Beloc, Haiti, revisited: multiple events across the KT boundary in the Caribbean

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ABSTRACT

Examination of new expanded K/T boundary sections near Beloc, Haiti, reveals deposition of a glass sphere-like rich deposit (SRD) and two (PGE) anomalies (one Ir-dominated and one Pd-dominated) during the early Danian Parvularugoglobigerina eugubina Zone [Plat(1)]. The presence of the Haiti SRD within the early Danian is interpreted as being due to reworking. It is only slightly elevated within the SRD but forms an anomaly at the top of the SRD extending into the overlying pelagic limestones. It is unclear at present whether this Ir anomaly results from mechanical reworking of an impact at the K/T boundary, or an additional impact event in the early Danian. The second PGE anomaly upsection is dominated by Pd and Pt and is more compatible with a magmatic origin. This suggests a multi-event scenario consistent with one (and possibly two) impact(s), followed by a PGE-enriched volcanic event in the Caribbean.

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Introduction

Glass spherules, shocked minerals and an iridium anomaly in Cretaceous–Tertiary (K/T) sediments near Beloc, Haiti, are frequently cited as critical evidence in support of a large extraterrestrial impact at Chicxulub, Yucatan, Mexico. The evidence consists of the chemical similarity of Haiti glass spherules, which are considered altered tektites (Izett et al. 1990; Izett, 1991; Sigurdsson et al. 1991; Kring et al. 1991; Koeberl and Sigurdsson, 1992; Koeberl, 1992), with those at Mimbrel, Mexico (Smit et al. 1992; Stinnesbeck et al. 1993) and melt rock in subsurface cores at Chicxulub (Koeberl, 1993). Although most studies suggest that this evidence supports an impact at the K-T boundary, some authors have suggested that volcanism (Lyons and Officer, 1992), two impacts (Leroux et al., 1995), or one impact and one volcanic event (Jehanno et al. 1992) produced the glass spherules and iridium anomaly. Our work on the Beloc sections was prompted by a desire to reconcile the complex depositional sequence observed in the Mexican sections with that reported from Haiti (e.g. Maureas and Sen, 1991; Jehanno et al. 1992; Leroux et al. 1995).

Location and methods

The road from Port au Prince to Beloc and Jacmel was widened recently, exposing new roadcuts where Cretaceous and Tertiary rocks of all but one of the previously reported sections are exposed. All of the roadcuts are intensely faulted, folded, and sheared parallel to or at small angles to the bedding plane. In particular, the K/T boundary clay is generally sheared, highly condensed, and the basal Danian is missing (Keller et al., in press).

We collected at two K-T outcrops along the road of which one (B6) is the locality H of Jehanno et al. (1992) and Leroux et al. (1995), and the other (B1) is a newly exposed outcrop nearer to Beloc. About 1 km north of Beloc on a steep slope and 30–40 m below the road, a more complete K–T interval is preserved in a tectonic graben with no evidence of tectonic deformation. We collected along three K–T transects: section B2 is a poorly exposed outcrop that was described by Maureas and Sen (1991); sections B3 and B4a are better exposed than B2 and located approximately 25 m and 60 m, respectively, to the north of B2 along the same slope (Fig. 1).

This study is based on biostratigraphical, geochemical, and sedimentological analyses. Biostratigraphical age determinations are based on planktonic foraminifera that are common to abundant and well preserved in most sampled sections. Samples were processed by standard techniques (Keller et al. 1995) and washed through a 38 µm screen. All Danian species are found to be within the 38–63 µm size-fraction. This small size-fraction is generally discarded in standard sample processing and biostratigraphical analyses. Larger specimens appear only in the upper part of the Parvularugoglobigerina eugubina Zone [Plat(2)]. Analysis of the smaller size-fraction plus samples from weathered outcrops may explain why previous workers were unable to find Danian species close to or within the spherule-rich deposits (SRD) (Sigurdsson et al. 1991; Maureas and Sen, 1991; Leroux et al., 1995). Samples were also analysed for iridium and other Platinum Group Elements (PGEs) using ICP/MS (after preconcentration by nickel sulphide fire assay, Cubelie et al., 1997). Thin sections were made of all samples and lithological changes documented.

Depositional sequence and biostratigraphy

In 4 of the 5 Beloc sections examined (all except B2) pelagic marly limestone of late Maastrichtian age is present and contains radiolarians, calcispheres, sponge spicules, ostracods, benthic foraminifera, and abundant planktonic foraminifera including Plummeria hantkeninoides (details of the biostratigraphical study are published in Keller et al., in press). The index species Plum-
merita hankenioidea characterizes the last 300 kyr of the Maastrichtian (Par-
do et al., 1996; Li and Keller, 1998). An undulating erosional surface separates
the SRD from the upper Maastrichtian limestone. This unconformity is marked
by subrounded clasts of lime-
stone, mudstone and wackestone, some of which contain reworked early late
Maastrichtian planktonic foraminifer
(e.g. Globobotruncana lineana, G. for-
nicata, G. plummerae). The SRD corre-
spends to the interval that contains
glass spherules, bioclastic limestone
with spherules and volcanic debris
(Fig. 2). The spherules are 1–5 mm in
diameter, commonly hollow or infilled
with sparry calcite or smectite. Larger
spherules generally contain several ve-
ciles that may be infilled with calcite or
smectite similar to the composite spher-
ules of Mimbral, Mexico (Stinnesbeck
et al. 1993). Most spherules are spheri-
cal, although elongate, tear-drop and
dumb-bell shapes are common. Volca-
nic minerals (e.g. feldspars, amphi-
boles), zeolites and smectite with che-
totype-composition are common to
abundant (see also Iezzi, 1991).
The SRD ranges in thickness from 10
to 30 cm in road outcrops to a max-
umum of 70 cm along the slope where it
consists of up to nine lithologically
distinct layers (B3). These layers alter-
nate in the abundance of spherules and
bioclastic debris (Fig. 2). The layers are
separated by erosion surfaces and size-
graded reworked material, which sug-
gest that redeposition occurred as a
series of discrete events. Layers with
abundant spherules grade into bioclas-
tic limestone containing spherule clus-
ters and lenses. Two distinct lithologi-
cal units are present in the SRD (Figs 2,
3). Unit 1 forms the basal 10–20 cm of
the SRD at B3 and B4a and is charac-
terized by abundant spherules altered
to sparry calcite and smectite with sur-
face cracks. No glass was observed in
unit 1 (Fig. 4a). Unit 2 is 5–15 cm thick
and characterized by the presence of
abundant black glass spherules with al-
tered rims. Abundant fragmented sphere-
ule debris and rounded limestone clasts
are also present in a matrix of sparry
calcite of this unit (Fig. 4b). Unit 2 was
detected in all sections and disconform-
ably overlies Maastrichtian limestone in
sections B1, B2 and B6 (Fig. 2).
Unit 3 consists of a 2-cm-thick grey-
green shale with a thin, rust-coloured
layer containing maximum concentra-
tions of iridium and shocked minerals
(see Leroux et al., 1995 for distribution
of shocked minerals). It is referred to as
the Ir anomaly. Unit 3 is located 40 cm
above the base of the SRD in B6 and
B2, and 70 cm in B4a and B3 (Figs 2, 3).
Iridium anomalies have been reported
from B2 (no values given, Maurrasse
and Sen, 1991; Lamolda et al. 1997), and
B6 with a maximum concentration of
28 ng g⁻¹ and a tail to 20 cm below unit
3 (section H of Jéhanno et al., 1992;
Leroux et al. 1995). The Ir anomaly in

Fig. 1 K–T boundary sections 1 km north of Beloc, Haiti. Note that the most expanded sections are present along the steep
slope below the road (B2, B3, B4a). B2 is the section of Maurrasse and Sen (1991) and Lamolda et al. (1997). B1 and B6 are road
outcrops that are condensed and tectonically disturbed (faulted, folded and sheared). B6 is section H of Jéhanno et al. (1992) and
Leroux et al. (1995).
B3 is broad (B3-14 to B3-19), centred at the rust-coloured layer (B3-16) overlying a 6-cm thick cross-bedded bioclastic limestone, and tailing to the base of unit 2 (black glass spherule layer) of the SRD (Fig. 3). Well-preserved clear vesicular glass is common in the cross-bedded interval. The maximum Ir concentration is 1 ng g\(^{-1}\) and only minor enrichments of Pt, Rh and Pd were determined. Unit 4 is 120 cm above the base of the SRD and referred to as the PGE anomaly (Fig. 2). It is characterized by a palladium-dominated enrichment of PGEs (6.2 ng g\(^{-1}\) Pt, 0.1 ng g\(^{-1}\) Rh, 8.9 ng g\(^{-1}\) Pd), but relatively low Ir values (0.6 ng g\(^{-1}\)). This PGE anomaly is within a 0.5-cm thick rust coloured layer (B3-29), overlain by a 1-cm thick volcanic tuff layer and a 10-cm thick volcanic-rich marl layer (Figs 4d, 5).

A very tiny, early Danian Zone P1a(1) planktonic foraminiferal fauna, indicative of high-stress environments (e.g. Eoglobigerina fringa, Parvularugoglobigerina eugubina, P. longiapertura, Globocassis conusa, G daubjergensis, Woodringina hornerstownensis; see also Keller et al. 1998, in press), is present in the matrix throughout the SRD of all sections, although it is rare in the lower 30 cm of the SRD in section B3 (Fig. 5). The similar sequence of first appearances of early Danian species in the matrix of the SRD and the sediments above it in all sections examined indicate that these assemblages are in situ. An early Danian interpretation is also supported by the presence of characteristic early Danian Thoracosphaera blooms (Percival and Fisher, 1977; Perch-Nielsen, 1988) in the marly limestone associated with the Ir anomaly of unit 3 (Fig. 4c). Cretaceous species are
Fig. 3 Stratigraphical and lithological correlation of five K–T boundary transects in the Beloc area. Note that three marker horizons can be correlated: Unit 1 is characterized by abundant spherules altered to sparry calcite and smectite with surface cracks, No glass is preserved. Unit 2 contains abundant black glass spherules with altered rims. Unit 3 is an Ir-rich layer consisting of a thin grey-green clay underlying a 2-4-mm thick, rust-coloured layer containing small rounded grains of Fe-oxides or Fe-silicates (chamosite). Unit 4 is a Pd-dominated PGE anomaly within a 5-mm thick rust-coloured layer, a 1-cm thick volcanic tuff followed by a 10-cm thick volcanic-rich marl; unit 4 was only sampled in section B3.
most abundant in reworked clasts, though some mudclasts also contain early Danian Pla assemblages. This suggests that the SRD consists primarily of reworked Cretaceous sediments with a minor component of reworked early Danian Pla material, but that its current deposition occurred in the early part of the *P. eugubina* (Pla(1)) zone (for details of the stratigraphical analysis see Keller et al., in press).

**Discussion**

Stratigraphical, lithological and geochemical data from the Beloc sections provide no simple answers to the events that occurred across the K–T transition. These data indicate a complex sequence of events that is not easily reconciled with the current single impact scenario. In particular, explanations must be found for the presence of common early Danian Zone Pla planktonic foraminifera and *Thoracosphaera* blooms in the SRD, the Ir anomaly of unit 3, and the PGE anomaly of unit 4. The critical questions concern the age of the spherules, the origins of the Ir and PGE anomalies, and whether these units represent a single impact event or multiple events.

**Are Beloc spherule deposits reworked?**

The $^{40}$Ar/$^{39}$Ar age of the spherules is estimated at 64.42 ± 0.06 Myr (Izett et al. 1991; Dalrymple et al. 1993). However, only biostratigraphy can tell us when spherule deposition occurred relative to the K–T boundary. The Beloc SRD disconformably overlies upper Maastrichtian limestone, but contains a diverse tiny early Danian planktonic foraminiferal assemblage of Zone Pla(1) age (lower part of *P. eugubina* Zone). Are these faunas in situ or reworked? Downward reworking might have occurred as a result of bioturbation or by pore fluid transport of these tiny shells. Neither seems likely. We observed no evidence of bioturbation, and although pore fluid transport may have occurred within the SRD, this is not likely across the dense limestone.

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**Fig. 4** Photomicrographs of thin sections of characteristic sediment units of the early Danian Zone Pla at Beloc 3. (a) Composite calcite and smectite spherules of the basal spherule-rich deposit. Spherules show surface cracks, no glass is preserved (sample B3-7). (b) Composite spherules containing relict black glass in a matrix of sparry calcite (sample B3-12). (c) Micritic limestone (packstone) with blooms of tiny calcareous spheres of *Thoracosphaera* which are characteristic in the early Danian Zone Pla (sample B3-26). (d) Volcanic ash layer in Zone Pla with enriched PGEs (sample B3-30, see Fig. 4 for Ir and Pd anomalies within this ash layer).
layers that are interbedded with the spherules. In particular, it is highly
unlikely that an entire early Danian assemblage with the temporal distribution
of evolutionary first appearances intact, including the diverse relative
species abundances known from sec-
tions elsewhere, was somehow trans-
ported downward into Cretaceous sed-
iments (Keller et al., in press). We
therefore conclude that deposition of the SRD (including units 1 and 2), and
the Ir anomaly (unit 3) at Beloc oc-
curred in the early Danian Zone Pla(l).
However, the presence of abundant clasts with late Maastrichtian faunas
indicates reworking and suggests that the spherule deposits may also be re-
worked from older sediments.

Earlier studies identified the Ir
anomaly of unit 3 as the K–T boundary
event (Jehanno et al., 1992; Leroux et al.,
1995), or placed the boundary at the
base of the SRD (e.g. Sigurdsson et al.,
1991; Izett, 1991; Maurrasse and Sen,
1991; Lamolda et al., 1997). Lamolda et
al. (1997) and Maurrasse and Sen (1991)
reported the first early Danian species
30 cm below the Ir enrichment in the
Maurrasse section (our B2 section). Our
investigation reveals the presence of a tiny (38–63 μm), diverse early
Danian Pla(l) fauna beginning at the
base of the SRD (see also Keller et al.,
in press). We therefore place the K–T
boundary at the base of the SRD. An
erosional disconformity separates the
SRD from the underlying Maastrich-
tian limestone. Sediments representing
a maximum of 100–250 kyr may be
missing at this disconformity. This is
suggested by the juxtaposition of early
Danian Pla(l) and the lower part of the
latest Maastrichtian CF1 Zones; the
latter zone is characterized by Plan-
merita hantkeninoides which spans the
last 300 kyr of the Maastrichtian (Pardo
et al., 1996; Li and Keller, 1998). If the
spherules of the Beloc SRD are re-
worked, they would thus have come
from the missing interval. Interestingly,
in the Mexican sections the SRD is with-
in CF1. It is separated from the Ir
anomaly at the K/T boundary by a clastic deposit that contains multiple
horizons of repeated colonization by
invertebrate faunas. This bioturbation
must have taken considerable time to
establish (Keller et al., 1997; Ekdale and
Stinnesbeck, 1998). Thus, if the Mexican
spherules originated from an impact,
this event preceded the K/T boundary.

Are SRD and Ir anomaly reworked?
The presence of reworked Cretaceous
species and other transported debris
from various sources (e.g. volcanic, im-
 pact, pelagic) within the SRD supports
a scenario of transport and reworking. There are at least four erosional surfaces and two discrete units of differentially altered spherules within the SRD (units 1 and 2), plus several erosional surfaces above the Ir anomaly. This suggests intermittent high-energy conditions over an extended period of time (Fig. 5). It is difficult to determine whether the Ir anomaly is part of the spherule-producing impact event, or if it represents a second, later event as suggested by some workers (Jéhanno et al. 1992; Leroux et al. 1995). If we assume that the SRD and Ir anomaly originated from the same impact event, then their current stratigraphical separation would have to be explained by either postdepositional mobilization of Ir, or mechanical reworking.

Multi-event origin of Ir and PGE anomalies?
The distributions and absolute concentrations of the PGEs in the two anomalies (Ir and PGE) observed in section B3 clearly suggest two different sources. The concentrations of the palladium-dominated PGE anomaly in unit 4 (8.9 ng g⁻¹ Pd, 6.2 ng g⁻¹ Pt, 0.1 ng g⁻¹ Rh, 0.6 ng g⁻¹ Ir) are more compatible with concentrations in ocean flood basalts (Greenough and Fryer, 1990), Hawaiian basalts (Crochet and Kabir, 1988), or rifting-related acidic volcanics (Borg et al., 1988), than with extraterrestrial material. In contrast, the anomaly of unit 3 is clearly Ir dominated (only minor Pd, Pt, Rh) and PGE distributions are more similar to patterns described for extraterrestrial origins (e.g. Ganapathy, 1980).

As secondary effect, a possible diagenetic mobilization of the PGEs and displacement of the anomalies has to be considered. Wallace et al. (1990) interpreted the displaced PGE anomaly in the vicinity of the Lake Acraman impact structure as secondary enrichment by diagenetic mobilization. This anomaly is associated with a minimum in iron and zinc, and a copper enrichment of several orders of magnitude that marks redox entrapment processes. Mobilization of PGEs can also occur under very acid chloride-rich conditions with high Eh (Bowles, 1986). At normal Eh–pH conditions, iridium is immobile in the marine environment.

At Beloc, no geochemical evidence for diagenetic mobilization of the PGEs can be observed in either the Ir or PGE anomalies of units 3 and 4, or the adjacent sediment layers. Therefore, if we assume that the Ir anomalies are not in situ, then mechanical reworking is the more probable explanation for their presence. Iridium is only slightly enriched in units 1 and 2 and is probably reworked along with the spherules from an earlier impact at or near the K–T boundary. It remains unclear whether the Ir anomaly of unit 3 above the SRD is also reworked, or whether this anomaly represents a second collision event, as previously suggested by Jéhanno et al. (1992) and Leroux et al. (1995) based on the distribution of shocked minerals and Ni-rich spinels. There is support for this scenario in Guatemalan sections where Fourcade et al. (1998, 1999) reported a SRD and iridium enrichment in the early Danian Zone Pla. At Beloc, the unit 3 Ir anomaly may also represent an early Danian Zone Pla impact, although mechanical reworking of the earlier K/T impact Ir anomaly cannot be excluded. In contrast, the Ir and Pd-dominated anomalies in the upper part of Pla are associated with an ash layer and represent a volcanic event that has not been identified previously.

Conclusions
Our investigations of the Haiti sections suggest that the Caribbean suffered a major extraterrestrial impact at or before the K–T boundary as suggested by the SRD, possibly a second impact event in the early Danian zone Pla(I) as suggested by the Ir anomaly, and a major volcanic event in the upper part of Pla(I), as suggested by the palladium-dominated PGE anomaly.

1 The K–T boundary in sections at Beloc, Haiti, is at an erosional disconformity between the base of the SRD and the underlying Maas- trichtian limestone, where an interval representing about 100–250 kyr appears to be missing (juxtaposition of planktonic foraminiferal Zones Pla/CF1). Diverse in situ assemblages of tiny, early Danian Pla planktonic foraminiferal assemblages are present from the base of the spherule-rich deposit (SRD) upsection.

2 Spherule deposits appear to be reworked, but most likely originated from an impact at or near the K–T boundary.

3 Iridium is only slightly enriched within the SRD and its presence may be due to mechanical reworking. The broad Ir anomaly of unit 3 above the SRD contains only minor Pd, Pt and Rh, and PGE distributions and these are similar to patterns observed for extraterrestrial remnants. No evidence of diagenetic mobilization was observed. It is possible that this Ir anomaly represents a second early Danian (lower part of zone Pla) impact event.

4 The palladium-dominated PGE anomaly in unit 4 is compatible with a magmatic origin and suggests a major volcanic event in the Caribbean in the upper part of the early Danian zone Pla(I).

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