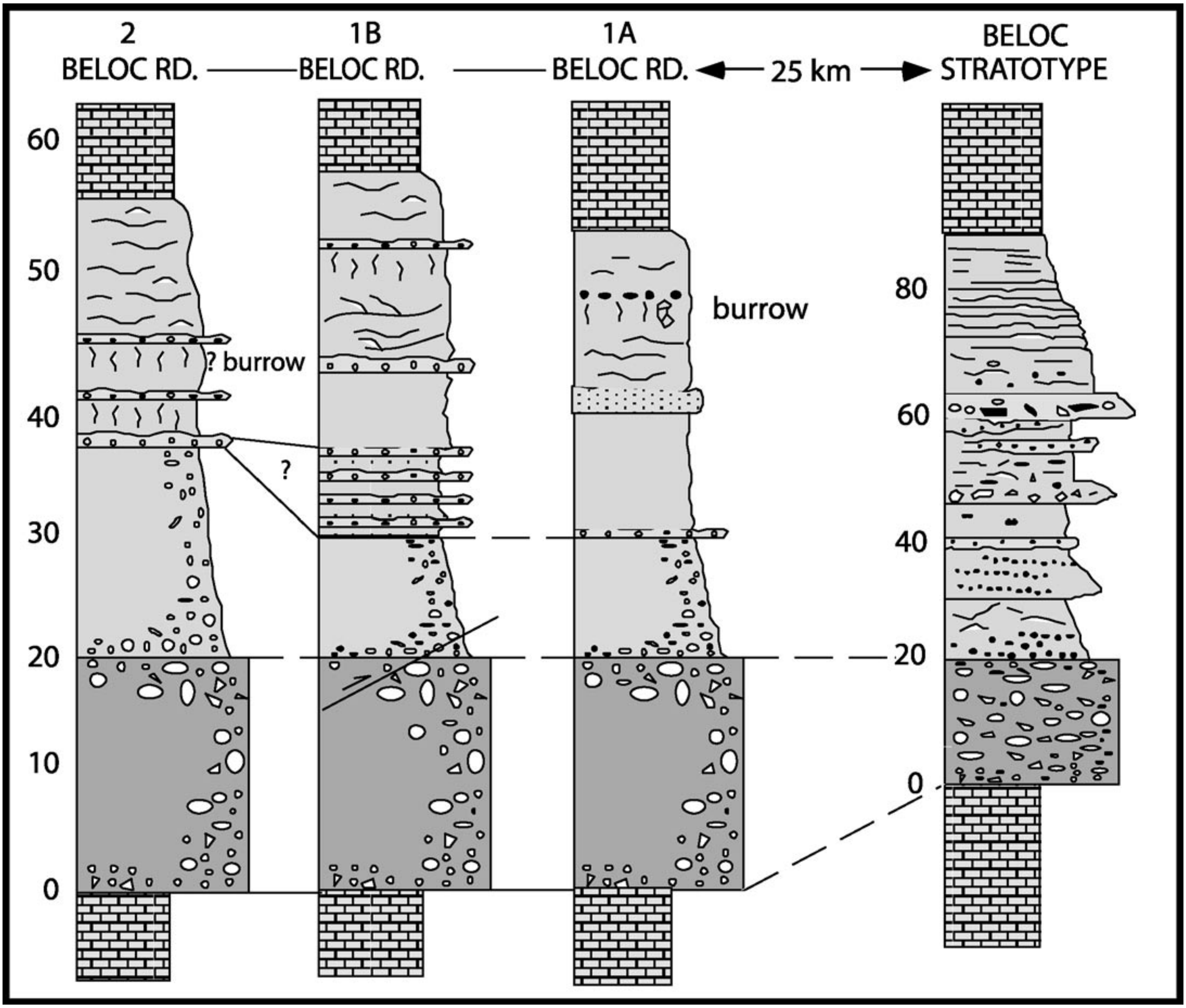


Fig. 5. - Spatial and vertical variations in the boundary layer at localities 1 and 2 shown in Fig. 2.
Fig. 5.- Variaciones verticales y espaciales en la capa del límite en las localidades 1 y 2, ver Fig. 2.

most of the time little attention has been given to their presence, their ubiquity (Bourgeois, *et al*., 1988; Maurrasse and Sen, 1991a; Alvarez *et al.*, 1991a; 1991b; 1992; Smit *et al.*, 1992; Norris *et al.*, 2000; Bralower *et al.*, 2002) is yet another line of evidence that indicates uniformity of response of the ocean bottom to a common causing event. Primary sedimentary structures within the boundary layer of the Beloc Formation consist of cryptic cross-lamination, wavy lamination, and discontinuous lenticular units or lenses parallel to bedding plane with varying grain sizes (Figs. 2 and 5). By comparison, the microstructures, which are constant throughout the Haitian boundary layer at all the different sites, are similar to those found associated with the KTB layer at DSDP Site 151 (Premoli-Silva and Bolli, 1973) located at the southern end of the Beata Ridge, in the Caribbean Sea south of the Southern Peninsula of Haiti. At Site 151 the cross-laminated boundary layer is rich in planktonic foraminifers, which alternate with hematitic smectite laminae derived from the alteration of tektites (Izett *et al.* 1990). In addition, two localities of the Southern Peninsula (Platon Piton and Madame Toussaint), display a volcanogenic layer, up to 75 cm thick, that includes the same type of primary flow structures. The volcanogenic layer is dark olive gray (5Y 5/1) and occurs 7 meters below the KTB layer. In addition to earlier works (Maurrasse *et al.*, 1979/1985; 1982b) more detailed studies of planktonic foraminiferal and nannofossil assemblages allowed to distinguish a complete biostratigraphic succession across the K/T transition (Lamolda *et al.*, 1997b). Furthermore, magnetostratigraphy confirmed the position of the boundary in the reversed magnetic polarity zone correlative to C29r (Van Fossen *et al.*, 1995), as found at Gubbio, Italy (Lowrie and Alvarez, 1981). The stratigraphic position of the KTB is further confirmed by more recent studies of nannoplanktons from other outcrops; e.g., the *Micula murus* (part), *Micula prinsii* and *Cruciplacolithus primus* (part) Subzones (see Aguado *et al.*, this volume).

At Platon Piton, the KTB layer also consists predominately of tektites, and conforms to the composition of the main boundary layer as previously described. In the field and in hand specimens the distinctly olive gray (5Y 5/1) color of the volcanogenic layer is due to the predominance of dark green glassy hornblende crystals (Fig. 9), which constitute up to 42 % of the coarse residues greater than 38 micrometers. Mineralogically, dominant minerals of the coarse residues are mostly dark green euhedral hornblende crystals and fragments that are usually very well preserved, and ilmenite. Composition and textural appearance of the hornblende crystals (average 0.6x0.8 mm) are similar to amphibole phenocrysts found in andesites. Plagioclases make up 15 % of the coarse fraction, and their composition is within the range of plagioclases found in mafic and intermediate igneous rocks. Subspherical quartz crystals (Fig. 10) also occur throughout the layer.

Composition and textural appearance of the amphibole crystals indicate that they were originally phenocrysts in an andesite. Plagioclases (An_{44-57}; average: An_{55}) are also abundant and constitute up to 15 percent of the coarse fraction. The highly angular habit of the volcanic components of this layer is in contrast with tear drop and dumbbell shapes of the microtektites found in the marker bed (Izett *et al.*, 1991) Also, while volcanic fragments have largely remained unaltered, the microspherules are almost all altered except in some calcareous lenses (Maurrasse and Sen, 1991a; Sigurdsson *et al.*, 1991a). Similar to the tektite layer, however, the internal fabric of the volcanogenic layer shows anisotropic distribution of the clasts supported by 2 to 30 % matrix, and their long axis is predominantly sub-parallel to bedding planes. The volcanogenic layer includes a mixed foraminiferal assemblage indicative of the Latest Maastrichtian, as well as scarce radiolarians such as *Archaeodyctiomitra lamellicostata* (Foreman), *Amphipyndax pseudoconulus* (Pessagno), *Dictyomitra multicostata* Zittel; Pessagno, *Dictyomitra* aff. *koslovae* Foreman, *Cryptamphorella* aff. *conara* (Foreman), that also indicate mixing of Campanian to Maastrichtian taxa (Figs. 8a,b). Foraminifers

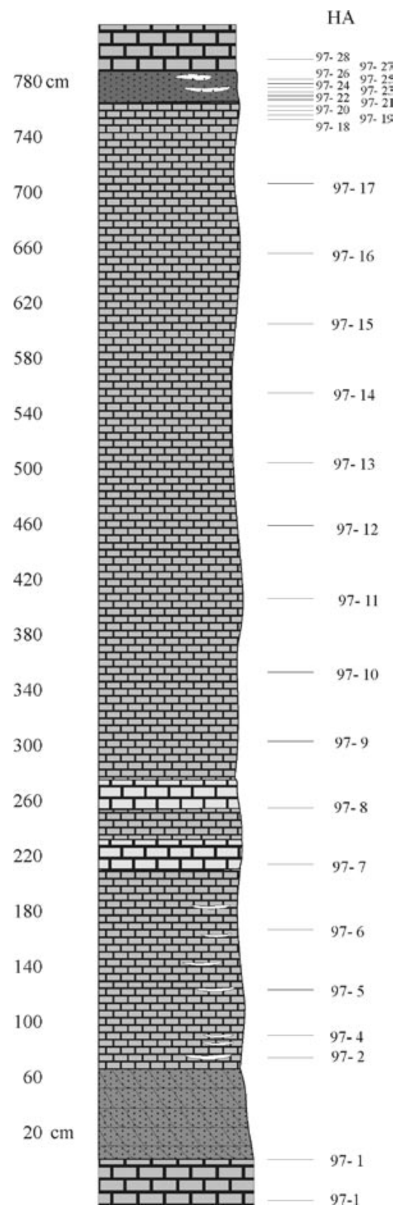


Fig. 6.- K/T boundary section at Platon Piton showing position of volcanogenic layer.

Fig. 6.- El límite K/T en la sección de Platon Piton mostrando la posición del lecho volcanogénico.

found mixed with the volcanogenic elements consist mostly of *Heterohelix* spp, deformed rugoglobigerinids cf. *Rugoglobigerina rotundata* Brönnimann (Fig. 8c) and rare *Trinitella scotti* Brönnimann. Sediments immediately above and below the volcanogenic layer contain well diversified assemblages of planktonic foraminiferas dominated by *Heterohelix* spp., and fewer taxa such as *Rugoglobigerina rugosa* (Plummer), ? *Guembelitria cretacea* Cushman, *Hedbergella* sp. cf. *H. holmdelensis* Olsson, other minute globigerinid-like taxa, and very rare *T. scotti*. Small Hedbegellidae taxa are also present.

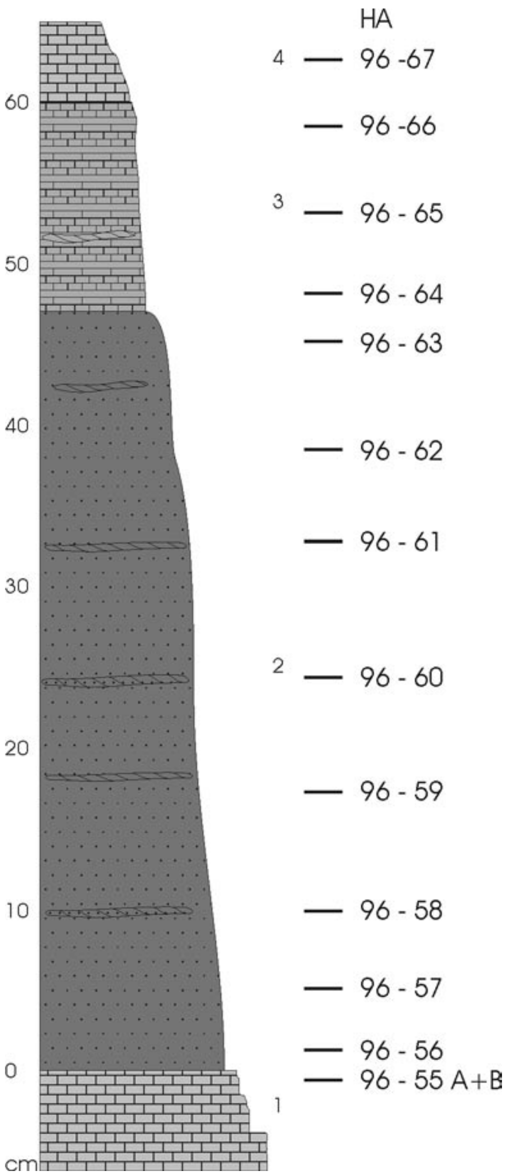


Fig. 7.- Sketch of the volcanogenic layer at locality called Mme Toussaint, site 4 in Fig. 2.

Fig. 7.- Esquema del lecho volcanogénico en el lugar de Mme Toussaint, localidad 4 de la Fig. 2.

In thin section the rocks from either side of the volcanogenic layer are sparse foraminiferal biomicrites with heterohelicids as the dominant group. Marl directly above the volcanogenic layer contains a faunal assemblage with more than 70 percent of the total fauna represented by heterohelicids and well diversified rugoglobigerinids *(Rugoglobigerina macrocephala* Brönnimann, *R. rugosa, T. scotti)*, indicative of the latest Maastrichtian (Masters, 1977). In contrast, only small-shelled planktonic foraminifers (Fig. 8d) occur above the tektite layer at Platon Piton.

Because the components of the facies between the volcanogenic layer and the tektite layer include essentially planktonic foraminifers and nannos, with sparse radiolarians (Figs. 8a, b), these pelagic deposits indicate essentially identical deep-water conditions in the basin between the volcanic event and the subsequent boundary event.

The volcanic layer in the outcrop at Madame Toussaint (Fig. 7) is 60 cm thick with mineralogical and microfaunal characteristics similar to those described at Platon Piton. The mixed volcaniclastic nature of the bed is also clearly defined in its carbonate content that is consistently lower than 5 %, in contrast to values of 25 to 40 % in the infrajacent and superjacent marl and limestone layers.

Arguments can be made for a pyroclastic origin of this layer, although such an origin is inconsistent with the geologic history of that part of the Caribbean at that time (Donnelly and Rodgers, 1978; Donnelly *et al.*, 1990; Pindell and Barrett, 1990), because non-explosive tholeiitic volcanism occurred earlier within the Upper Cretaceous. The exact provenance of these eruptive materials remains to be determined.

4. Discussion

4.1. The Boundary Layer

Geochemical analyses (Hildebrand and Boynton, 1990; Maurrasse and Sen, 1991a; Sigurdsson *et al.*, 1991a; Koeberl and Sigurdsson, 1992; Thorpe *et al*., 1994; and others) have certainly demonstrated the tektite origin of the spherules which can be chronologically related to the impact event recorded at Chicxulub, Yucatan, Mexico 65 million years ago (Swisher *et al.*, 1992). At all sites the tektite layer is also characterized by inconspicuous primary structures such as cross-stratification, wavy lamination, and discontinuous lenticular units or lenses parallel to bedding plane with varying grain sizes (Figs. 3, 5). Since these structures persist throughout the Haitian boundary layer from the different sites, and they are similar to structures found at the K/T boundary at DSDP Site 151 (Premoli-Silva and Bolli, 1973), they indicate that the subaqueous flow process was basin wide regardless of the depth and the material being moved.

4.2. The Volcanic Event relative to the Tektite Event

The volcanogenic layer is distinctive from the overlying tektite-rich boundary layer by the absence of microspherules while dominated by euhedral hornblende, and unaltered minerals. Despite their differences in composition, however, it is most relevant to note that identical structures developed in both layers by a cohesionless movement of particles of similar textures requires identi-

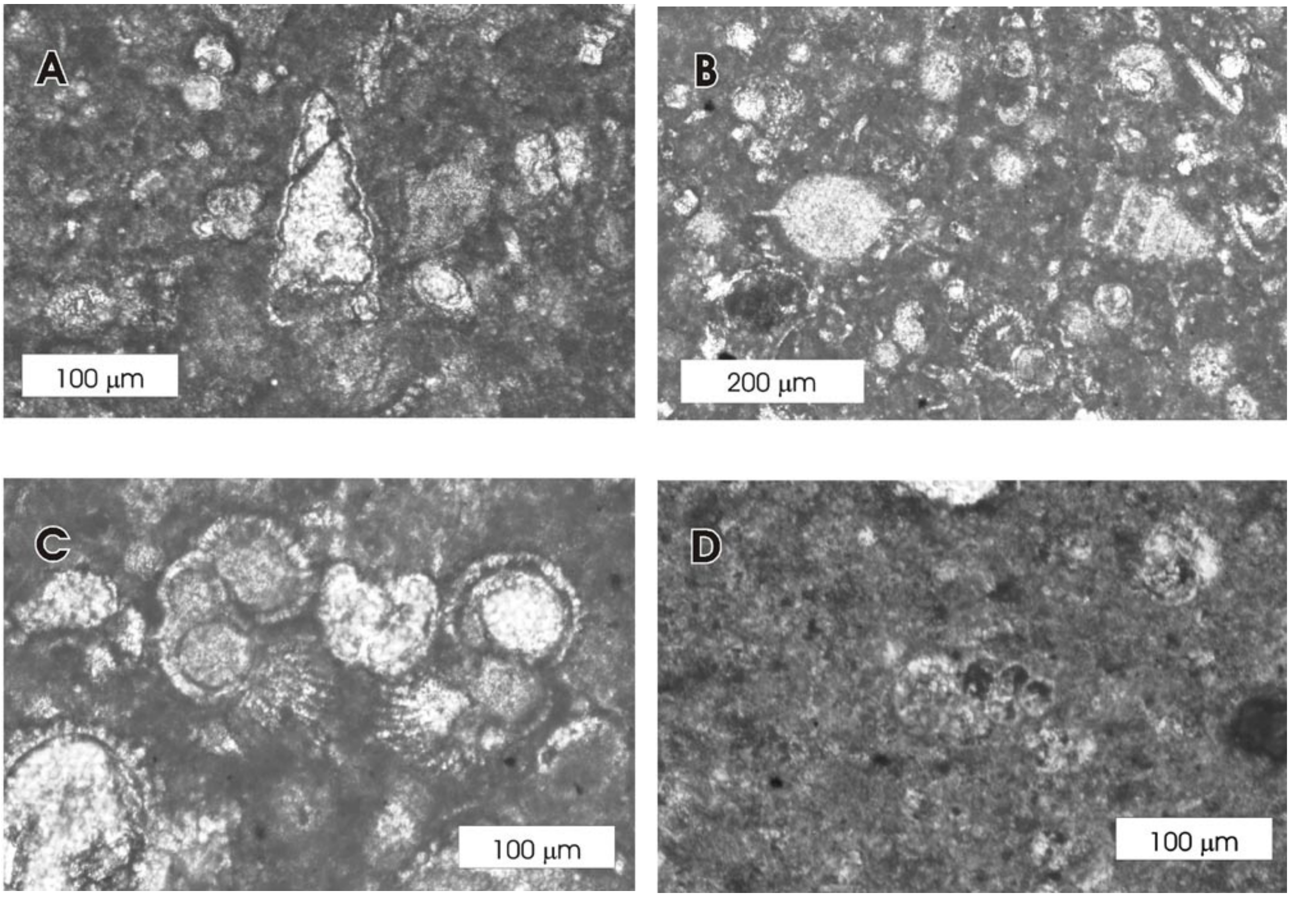


Fig. 8. - Photomicrography of sample 97-11(see Fig. 6 for stratigraphic position) showing in **a**: *Dictyomitra* cf. *multicostata*; in **b**: *Spongatractus* sp (left center), *Dictyomitra* cf. *koslovae* (right center); in **c**: *Rugoglobigerina* cf. *rotundata*; in **d**: Small planktonic foraminifer heterohelicids.

Fig. 8.- Fotomicrografía de la muestra 97-11 (ver Fig. 6 para la posición estratigráfica) mostrando en **a**: *Dictyomitra* cf. *multicostata*; en **b**: *Spongatractus* sp (centro izquierda), *Dictyomitra* cf. *koslovae* (centro derecha); en **c**: *Rugoglobigerina* cf. *rotundata*; en **d**: pequeños foraminíferos planctónicos heterohelícidos.

cal hydraulic behavior at the bottom. These similarities permit the inference that the structures must have developed under comparable kinetics in the water column. Microfossil components associated with the two layers also concur that the depth of the basin was practically unchanged when the two distinct events occurred. Thus, given a threshold of physical perturbation in the water column, the physical behavior of particulate matter is expected to reflect the type of movement in response to different parameters such as internal fluid shear stresses, the force of gravity and settling velocity of the given particles.

Assuming an average rate of sedimentation of 2.5 cm/Kyr for similar pelagic oozes in modern oceans, the time span between the volcanic event and the boundary layer is estimated at:

*980 /(2. 5 cm/Kyr) x 1000 = @392 Kyrs

[*Taken account of the average porosity of similar deep-sea oozes, a possible 40% shrinkage may have resulted from lithostatic pressure and dewatering, hence the 700 cm-interval can be decompressed to an average original thickness of about: 700 + (700 x.40) = @ 980cm].

Percival and Fisher (1977) assigned a duration of approximately 1.8 million years to the *A. mayaroensis* Zone. Assuming a nearly constant rate of sedimentation at the site of the Southern Peninsula, the total estimated thickness of sediments that could have accumulated during that time is: 1.8 MA/1000x 2.5 = @45 meters.

Thus, the stratigraphic position of the volcanogenic layer is well within the upper range of sediment thickness of that time interval, as corroborated by the microfossil content, and is compatible with thicknesses observed at DSDP Caribbean Site 146/149 (Edgar *et al.*, 1973). Furthermore, in the Beloc Classic section the nannofossil *Micula prinsii* Subzone is 14m thick (Aguado *et al.*, this volume). We may assume a similar thickness in the Platon Piton section for that subzone, according to their similar lithology. Therefore, the volcanogenic layer can be placed about in the middle level of the *M. prinsii* Subzone. Duration of this interval is estimated between 1 Ma (Norris *et al.*, 1998) and around 400 Kyrs (Herbert *et al.*,

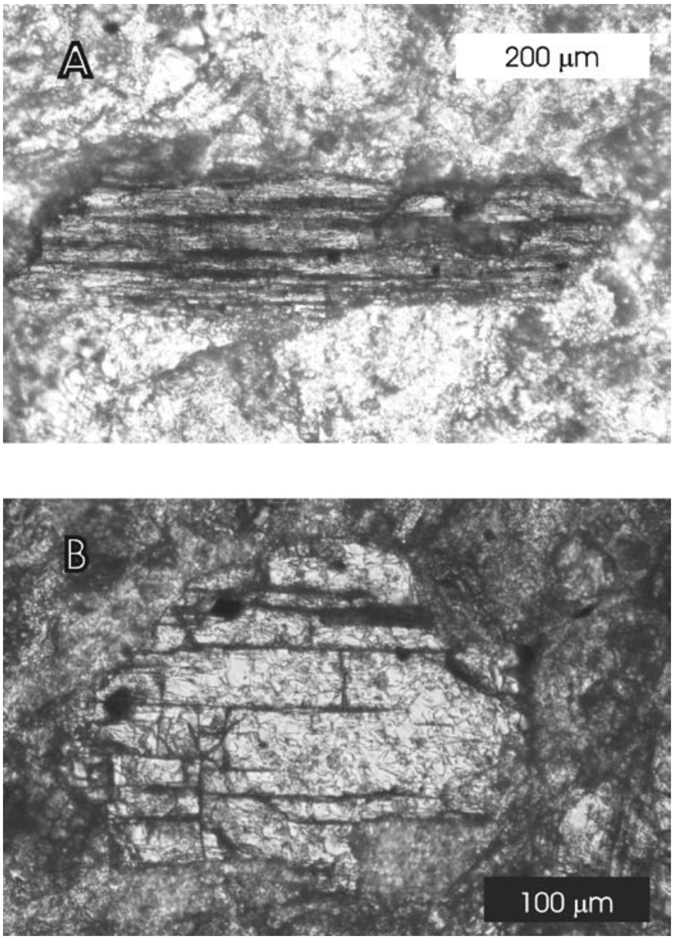


Fig. 9.- Hornblende (a) and pyroxene (b) crystals in sample 97-4 (see Fig. 6 for stratigraphic position) from Platon Piton.

Fig. 9.- Cristales de hornblenda (a) y piroxeno (b) en la muestra 97-4 de Platon Piton (ver Fig. 6 para la posición estratigráfica).

1995). Based on these values, the volcanic event can be placed approximately between 200 and 500 Kyrs before the impact, at the close of the Maastrichtian, and within the same foraminiferal biozone concurrent with the *A. mayaroensis/Trinitella scotti* Zone.

4.3. Significance of inconsistent paleontological records and microstructures observed in the Volcanogenic and Boundary Layers

The diverse biozonation schemes that define the uppermost Maastrichtian (Premoli-Silva and Bolli, 1973; Masters 1977, and other) exemplify the fundamental problem of taxonomic reliability beyond provinciality factors within that time range. A wealth of evidence from the paleontological record shows that problems of stratigraphic discrepancies are widespread at the Cretaceous /Tertiary boundary. Reports of appearance of Danian species in the upper Cretaceous series and/or Cretaceous taxa in the Danian are discussed in almost every aspect of the published literature, but the unanswered question remains why does the K/T boundary level appear so inconsistent.

As most authors recognize these occurrences require significant reworking within the uppermost Cretaceous materials (Magaritz *et al.*, 1985; Maurrasse 1982a; 1982b; Maurrasse *et al.*, 1979/1985, and others), into the Danian, or the unlikely phenomenon of selective downward leaking of Danian taxa into the upper Cretaceous. Worldwide discrepancies of the biostratigraphic and lithologic successions, and geochemical signals have been, indeed, the hallmark of the KTB since the early works on the terminal Cretaceous event until the more recent literature (for instance, see Meijer, 1959; Hofker, 1960; Luterbarcher and Premoli-Silva, 1964; Perch-Nielsen, 1969; Romein, 1977; Schlich, *et al.*, 1979; Hsü *et al.*, 1982; Magaritz *et al.*, 1985; Kyte *et al.*, 1985; Hansen *et al.*, 1986; Preisinger *et al.*, 1986; Graup *et al.*, 1989; Schmitz, *et al.*, 1992; Olsson and Liu, 1993; Jaiprakash *et al.*, 1993; Robin *et al.*, 1993; Meisel *et al.*, 1995; Koutsoukos, 1996b; Lamolda *et al.*, 1997a; 1997b; Molina *et al.*, 1998; Arz *et al.*, 2001; Stinnesbeck *et al.*, 2002, and others). Although most authors propone a single event to explain the biotic mass extinction at the close of the Maastrichtian, however, recurrent inconsistencies at various sites have provided sufficient evidence to suggest more than one disruption associated with the K/T boundary (Maurrasse and Sen, 1991a; Robin *et al.*, 1993, and others). This is because the unsolved uncertainty in the extinction pattern remains one of the KTB enduring puzzles, and a genuine solution to faunal mixing caused by reworking versus survivorship is still conjectural (Molina *et al.*, this volume). In general, while some argued that the extinction was sudden and catastrophic, others indicated that many Cretaceous taxa survived mass extinction and extended into the lower Tertiary. Just as the microstructures indicate vigorous reworking, the micropaleontological evidence at Beloc includes the occurrence of several reworked Cretaceous nannofossil taxa (Lamolda *et al.*, 1997a; 1997b). Similarly, the Upper Cretaceous nannos include Lower Cretaceous species - *Crucibiscutum salebrosum* (Sigurdsson *et al.*, 1991b), and Campanian or Lower Maastrichtian species in the uppermost Maastrichtian (Lamolda *et al.*, 1997b). Figures 3, and 5, show the boundary layer at Beloc where it displays conspicuous evidence of multiple depositional events (Maurrasse *et al.*, 1979). As pointed out earlier, similar discreet structures are also present in the volcanogenic layer below, and their presence in a deep basinal environment, as substantiated by the associated pelagic facies, is one of the major issues that we will discuss further.

Significant spatial and temporal variations over relatively small areas wherever the KTB layer occurs at more than one outcrop (as for instance in Haiti, Mexico, Spain, The Netherlands, Denmark, Italy, etc..) not only argue in favor of widespread turbulent action at the ocean bottom, but they also imply that movement was non-uniform within the basins. Repeated lateral and vertical variations in texture also imply changing and recurrent flow regime, such as those that develop in oscillatory waves that last for an extended period of time to allow succession of deposition and resuspension with decreasing hydrodynamic conditions. Indeed, simple gravitational free fall of the ejecta can be ruled out in most basins because such process could not have caused reworking or amalgamation of the sediments. Instead the impact ejecta materials would have formed a relatively uniform blanket fining upward, and characterized by spatial textural gradation inversely proportional to distance away from the impact site (Ahrens and O'Keefe, 1983). What kind of subaqueous-flow process may be responsible for generating such structures simultaneously in shallow, as well as in deep-water environments, as triggered by a large impact?

Answers to this question will help understand mixing patterns, and a confusing biostratigraphic record in different basins worldwide. In the absence of modern analogs to explain such structures in deep waters, as we indicated before, several known processes such as turbidity currents, tsunamis (Bourgeois *et al.*, 1988; Alvarez *et al.*, 1991b, and others), and bottom currents have been invoked as causative agents to explain the structures and the discrepancies. In the following discussion we will analyze each of these mechanisms as potential causative agent for the differences in the KTB record.

Comparisons with structures known to take form in deep-water environments related to ordinary turbidity currents, and contour currents (Bouma and Brower, 1964; Heezen and Hollister, 1971) as typified in well known deep-sea sequences (Ericson *et al.*, 1961; Horn *et al.*, 1969; 1971; 1972) show many similarities with those observed in the Upper Cretaceous layers in the Beloc Formation and elsewhere. However, significant differences exist, as amalgamated structures in the Beloc layers (Fig. 3) typically do not show the usual stacked multilayered independent units with continuous sharp basal contact that develop in multiple turbidite deposits. Moreover, correlation of the marker bed at different sites of Beloc shows that the marker bed or the volcanogenic layer are not graded as in ordinary turbidites (Bouma and Brower, 1964). At the Beloc stratotype, or "Beloc Classic" for instance, the boundary layer includes successive series of laterally discontinuous graded beds intermingled with coarser materials toward the top. The complexity of recurrent disturbances in the marker bed does not conform to that of ordinary turbidites as typified in well-known deep-sea deposits (Ericson *et al.*, 1961; Horn *et al.*, 1969; 1971; 1972). Furthermore, anisotropic distribution of sand-size grains in the boundary layers is clear evidence of traction structure developed by cohesionless grain flow, as are revealed in structures associated with contour currents. Unlike these structures, however, the boundary layers show cross-stratification and elongate lenticular units that vary in magnitude, shape, and grain size in their spatial and temporal distribution in any given area. Such distribution implies that deposition was intermittent with successive removal and replacement of particles by different hydraulic regimes, in other words a current that changed direction and carrying capacity. The best set of evidence that clearly shows multiple reworking associated with the KTB layer can be found in Mexico (Smit *et al.*, 1992), and summarized in the excellent work by Jose López-Oliva (1996). Clearly, as seen in the Beloc sections, the El Mimbral section in east-central Mexico, State of Tamaulipas, is distinctly unevenly multilayered, with lenticular and cross-laminated structures that occurred at different times. Other examples of distant sites that also illustrate similar effects at abyssal to bathyal depths are the following localities: Blake Nose, western North Atlantic, ODP Site 1049C core 8X-5, 112.86-113.17 mbsf (meters below sea floor) where in the KTB layer "the lowest part of the sandy layer is a faintly laminated layer consisting largely of green spherules as long as 3mm that are accompanied by large Cretaceous planktic foraminifera, clasts of chalk as much as 1 cm in diameter…" (see Fig. 1 in Norris *et al.*, 1999). Bermuda Rise, western North Atlantic, DSDP Site 386, core 35, 636.0-639.0 mbsf where the KTB is complex and shows two levels of cross-laminated chalk (see Figs. 2 and 3, in Norris *et al.*, 2000). Northeastern Brazil (Koutsoukos, 1996a), where fine lamination and confusing reworking signals at the KTB are consistent with multiple events. The Netherlands, Geulhemmerberg section at the Curfs quarry also shows clear evidence of vigorous intermingling of layers (see Figs. 2 and 3 in Smit and Brinkhuis, 1996). Shatsky Rise, northwest Pacific Ocean at DSDP Site 47.2 atop the southwest flank of the Southern High (Douglas, 1971), where the KTB in core 11 is associated with coarser sediments, mixed assemblages of Danian and Maastrichtian species. Furthermore, Douglas (1971, p. 1036) reported that the "most common damage is loss of the last-formed chamber, which is thin-walled and therefore fragile. Approximately 6 to 8 percent of the species from the upper part of Core 11 have broken chambers, probably as a result of various kinds of mechanical abrasion. The assemblages containing an admixture of Paleocene zones from sections 3, 4, 5, and 6 of Core 11 have nearly twice as many broken specimens". Shatsky Rise, ODP Leg 198 (Bralower *et al.*, 2002) at site 1209 where cores 1209A-25H-6, and 1209C-15H-4 include small clast of chalk lenses with reworked taxa. These examples demonstrate that the KTB structures do not conform to typical tractions structures known to occur because of simple bottom currents (Shanmugam *et al.,* 1993). Tsunamis have been proponed by most authors, following the work of Bourgeois *et al.*, (1988) on outcrops at Brazos River in Texas, USA, where they correctly observed that amalgamation in the KTB layer was more appropriately explained by large waves more similar to such process. The consensus is that the El Mimbral (López-Oliva, 1996), the Brazos River (Bourgeois *et al.*, 1988) and the Geulhemmerberg (Smit and Brinkhuis, 1996) sections accumulated at estimated depths within the continental shelf to the uppermost bathyal zone. On the other hand, at Beloc and the other sites mentioned above in the Atlantic and the Pacific Oceans, deposition was within bathyal to abyssal depths beyond 1000 to 2000 meters. Yet, movement in the water column was sufficient to reach such depths and intermittently dislodge grains up to 1.50 mm in diameters in the amalgamated boundary layer (Fig. 3) until the top part of the layer. The intermittence in accumulation thus clearly indicates that a sufficiently vigorous flow developed in pulses of varying intensities over an extended period of time. Tsunamis can affect shallow-water environments of the shelf, but according to the Airy's (1842) wave theory they behave as shallow-water waves, therefore the effects of water movement observed at the surface are not transferred to great depths. Pickering *et al.*, (1991), further argued that the passage of ordinary tsunami waves is unlikely to entrain sediment coarser than silt (less than 65 microns) to fine sand in water depths in excess of 200 meters, that is the outer shelf. Because the structures observed in the layers at Beloc occur in lower bathyal environments (in excess of 2000 meters), clearly their origin by tsunamis proper can be ruled out. Arguments cannot be made either for the effects of ordinary wind-driven waves that could have developed with atmospheric disturbances associated with the effects of the blast, because inertia and friction of the water mass would limit their effects to the uppermost 100 meters or less of the water column. Likewise, density currents and internal waves (Garrett, 2003) cannot develop recurrent patterns, as observed in the microstructures of both the KTB layer and the volcanogenic layer. These primary sedimentary structures are instead closely related to well-known bedforms associated with movements in oscillatory waves, or flows that periodically change direction.

Let us discuss how relevant such oscillatory flow mechanism can be relative to the implied catastrophic scenarios proposed for the bolide impact. Theoretical calculations (Gault *et al.*, 1979; O'Keefe and Ahrens, 1982; Gault and Sonett, 1982; Ahrens and O'Keefe, 1983; Sonett *et al.*, 1991) imply that an oceanic impact site for the K/T boundary bolide would have the potential to trigger gigantic waves up to several kilometers in magnitude at the target site. Understandably, such disturbance could cause ocean water movements to not only affect virtually any depth of the ocean basins, but also to reach considerable extent. The obvious result would cause large-scale turbulence, vigorous mixing and reworking in proximal basins, which the record of mixing at sites around, and distant from, the Chicxulub target site cited previously fully corroborates. Nevertheless, given the recurrent mixing pattern observed at great depths as well, the kind of water movement that was generated ocean wide is not fully understood and therefore needs to be further addressed. Here we argue the well established positive correlation between sedimentary structures and hydrodynamics (Bagnold, 1946), whereby movement of hydraulic-equivalent particles are produced by water of equal velocity. Thus, given such assumption, Hjulström model can be applied to approximate water movements either at, or close enough to, the ocean floor and infer velocities.

Extensive spatial and temporal heterogeneity recorded in the boundary layer, in proximal as well as distal areas of the impact site, provides a strong basis in support of our postulate that the transport mechanism must have been associated with *free oscillations* (Stokes, 1847; Neumann and Pierson, 1966) in the water column. Such movements develop as standing waves, where water oscillates such as in seiches (McLellan, 1965; Wilson, 1966; Neumann and Pierson, 1966; Korgen, 1995). Similarly, as seiche theories imply, the KTB structures permit to infer that oscillating movements in the water column were capable of causing bottom displacement of sediment at different intensities, and at different times. Of special interest to our understanding of what may trigger large-scale water movement in the Caribbean basin is the volcanogenic layer in the Beloc Formation that also displays same characteristics of primary sedimentary structures as the boundary layer. Hence, these structures also imply that seiche motion occurred in the basin in association with a major explosive volcanic event in the area prior to the bolide impact 65 million years ago. Thus, both layers indicate that energy released by the KTB impact-generated shock waves, as well as shock waves induced by a major volcanic eruption were capable to trigger standing waves or seiche in the Caribbean Basin in the latest Maastrichtian.

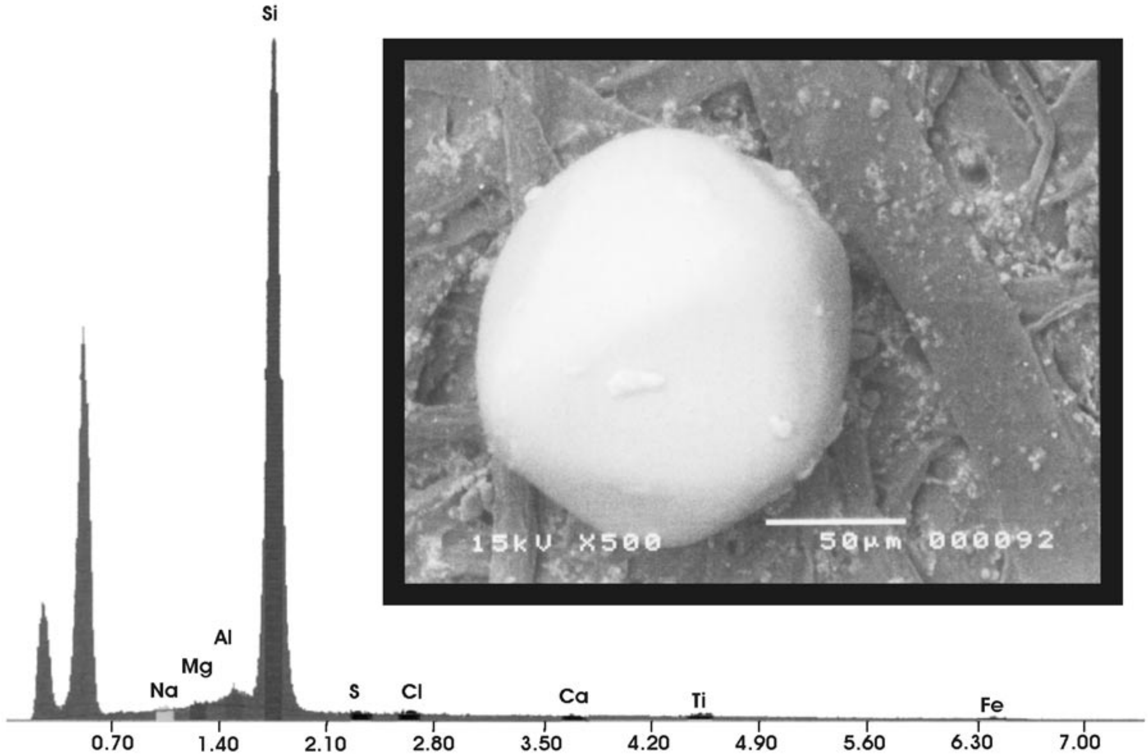


Fig. 10.- SEM analysis of sub-spherical quartz grain in sample 97-1(see Fig. 6 for stratigraphic position) from Platon Piton.
Fig. 10.- Análisis SEM de un grano subesferoidal de cuarzo, muestra 97-1 de Platon Piton (ver Fig. 6 para la posición estratigráfica).

It has been well established that seiche is the resonant oscillation of water in the form of a standing undulating long modal wave, and it occurs in enclosed bodies of water, which may have a number of natural resonances (resonance being the condition of maximum response to an applied periodic force forming "standing waves" of oscillation as shown in Fig. 11). Seiche motions induced by strong atmospheric disturbances, sustained winds over lakes (Wetzel, 2001), and enclosed shallow basins and bays, have been well studied and are quite well known. Unknown, however, are large-scale seiche motions in the oceans, and how they can develop over wide areas in different basins. In absence of historical record of such large-scale phenomena that could be used as analogs, we believe that mixing patterns and primary sedimentary structures at the KTB layer can be linked to such movements by approximation of particle dynamics. Indeed, sedimentary structures observed at the KTB layer in many areas worldwide are compatible with complex bottom water turbulence caused by the physical effects associated with the known magnitude of the KTB impact event (Alvarez *et al*., 1980). Contemporary observations and theoretical calculations (Donn, 1964; Neumann and Pierson, 1966) indicate that seiche motion may develop as a result of impulsive physical disturbance within the basin causing the water level to oscillate around a node or several nodes (Fig. 11.II). Put in simple terms, an understandable comparable model closest to the actual motion we can envision in the ocean at that time being that of water sloshing in a bathtub that may be set up by a sudden disturbance caused by the bather within the tub. In fact, seismic waves and other vibration in the earth that mechanically displace the water column (Donn, 1964; Myles, 1985) can trigger seiche motion. During an earthquake, the earth's crust shakes at very high amplitude close to the epicenter, but its shock waves span a great area and they exhibit smaller amplitude and longer wavelengths. The latter therefore serve better to accentuate the rhythmic movement of a body of water, and different basins can behave differently because every enclosed body of water has a number of natural resonances. It has also been demonstrated that when the vibration in the earth caused by the seismic disturbance coincides with the natural period of oscillation, it reinforces the motion. This is known as sympathetic vibration and can cause extremely high seiches, which may not occur close to the epicenter of the earthquake, but farther away. A seiche can occur, for instance, in a lake far from the earthquake

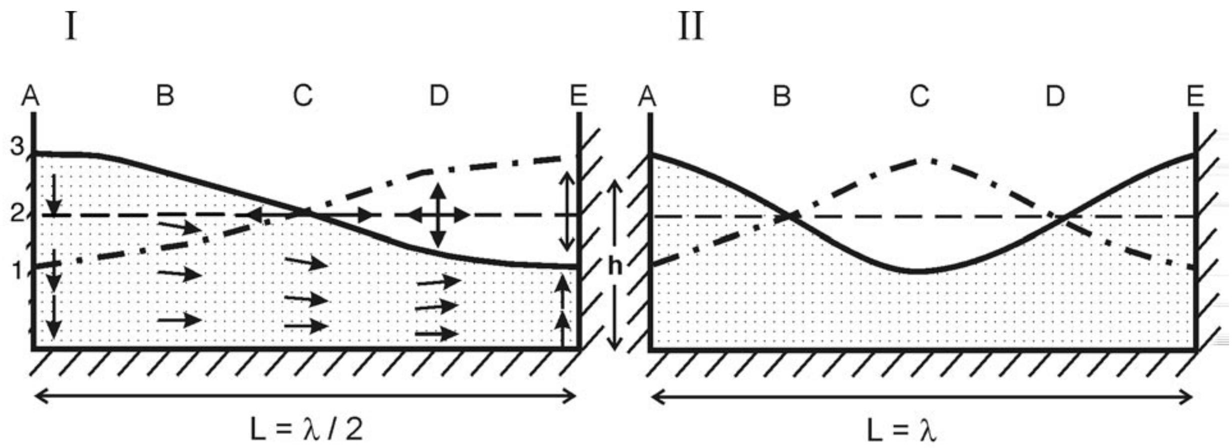


Fig. 11.- Mode of oscillation in seiche. I, illustrates a case where length of basin **L** is one half the period of the entering wave λ, a single node develops about the center at C. Restoring forces generate a strong downward vertical displacement of water at antinode A, and horizontal displacement at C toward antinode E. Simultaneously, upward push starts to develop at the opposite end or antinode E. At a quarter period water in the whole basin will be in position 2, at same level as at the node C, and most water movement is horizontal flowing to the right. Concurrently, strong upward vertical displacement develops between C and E. At half period water at right side will crest at E, as shown by dashed curve, a height corresponding to line-level position 3. Conversely, water on left side will be in position 1, and strong downward vertical movement begins at crest E when maximum height is attained. Again, restoring forces generate movements toward antinode A, in reverse of what occurred before. Thus, at three quarter period water will be back in position 2 with horizontal water movement flowing opposite of previous quarter period, that is now water flows to the left. At a full period water will be back in position 3,cresting again at A, as seen in the illustration, and oscillation continues back and forth until energy is phased out. II, illustrates a case where length of basin is equal to the wave period; oscillation will be multinodal as shown at B and D, respectively. Note that, in either case, at the nodes, which is halfway between crest and trough, water movement is only horizontal. As discussed in text, depth, horizontal dimensions and overall physiography of the basin(s) will drive frequencies of preferred oscillation involved in each case.

Fig. 11.- Modo de oscilación de un seiche. I: en este caso (línea continua) la longitud de la cuenca 'L' es la mitad de la longitud de onda 'λ', con un nodo hacia la parte central 'C'. En el antinodo 'A' se producen movimientos del agua hacia abajo que la desplazan hacia la derecha. Estos movimientos son horizontales en la posición del nodo 'C' y verticales hacia arriba en la posición del antinodo opuesto 'E'. Tras la mitad del periodo, la situación está representada por la línea curva discontinua, invirtiéndose la posición relativa de los antinodos 'A' y 'E'. Al final del siguiente medio periodo se recrearía la situación inicial; durante el mismo habría descensos en el antinodo 'E', ascensos en el 'A' y un desplazamiento del agua hacia la izquierda hasta situarse la cresta de la ola en la posición 'A'. La oscilación continuará de uno a otro lado hasta que se consuma la energía del seiche. II: aquí se ilustra el caso en que la longitud de la cuenca y la longitud de onda de la oscilación sean iguales. La oscilación puede ser multinodal, nodos en B y D en el ejemplo. En cualquier caso, los nodos se encuentran a mitad de camino entre las crestas y los valles (λ/4), pero el movimiento del agua horizontal tiene sentido inverso en dos nodos contiguos. Tal como se discute en el texto, la profundidad, el tamaño y la fisiografía de la cuenca influyen en la frecuencia de oscilación preferente en cada caso.

source if the earthquake is large. Historical examples of earthquake-generated seiches are given by the particularly severe seiche activities that were recorded in Europe following the Portuguese earthquake that occurred in Lisbon in 1755 (Myles, 1985). Seiches developed more than 1500 miles away in Amsterdam, Rotterdam, Dartmouth and Plymouth. During the great 1964 Alaska earthquake (March 1964), the largest earthquake that ever hit the United States in Prince William Sound, Alaska, seismic waves created seiches thousands of miles away, in Louisiana, Texas, Cuba and Puerto Rico. Seismic waves from the earthquake caused seiches in rivers, lakes, and bayous along the Gulf Coast of Louisiana and Texas. Seiche developed in fourteen inland bodies of water in the state of Washington, and swimming pools located even as far as Puerto Rico, in the Caribbean, experienced oscillations. Punongbayan *et al.*, (1994) also reported minor seiches at Naujan and Baruyan lakes during the Mindoro earthquake in the Philippines on November 15th, 1994. In Lake Naujan, the water suddenly became murky as a result of lake bottom agitation, which required several days before the water became clear again (Punongbayan *et al.*, 1994). Studies on seiches confirm that the largest movements are formed when the period of the shock waves matches approximately the same period as one of the seiche modes or frequency of oscillation of the body of water, and complex stationary waves have several nodes and antinodes. Given the different parameters involved in generating oscillating conditions, known seiche motion oscillate with varying frequencies and last anywhere from a few minutes to a few hours.

Basic hydrodynamic studies of an oscillating body of water have established the following conditions for resonance:

-Resonance occurs when the water wave entering a given basin has a natural period of oscillation close to that of the basin.

-Conditions necessary for resonance can occur by stimulating the water mass either in the center of the basin or at its edge.

-In either case it will be necessary that the causing stimulus of the system must be at a specific frequency or period to generate and maintain oscillations.

-The period of oscillation depends on the depth of water, becoming less as the depth increases.

-Application of a more frequent periodic stimulus triggers several nodes.

In the simplest case of a seiche occurring where depth is constant across the basin, the wave speed is single valued and all permissible modes are harmonics of the fundamental. In real basins with random geometry and inhomogeneity of depth configuration, complex set of frequencies will develop multinodal seiches compatible with the natural periods of oscillation that will be the "seiche periods" for the basin (McLellan, 1965). In simple harmonics, the period of oscillation (length of time for one complete oscillation) of a seiche is expressed by the equation:

$$T_n = 1/n\ [2l/(gz_m)^{1/2}]$$

Where: T = period of oscillation (measure of time); n = 1, 2, and 3, nth... (n is an integer for the number of nodes); l = length of the basin; g =accelaration due to gravity; z_m = depth of the basin) (Wilson, 1966; Wetzel, 2001).

This equation indicates that the period of Cretaceous ocean seiches would increase with length of the basin, and decrease with increasing depth. Although it only gives a rough approximation of the role of important parameters in the control of oscillatory periods that must have developed in the diverse Cretaceous basins, nonetheless it provides an understanding of the complex set of frequencies and nodes that should have been generated in the different basins due to random irregularity in coastal morphology and depth. Understandably, the magnitude of crustal disruption caused by the KTB impact must have generated severe long-term local structural instabilities, and subsequent readjustment further induced appropriate stimuli to create independent seiche motion in different basins at different times. Hence, we assume that ephemeral instability caused by the impact, coupled with plate movements, triggered localized major collapses in different basins at different times thus further complicating the spatial and temporal expression of the event worldwide. Such assumption is supported by distinct complex sedimentary flow structures and mixing patterns that are consistent in the record of sites representatives of basins worldwide, and widely different in depth and physiography at the time of the event, as for instance: the Southern Peninsula of Haiti (Maurrasse *et al*., 1979/1985; Maurrasse and Sen, 1991a), Mexico (Smit *et al*., 1992; Lopez-Oliva, 1996; Arz *et al*., 2001; Stinnesbeck *et al*., 2002; and others), the Gulf of Mexico (Alvarez *et al*.,1992; Bralower *et al*., 1998); the United States (Bourgeois *et al*., 1988; Montgomery *et al*., 1992; Terry *et al*., 2001), Blake Nose, western North Atlantic (Norris *et al*., 1999; 2000; Klaus *et al*., 2000), Denmark (Christensen *et al*., 1973), Southeastern Netherlands (Smit and Brinkhuis, 1996); Spain (Lamolda, 1990); and others), Italy (Premoli-Silva and Luterbarcher, 1966), and elsewhere (Alvarez *et al*., 1991b; Smit, 1999).

Since the Cretaceous physiography no longer exists to allow a calculation of their spectral properties and determine how particulate matters may have been moved at the bottom, we can postulate a workable model of the kinetics of cohesionless sediments based on the classic Hüjlstrom's diagram (1935). These experimental values for particle movements can be used as proxy to approximate hydrodynamic conditions associated with the movement of loose sediments during the passage of the oscillatory waves and deposition of the K/T boundary materials. Although in situ movement of cohesionless particles in deep-water conditions is scarcely known (Heezen and Hollister, 1971), the use of the Hüjlstrom's values most closely show the effect of velocity on particle size in erosion, transport, and deposition, and therefore provide important relations between the particle sizes and water flow required to set them in motion. In the case of the KTB layer at Beloc, most particles involved are essentially within sand-size ranges, although some tektites reach sizes as large as 4 and 5 mm. Assuming that all tektites, either associated with yellow or black glasses (Maurrasse and Sen, 1991a; Sigurdsson *et al*., 1991a), have the same density of about d = 2.65, they would require a flow velocity greater than 60cm/sec (2.16 Km/h) to initiate and sustain movement. When such velocity is recurrent at different sets of frequencies, as amalgamation of the units indicates, ambient water flow would certainly be more than sufficient to keep all smaller size fraction less than 1 mm in suspension for an extended period. The net effect of such water movement that is capable of initiating and sustaining repeated motion of the larger particles, will be that the fine grained particles can remain in suspension even when translational movements diminished to velocities below the threshold of transport velocity of 20cm/sec (720 m/h) for the largest grains. Hence, as a result, strong spatial and vertical inhomogeneities will develop in the form of amalgamated fabric in the boundary layer. Variations of the deposit will depend on the type of particulate matter sets in motion, and the different seiche modes and oscillation of the basin. In the case of very fine sand-size to clay-size grains of pelagic deposits the structures may be inconspicuous to the casual observer. Temporal inhomogeneity will indubitably lead to random reworking which may include elements of different stratigraphic levels randomly redeposited. Combining Hüjlstrom's values applied to the Stokes' Law (*$v = 2g(d_1 - d_2)R^2/9\eta$, which follows simple Newton laws of dynamics), when the threshold velocity decreases sufficiently, the coarsest KTB particles would have taken about 15 seconds (uncorrected values) to settle:

*Where, v = settling velocity; d_1 = density of the particle; d_2 = density of the fluid; η = viscosity of the fluid; g = gravitational force; R = radius of particle.

We should point out, however, that the actual settling velocity could have been greater because the Stokes' formula relates to a single grain in a motionless fluid. Nonetheless, the settling time gives an approximation of the wave period, which is compatible with seismic waves, which tend to have most of their energy at periods (the time from one wave crest to the next) within the range of ten seconds to a few minutes, whereas tsunamis gravitate toward periods of five minutes to as much as an hour. These relatively short frequency oscillations would have been responsible for the structures and the reworking observed at the KTB sites worldwide.

As far as long-term disturbances related to various local and regional instabilities, we can postulate, for instance, that based on a detailed temporal distribution of iridium shown for the Gosau Basin (Preisinger *et al*., 1986), resuspension processes due to subsequent disturbances may have occurred in that basin for over three thousand years (@ 5cm of sediment with a calculated accumulation rate of 1.83cm.kyr^{-1}).

Such long-term and large-scale stirring of the ocean waters in the aftermath of the KTB impact must have had profound effects on water chemistry, rapid nutrient cycling, and biotic production. In addition, coincidence with the emplacement of a Large Igneous Province documented by the eruption of huge volumes of Deccan magma in India also had an influence on the ocean's geochemical balance (Ravizza and Peucker-Ehrenbrink, 2003). Could, perhaps the compounded effects of these geochemical changes be the cause of dinoflagellate blooms so characteristic of the KTB transition zone, and have an effect on extinction of other marine organisms?

The widespread presence of unusual dominance of photosynthetic dinoflagellate blooms (e.g., *Thoracosphaera, Braadurosphaera*) is well reported in the literature and in the Haitian sequence (Aguado *et al*., this volume), and at all sites it begun before the impact event and peaked shortly thereafter. Taken modern Braarudosphaeracea as analogs, they are most common in high-nutrient, low-salinity coastal waters and are scarce in modern open oceans. Such distribution is also compatible with the paleobiogeographic distribution of the fossil equivalents as known from the Mesozoic to the Holocene, where they are prevalent in facies indicative of environments closest to the neritic zone instead of the open ocean (Perch-Nielsen, 1985a, b). Furthermore, dinoflagellates are well known in modern oceans to have explosive blooms due to surplus of nutrients, and they are also known to cause the phenomenon called "red tide". As argued before, perhaps the unusual sustained bloom recorded worldwide associated with the KTB event is further indication of recurrent disturbances that stirred the ocean waters at sufficiently enough intervals to maintain surplus of nutrients in surface waters that sustained such blooms in the open-ocean environments. Also, modern dinoflagellate blooms (e.g. *Protogonyaulax catenella, Gessnerium monilatum, Ptychodiscus brevis*) are often associated with the production of lethal toxins, and the resulting effects cause massive kills of a wide variety of taxa, including fish, shellfish, and other forms of marine organisms. Based on the KTB stratigraphic record discussed herein, we believe that these sustained blooms may have contributed to the mass extinction whether by competitive exclusion or by the effects of their toxins.

5. Conclusion

The uppermost Maastrichtian and lowermost Danian stages in the Beloc Formation of the Southern Peninsula of Haiti include a prominent boundary layer associated with microtektites and an infrajacent volcanogenic layer also constrained within the latest Maastrichtian, with an approximate time lag of 300 to 400 Kyrs. The tektite layer, or K/T boundary layer, can be correlated with the disruptive events originated from the Chicxulub impact at about 65.0 million years ago. The lower layer is volcanogenic and reaches thicknesses up to 65 cm, and originated from an earlier major explosive volcanic event in the area. Both layers include extensive reworking of different groups of microfossils, and anisotropic fabric indicative of intricate subaqueous flow structures. Similarly, widespread mechanical disturbances are reported at different KTB sites worldwide, which can be interpreted to indicate that primary traction of particles occurred on an ocean-scale spatial extent and depth. The best-fit model to explain such process is given by translational movement in water column associated with standing wave motion or seiche (Donn, 1964). The structures and different mixing patterns observed in the KTB record imply that complex geometries of the basins gave rise to different sets of frequencies and variation in resuspended sediments related to the different periods of "megaseiches" that attenuated slowly from one oscillation to the next, as observed in smaller-scale modern seiche. Rhythmic sloshing motion of the ocean waters was a natural response not only to direct disturbance of the water caused by the large impacting bolide (Alvarez *et al.*, 1981; Gault and Sonnet, 1982; Arhens and O'Keefe, 1983), but also by the resulting large amplitude seismic waves rippling the earth's crust (Donn, 1964) during the event, and subsequent crustal readjustment causing slumping (Busby *et al.*, 2002; Soria *et al.*, 2001; Norris *et al.*, 2000, and others). We also emphasize that random heterogeneity of the ocean basin topography must have been a critical factor in the development and behavior of the megaseiches, which must have been quite distinct in the different basins, hence different mixing patterns. As a consequence of subsequent crustal accommodation and plate motion, the initial record may have been further complicated by the reworking effect associated with collapses in the different basins that also triggered sloshing behaviors of lesser magnitude similar to the effect of the impact event. As the KTB record indicates, in certain areas these phenomena may have continued over a long period of time that apparently extended into the Danian, and should have been more significant closest to the target site because of more crustal instability in these proximal areas.

The mechanism associated with seiche movement is offered here as a viable substitute hypothesis instead of tsunamis as the main water movement to explain widespread spatial and temporal variability of the lithostratigraphic, biostratigraphic and geochemical records at the KTB layer in the Southern Peninsula of Haiti, and elsewhere worldwide. Perhaps, as it has been observed in modern-day events of much smaller scales, in certain basins initial tsunamis also contributed to enhance the development of seiche movement. Thus, variation in KTB can be attributed to oscillatory processes that caused varying degrees of mixing and heterogeneity at different sites. The variation is related to intense mixing and delayed settling of bottom sediments associated with turbulence induced by fluctuating bottom flow generated during sloshing movements. We further recognize that advective processes in the water column may have been of some factors, but they are still poorly understood, as illustrated, for instance, by the relationship between the propagation of internal tides (Sverdrup *et al.*, 1970) and ocean mixing (Garrett, 2003), and the influence of rough topography in the deep-ocean basins. Megaseiches that developed in the Cretaceous oceans are more consistent with the different records of the boundary layer observed worldwide. Although, perhaps, not complete in the details of different interacting parameters, the analogy captures the essence of the main mechanism that may have caused confusing mixing patterns recorded at the K/T boundary sites on a global scale. Clearly, further integrated studies that pay greater attention to the fine structures of the KTB layer are needed. Such studies will certainly shed much needed light for a better understanding of the relationships between the different factors involved that blurred the record during and after the impact event.

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