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

W. Stinnesbeck[1], G. Keller[2], T. Adatte[3], D. Stüben[4], U. Kramar[4], Z. Berner[4], C. Desremeaux[5] and E. Molière[6]

[1]*Geologisches Institut, Universität Karlsruhe, 76128 Karlsruhe, Germany,* [2]*Department of Geosciences, Princeton University, Princeton, NJ, USA,* [3]*Institut de Géologie, 11 Rue Emile Argand, 2007, Neuchâtel, Switzerland,* [4]*Institut für Petrographie und Geochemie, Universität Karlsruhe, 76128 Karlsruhe, Germany,* [5]*UFR Sciences de la Terre et de la Mer, Université de Bordeaux 1, 33400 Talence, France,* [6]*Ecole Nationale de Géologie Appliqué, Port-au-Prince, Haiti*

ABSTRACT

Examination of new expanded K/T boundary sections near Beloc, Haiti, reveals deposition of a glass spherule-rich deposit (SRD) and two (PGE) anomalies (one Ir-dominated and one Pd-dominated) during the early Danian *Parvularugoglobigerina eugubina* Zone [Pla(l)]. The presence of the Haiti SRD within the early Danian is interpreted as being due to reworking. Ir 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.

Terra Nova, 11, 303–310, 1999

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 Mimbral, 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 Jéhanno *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. Maurrasse and Sen, 1991; Jéhanno *et al.* 1992; Leroux *et al.* 1995).

*Correspondence: Tel: +49/7216082137, Fax: +49/7216082138; E-mail: wolfgang.-stinnesbeck@bio-geo.uni-karlsruhe.de

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 roadcut sections 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 Jéhanno *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 Maurasse 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 [Pla(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; Maurasse 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, Cubelic *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 *Plummerita hantkeninoides* (details of the biostratigraphical study are published in Keller *et al.*, in press). The index species *Plum-*

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).

merita hantkeninoides characterizes the last 300 kyr of the Maastrichtian (Pardo *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 limestone, mudstone and wackestone, some of which contain reworked early late Maastrichtian planktonic foraminifera (e.g. *Globobotruncana linneana, G. fornicata, G. plummerae*). The SRD corresponds 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 vesicles that may be infilled with calcite or smectite similar to the composite spherules of Mimbral, Mexico (Stinnesbeck *et al.* 1993). Most spherules are spherical, although elongate, tear-drop and dumb-bell shapes are common. Volcanic minerals (e.g. feldspars, amphiboles), zeolites and smectite with chetotype-composition are common to abundant (see also Izett, 1991).

The SRD ranges in thickness from 10 to 30 cm in road outcrops to a maximum of 70 cm along the slope where it consists of up to nine lithologically distinct layers (B3). These layers alternate in the abundance of spherules and bioclastic debris (Fig. 2). The layers are separated by erosion surfaces and size-graded reworked material, which suggest that redeposition occurred as a series of discrete events. Layers with abundant spherules grade into bioclastic limestone containing spherule clusters and lenses. Two distinct lithological 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 characterized by abundant spherules altered to sparry calcite and smectite with surface 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 altered rims. Abundant fragmented spherule 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 disconformably 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 concentrations 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

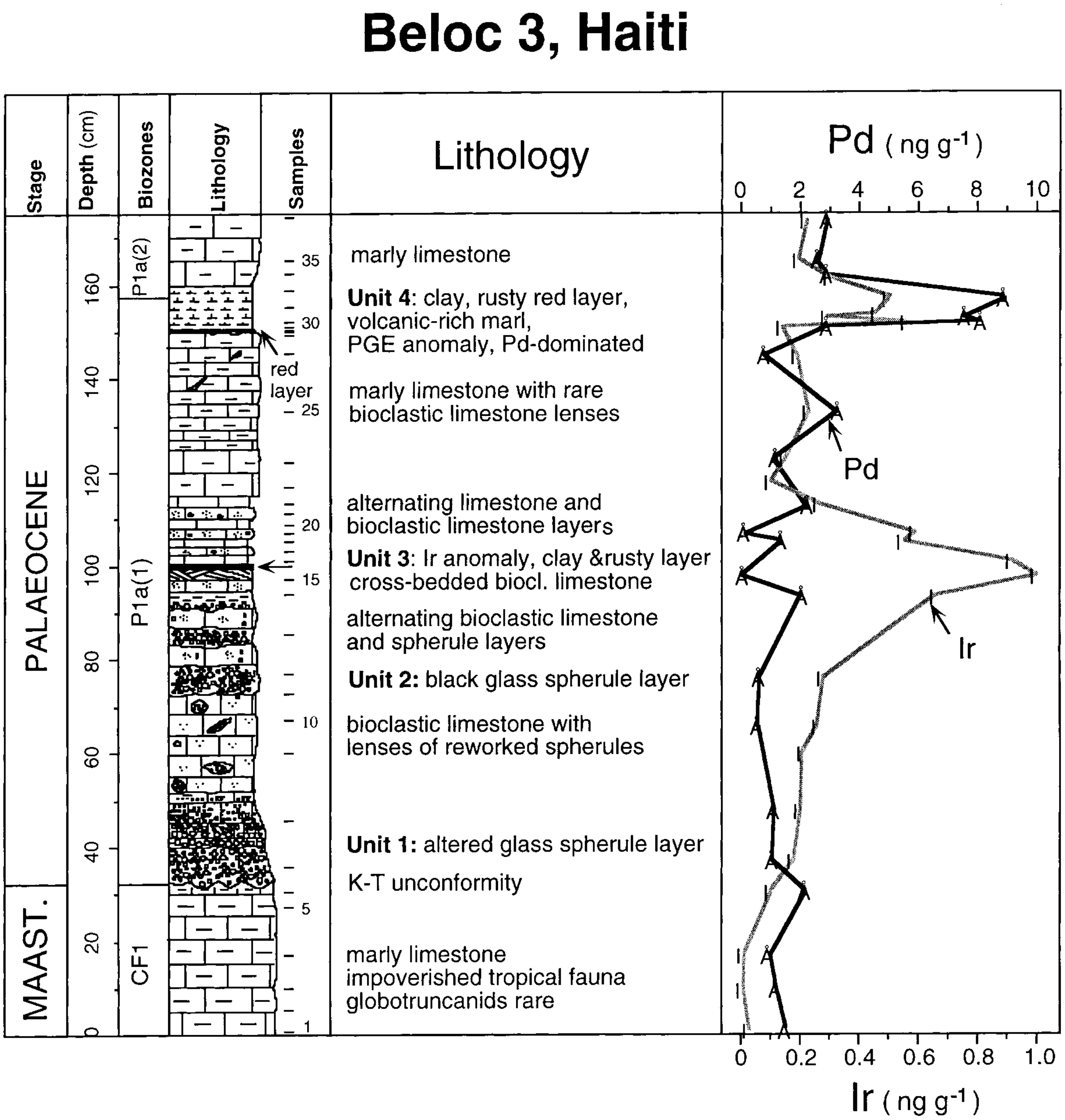

Fig. 2 Lithological sequence and definition of characteristic sediment units, Pd and Ir anomalies in the Beloc 3 section (B3).

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 Pla(1) planktonic foraminiferal fauna, indicative of high-stress environments (e.g. *Eoglobigerina fringa*, *Parvularugoglobigerina eugubina*, *P. longiapertura*, *Globoconusa 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

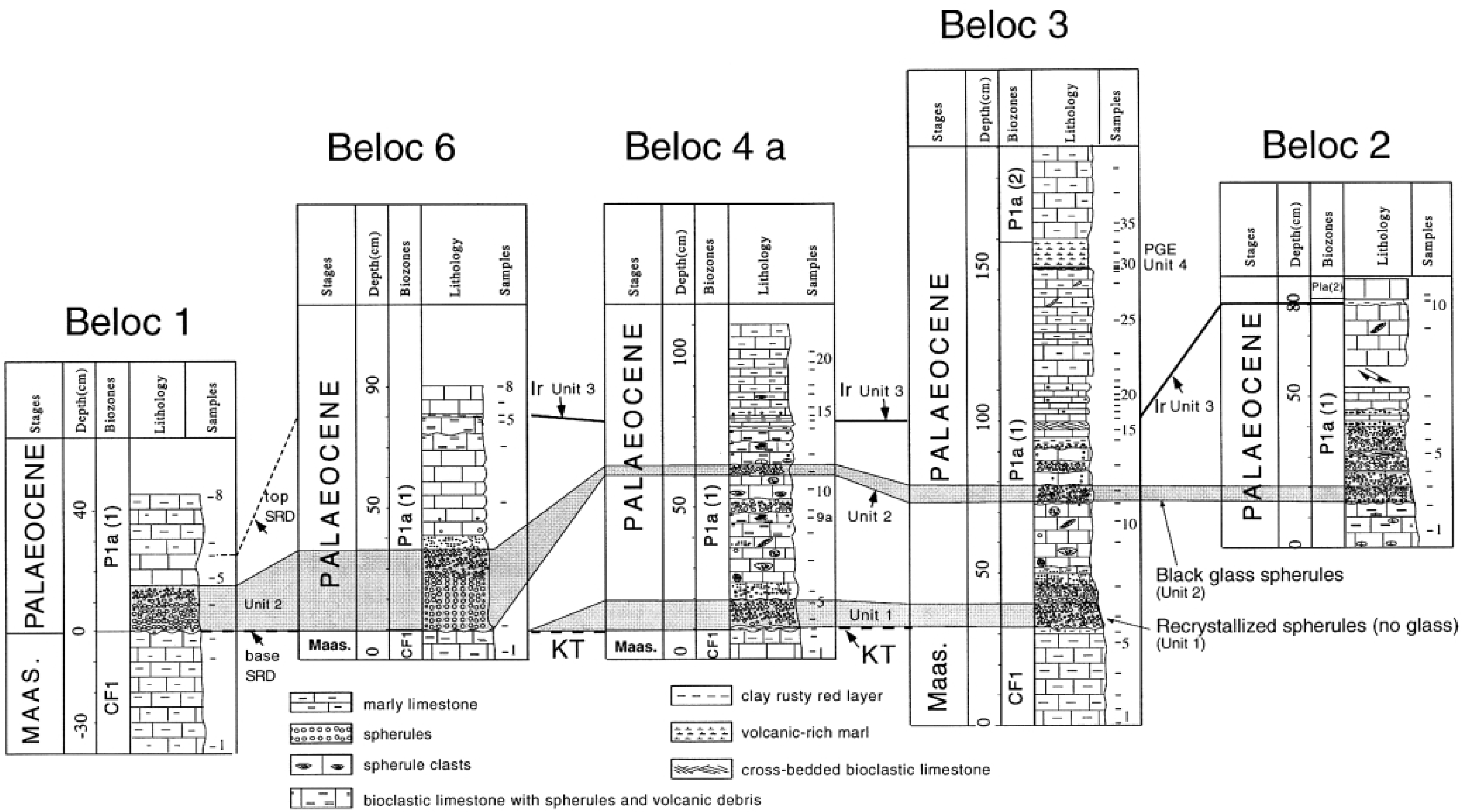

Fig. 3 Stratigraphical and lithological correlation of five K–T boundary transects in the Beloc area. Note that three marker horizons can be correlated: Unit 1 is characterized by abundant spherules altered to sparry calcite and smectite with surface cracks. No glass is preserved. Unit 2 contains abundant 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 l0-cm thick vocanic-rich marl; unit 4 was only sampled in section B3.

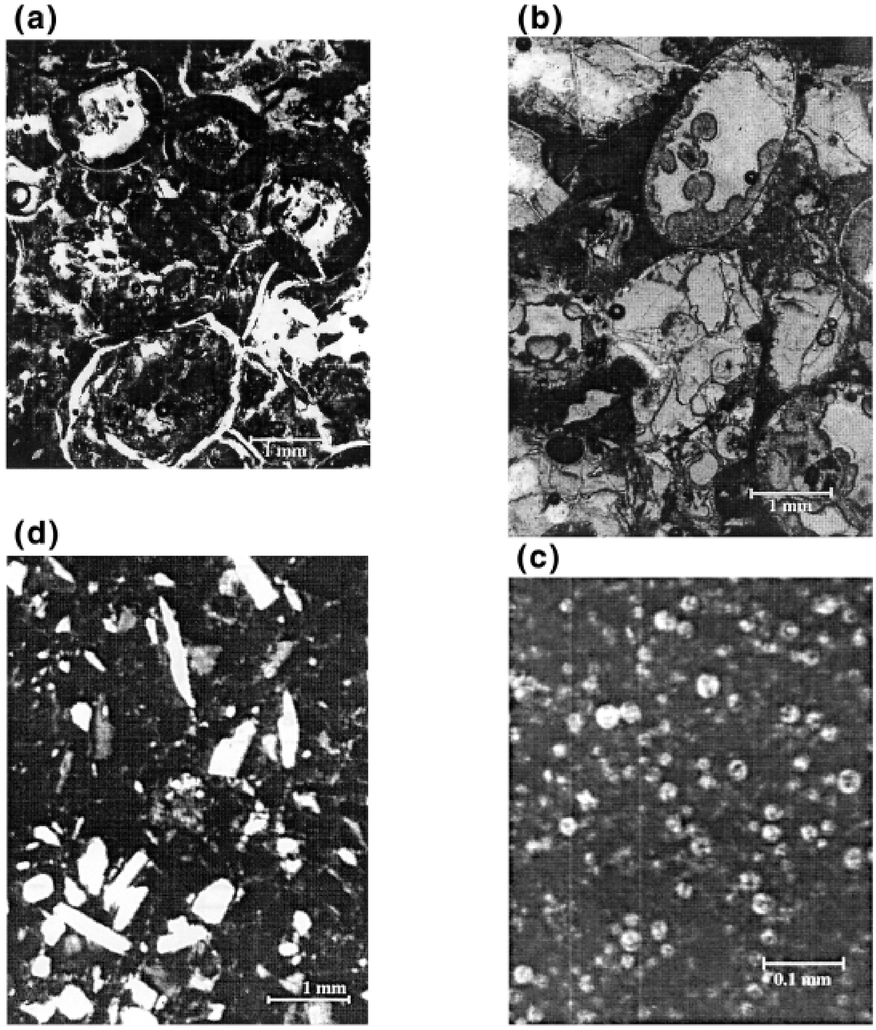

Fig. 4 Photomicrographs of thin sections of characteristic sediment units of the early Danian Zone P1a at Beloc 3. (a) Composite calcite and smectite spherules of the basal spherule-rich deposit. Spherules show surface cracks, no glass is preserved (sample B3-7). (b) Composite spherules containing relict 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).

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(l)] 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

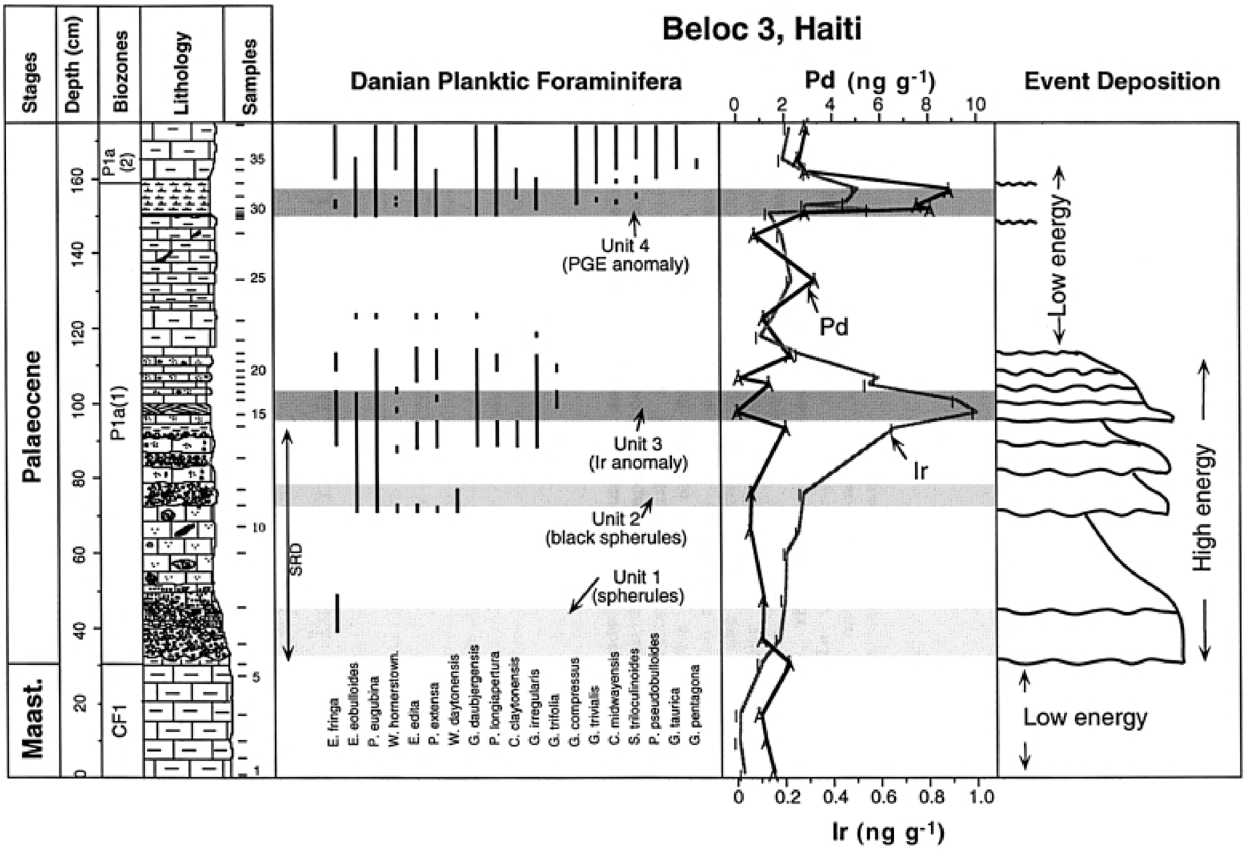

Fig. 5 K–T boundary transition at Beloc 3 showing lithological column, ranges of early Danian planktonic foraminifera, distributions of spherules, iridium and palladium, and depositional events consisting of graded calcarenites and spherules. Nine events reworking and redeposition are distinguished in the SRD and two minor reworking events, consisting of bioclastic layers and lenses, occur upsection in the interval of pelagic limestone. Shaded intervals mark lithological units 1–4, the extent of the spherule-rich deposit (SRD) is marked by an arrow (see text for discussion and Fig. 3 for symbols). Note that Ir values are low in the SRD and possibly due to mechanical reworking. The sharply peaked Ir anomaly in unit 3 may represent an early Danian impact event or reworking. The Ir-and Pd-dominated anomaly of unit 4 represents a major volcanic event.

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 sections elsewhere, was somehow transported downward into Cretaceous sediments (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 occurred 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 reworked from older sediments.

Earlier studies identified the Ir anomaly of unit 3 as the K–T boundary event (Jéhanno *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 Maastrichtian 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(1) and the lower part of the latest Maastrichtian CF1 Zones; the latter zone is characterized by *Plummerita 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 reworked, they would thus have come from the missing interval. Interestingly, in the Mexican sections the SRD is within 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, impact, 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 (Crocket and Kabir, 1988), or rift-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(l) as suggested by the Ir anomaly, and a major volcanic event in the upper part of Pla(l), 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 Maastrichtian 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 described for extraterrestrial origins. 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(l).

Acknowledgements

We thank three anonymous reviewers, Jerry Baum and Glen Izett for their comments and suggestions. This study was supported by the National Science Foundation (grant OCE-9021338), the Petroleum Research Fund (ACS-PRF grant 2670-AC8), the Deutsche Forschungsgemeinschaft (grants Sti128/2–1, 2–2, 2–3, and Stü 169/10–1), and the Swiss National Fund (grant 8220–028367).

References

Borg, G., Tredoux, M., Maiden, K., Sellshop, J. and Wayward, O., 1988. PGE- and Au-Distribution in Rift-related Volcanics, Sediments and Stratabound Cu/ Ag Ores of Middle Proterozoic Age in Central SWA/ Namibia. In: *Geoplatinum* (H.Prichard *et al.*, eds), pp. 303–317. Elsevier, London.

Bowles, J., 1986. The development of Platinum Group Minerals in Laterites. *Geology*, **81**, 1278–1285.

Crocket, J. and Kabir, A., 1988. PGE in Hawaiian basalt: Implication of Hydrothermal Alteration on PGE Mobility in Volcanic Fluids. In: *Geoplatinum* (H. Prichard *et al.*, eds), pp. 259. Elsevier, London.

Cubelic, M., Peccoroni, R., Schaäfer, J., Eckhardt, J.-D., Berner, Z. and Stüben, D., 1997. Verteilung verkehrsbedingter Edelmetallimissionen im Straßenrandbereich. *Umweltwiss. Schadstoff-Forsch.*, **9(5)**, 249–258.

Dalrymple, B.G., Izett, G.A., Snee, L.W. and Obradovich, J.D., 1993. $^{40}Ar/^{39}Ar$ Age spectra and total-fusion ages of tektites rom Cretaceous–Tertiary boundary sedimentary rocks in the Beloc

Formation, Haiti. *Bull. U.S. Geol. Surv.*, **2065**, 20pp.

Ekdale, A.A. and Stinnesbeck, W., 1998. Trace fossils in Cretaceous-Tertiary (KT) Boundary Beds in Northeastern Mexico: Implications for Sedimentation during the KT Boundary Event. *Palaios*, **8**, 593–602.

Fourcade, E., Rocchia, R., Gardin, S. *et al.*, 1998. Age of the Guatemala breccia: relationships with the asteroid impact on the Yucatan: *C. R. Acad. sci., Paris/ Sci. de la Terre et des Planetes*, **1998**, 47–53.

Fourcade, E., Piccioni, L., Escribá and Rosselo, E., 1999. Cretaceous stratigraphy and palaeoenvironments of the Southern Petén Basin, Guatemala. *Cret. Res.*, **20**, 793–811.

Ganapathy, R., 1980. A major meteorite impact on the earth 65 million years ago: evidence from the Cretaceous–Tertiary Boundary Clay. *Science*, **209**, 921–923.

Greenough, J.D. and Fryer, B.J., 1990. Leg 115 Indian Ocean Basalts. *Proc. Ocean drill. Proj., Sci. Results*, **115**, 71–84.

Izett, G.A., 1991. Tektites in the Cretaceous–Tertiary Boundary Rocks on Haiti and Their Bearing on the Alvarez Impact Extinction Hypothesis. *J. Geophys Res.*, **96**, 20, 879–20 820 905.

Izett, G.A., Maurrasse, F.J.-M.R., Lichte, F.E., Meeker, G.P. and Bates, R., 1990. Tektites in Cretaceous–Tertiary boundary rocks on Haiti. *U.S. Geol. Surv. Open File Rep.*, **90-635**, 31pp.

Izett, G.A., Dalrymple, G.G. and Snee, L.W., 1991. $^{40}Ar/^{39}Ar$ Age of Cretaceous/ Tertiary Boundary Tektites from Haiti. *Science*, **252**, 1539–1542.

Jehanno, C., Boclet, D., Froget, L. *et al.*, 1992. The Cretaceous–Tertiary boundary at Beloc, Haiti: No evidence for an impact in the Caribbean area. *Earth Planet. Sci. Lett.*, **109**, 229–241.

Keller, G., Li, L. and MacLeod, N., 1995. The Cretaceous/Tertiary boundary stratotype section at El Kef, Tunisia: how catastrophic was the mass extinction? *Paleogeogr. Paleoclim. Paleoecol.*, **119**, 221–254.

Keller, G., Lopez-Oliva, J.G., Stinnesbeck, W. and Adatte, T., 1997. Age, stratigraphy and deposition of near K/T siliciclastic deposits in Mexico: Relation to bolide impact? *Bull. Geol. Soc. Am.*, **109**, 410–428.

Keller, G., Adatte, T., Stinnesbeck, W. *et al.*, 1998. The Cretaceous-Tertiary transition on the Saharan platform of southern Tunisia. *Geobios*, **30**, 951–975.

Keller, G., Adatte, T., Stinnesbeck, W., Stüben, D. and Berner, Z., in press. Age, Chemo-and Biostratigraphy of Haiti spherule-rich sediments: a Multi-event K-T scenario. *Can J. Earth Sci.*, in press.

Koeberl, C., 1992. Water content of glasses from the K/T boundary, Haiti: an indication of impact origin. *Geochim. Cosmochim. Acta*, **56**, 4329–4332.

Koeberl, C., 1993. Chicxulub crater, Yucatan: Tectites, impact glasses, and the geochemistry of target rocks and breccias. *Geology*, **21**, 211–214.

Koeberl, C. and Sigurdsson, H., 1992. Geochemistry of impact glasses from the K/T boundary in Haiti: relation to smectites and new types of glass. *Geochim. Cosmochim. Acta*, **56**, 2113–2129.

Kring, D.A., Hildebrand, A.R. and Boynton, W.V., 1991. The petrology of an andesitic melt-rock and a polymict breccia from the interior of the Chicxulub structure, Yucatan, Mexico. In: *Abstracts of the XXII Lunar and Planetary Science Conference, Lunar and Planetary Science Institute, Houston, Texas*, pp. 755–756. Lunar and Planetary Science Publication, Houston, Texas.

Lamolda, M., Aguado, R., Maurrasse, F.J.-M.R. and Peryt, D., 1997. El tránsito Cretácico-Terciario en Beloc, Haití: registro micropaleontológico e implicaciones bioestratigráficas. *Geogaceta*, **22**, 97–100.

Leroux, H., Rocchia, R., Froget, L. *et al.*, 1995. The K/T boundary of Beloc (Haiti): Compared stratigraphic distributions of boundary markers. *Earth Planet. Sci. Lett*, **131**, 255–268.

Li, L. and Keller, G., 1998. Diversification and extinction in Campanian-Maastrichtian planktic foraminifera of Northwestern Tunisia. *Eclog. Geol. Helv.*, **91**, 75–102.

Lyons, J.B. and Officer, C.B., 1992. Mineralogy and petrology of the Haiti Cretaceous/Tertiary section. *Earth Planet. Sci. Lett.*, **109**, 205–224.

Maurrasse, F.-J.-M.R. and Sen, G., 1991. Impacts, tsunamis, and the Haitian Cretaceous–Tertiary boundary layer. *Science*, **252**, 1690–1693.

Pardo, A., Ortiz, N. and Keller, G., 1996. Latest Maastrichtian and K/T boundary foraminiferal turnover and environmental changes at Agost, Spain. In: *The Cretaceous/Tertiary Mass Extinction: Biotic and Environmental Events* (N. MacLeod and G. Keller, eds), pp. 155–176. W.W. Norton, New York.

Perch-Nielsen, K., 1988. Uppermost Maastrichtian and lowermost Danian calcareous nannofossil assemblages. In: *Abstracts of the Third International Conference on Global Bioevents: Abrupt Changes in the Global Biota, 9*. Kyoto, Japan.

Percival, S.F. Jr and Fisher, A.G., 1977. Changes in calcareous nannoplankton in the Cretaceous-Tertiary biotic crisis in Zumaya, Spain. *Evol. Theory*, **2**, 1–35.

Sigurdsson, H., D'Hondt, S., Arthur, M.A. *et al.*, 1991. Glass from the Cretaceous/ Tertiary boundary in Haiti. *Nature*, **349**, 482–487.

Smit, J., Montanari, A., Swinburne, N.H.M. *et al.*, 1992. Tektite bearing deep-water clastic unit at the Cretaceous–Tertiary boundary in northeastern Mexico. *Geology*, **20**, 99–103.

Stinnesbeck, W., Barbarin, J.M., Keller, G. *et al.*, 1993. Deposition of channel deposits near the Cretaceous /Tertiary boundary in northeastern Mexico: Catastrophic or 'normal' sedimentary deposits? *Geology*, **21**, 797–800.

Wallace, M., Gostin, V. and Keays, R., 1990. Acraman impact ejecta and host shales: evidence for low temperature mobilization of iridium and other platinoids. *Geology*, **18**, 132–135.,/bb>

Received 20 May 1999; revised version accepted 11 March 2000

