Proximal impact deposits at the Cretaceous-Tertiary boundary in the Gulf of Mexico: A restudy of DSDP Leg 77 Sites 536 and 540

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ABSTRACT

Restudy of Deep Sea Drilling Project Sites 536 and 540 in the southeast Gulf of Mexico gives evidence for a giant wave at Cretaceous-Tertiary boundary time. Five units are recognized: (1) Cenomanian limestone underlies a hiatus in which the five highest Cretaceous stages are missing, possibly because of catastrophic K-T erosion. (2) Pebbly mudstone, 45 m thick, represents a submarine landslide possibly of K-T age. (3) Current-bedded sandstone, more than 2.5 m thick, contains anomalous iridium, tektite glass, and shocked quartz; it is interpreted as ejecta from a nearby impact crater, reworked on the deep-sea floor by the resulting tsunami. (4) A 50-cm interval of calcareous mudstone containing small Cretaceous planktic foraminifera and the Ir peak is interpreted as the silt-size fraction of the Cretaceous material suspended by the impact-generated wave. (5) Calcareous mudstone with basal Tertiary forams and the uppermost tail of the Ir anomaly overlies the disturbed interval, dating the impact and wave event as K-T boundary age. Like Beloc in Haiti and Mimbral in Mexico, Sites 536 and 540 are consistent with a large K-T age impact at the nearby Chicxulub crater.

INTRODUCTION

The buried circular structure centered at Chicxulub, on the north coast of Yucatán, is a probable impact crater (Penfield and Camargo, 1981; Hildebrand et al., 1991). It contains a melt sheet within a platform-carbonate setting (López Ramos, 1980), and at 180 km in diameter, it would be the largest impact crater yet found on Earth. It is at least approximately of Cretaceous-Tertiary (K-T) boundary age (López Ramos, 1980) and has been put forward (Hildebrand et al., 1991; Pope et al., 1991; Hildebrand, 1992) as a candidate site for the K-T boundary impact.

Nearby K-T boundary sections may yield proximal deposits that may be accurately dated by using biostratigraphy, thus dating the crater. Studies of this kind at Beloc, Haiti (Hildebrand and Boynton, 1990; Izett et al., 1990; Maurrasse, 1980; Maurrasse and Sen, 1991; Sigurdsson et al., 1991), Brazos River, Texas (Smit and Romein, 1985; Bourgeois et al., 1988), the deep Caribbean (Hildebrand and Boynton, 1988, 1990), and Arroyo el Mimbral, northeastern Mexico (Smit et al., 1992) have identified extraordinary clastic deposits precisely at the K-T boundary; glassy tektites are still preserved in the Beloc and Mimbral sections. We here report a study of K-T boundary deposits from two Deep Sea Drilling Project (DSDP) sites only 400–500 km from the rim of the Chicxulub structure.

STRATIGRAPHY OF DSDP SITES 536 AND 540

Sediments of at least approximately K-T boundary age were recovered in the Gulf of Mexico during DSDP Legs 10 and 77. Pszczolkowski (1986) suggested that K-T deposits in sites 97 and 540 might bear on the impact hypothesis. We have restudied cores from sites 536 (lat 23°29.39′N, long 85°12.58′W, depth 2790 m) and 540 (lat 23°49.73′N, long 84°22.25′W, depth 2926 m), 93 km apart in the deep-water entrance to the Gulf of Mexico, between Yucatán and Florida. They have been described in detail by Buffler, Schlager, et al. (1984).

Both holes incompletely cored a current-bedded interval of approximately K-T age. Our mineralogical and Ir data presented below indicate that the current-bedded material in the two holes comes from a single, unusual, correlative unit, and so we have joined the cores from the two sites to provide a composite section across the K-T interval (Fig. 1). In the composite section, we recognize five units of interest (not the same as the Roman-numeral units of Buffler, Schlager, et al., 1984).

Unit 1: Autochthonous Cenomanian Limestone. The highest autochthonous Cretaceous sedimentary deposit in hole 540 is limestone of early Cenomanian age. Above the top of this unit 1 (540-36-1, 65 cm) is a hiatus comprising five of the six Upper Cretaceous stages. This entire hiatus possibly resulted from erosion triggered by a nearby K-T impact.

Unit 2: Pebbly Mudstone. This is at least in part a mudflow deposit, containing both coherently bedded mudstone and unsorted, matrix-supported pebbly mudstone with limestone clasts (Fig. 2F). The time of emplacement of unit 2 must have been between Cenomanian, on the basis of its forams (Buffler, Schlager, et al., 1984, and our restudy), and the basal Paleocene age of overlying autochthonous unit 5. It may or may not be a K-T boundary deposit.

Unit 3: Current-bedded Sandstone. This unit is represented by 2.6 m of sandstone in core 540-31 (Figs. 2D, 2E) and 0.6 m in core 536-9

Note: Additional material for this article is Supplementary Data 9225, available on request from the GSA Documents Secretary (see footnote 1).

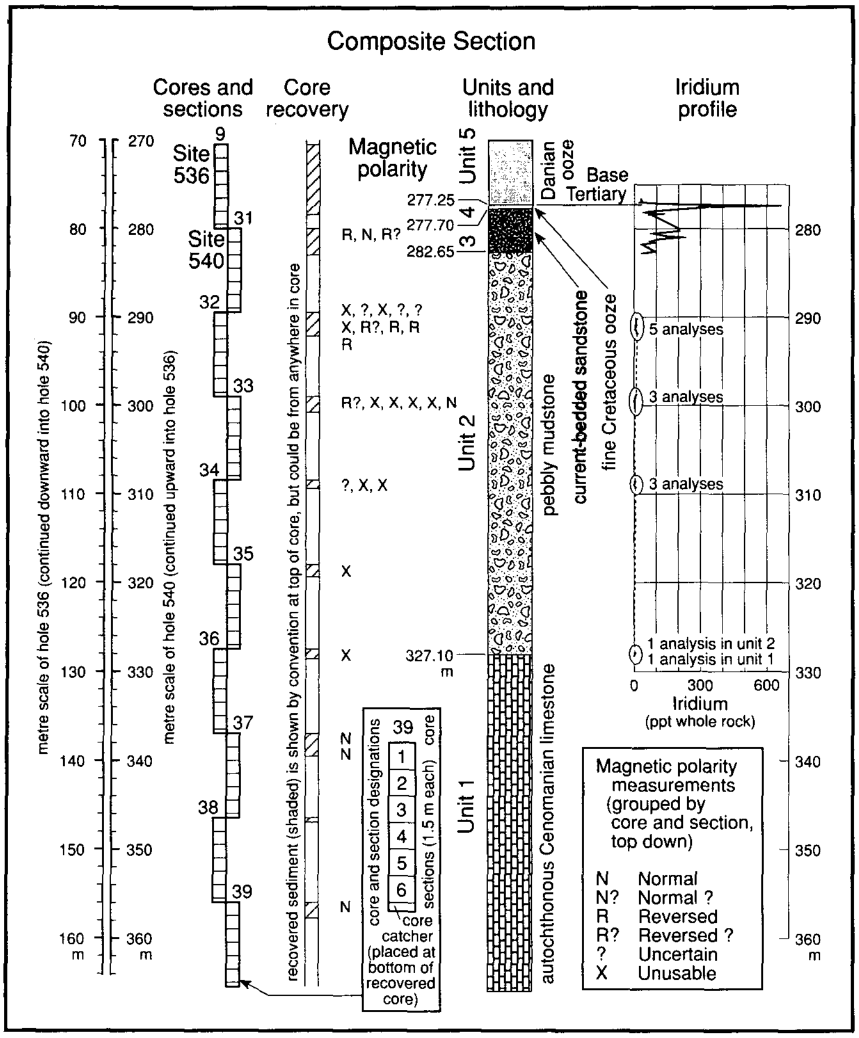

Figure 1. Composite section combining DSDP Sites 536 and 540.

(Figs. 2B, 2C). Unit 3 has an indistinct, gradational upward limit at about 120–125 cm in section 536-9-5. Initial core descriptions in Buffler, Schlager, et al. (1984) reported that the sandstone in core 540-31 is composed of grains of bioclastic limestone together with clay interpreted as altered volcanic material (p. 142) and that in core 536-9 it is composed principally of forams and clay (p. 243). Detailed studies at the time found the clay to be entirely smectite (Debrabant et al., 1984). We found the carbonate-free fraction to be mainly smectite, pyrite, and some gypsum, minor quartz and feldspar, and phillipsite in some samples. Because of differences in the proportions of the components, this unit varies from dark to light gray. Cross-bedding, locally bidirectional, is conspicuous in some intervals (Fig. 2D), but other parts are more massive (Fig. 2E). The detailed data given below lead us to the interpretation that this unit is composed of K-T boundary ejecta reworked by waves and currents generated by a nearby impact.

Unit 4: Fine Cretaceous Ooze. Above the gradational top of the current-bedded sandstone (Fig. 2B) is unit 4 (Fig. 2A), an interval about 50 cm thick (section 536-9-5, 75–125 cm) in which the only planktic forams are very small Cretaceous species. Small Paleocene forams are not mixed in with the small Cretaceous forams. We interpret unit 4 as the finest fraction of the sediment stirred up by a K-T impact wave, which was suspended and then settled out.

Unit 5: Danian Ooze. In section 536-9-5, between samples at 84 and 75 cm, the fauna of Cretaceous small planktic forams is replaced by extremely well preserved, small Tertiary forams of the basal Paleocene *eugubina* zone (Fig. 2A). Although the very basal Tertiary foram zone, P0—which was recognized directly above the mega-tsunami deposits at Mimbral (Smit et al., 1992)—was not found in site 536, it is rarely identified at K-T boundary sites. The P0 zone may represent as little as 5000–15 000 yr (Smit, 1990), and bioturbation and drilling disturbance can easily obscure P0-zone material by mixing it into the overlying *eugubina* zone. We conclude that the depositional age of units 3 and 4 cannot be distinguished from the age of the K-T boundary.

PALEOMAGNETISM

Magnetic polarity stratigraphy can constrain the emplacement age of mudflows fluidized and magnetically reset during emplacement (Alvarez and Lowrie, 1984). Remanent magnetizations of 27 samples (Fig. 1) were extremely weak. In units 2 and 3, natural remanent magnetizations (NRM) averaged only 2.3×10^{-5} A/m, and no usable signal was left after thermal cleaning to 300 or 400 °C. In some samples, thermal demagnetization aided by vector diagram analysis revealed a single magnetization component, but other samples gave only a stable end-point direction.

Three samples from unit 1 with stronger than average intensities had normal polarities, as expected for their Cenomanian age. Their inclinations average +30°, compatible with the +36° predicted for a paleolatitude of about 20°N (Smith and Briden, 1977).

In the unit 2 mudstones, 15 of the 21 samples were too weak or inconsistent to be usable. Section 33-1 yielded inconclusive results; one sample had uncertain reversed polarity and one had normal (possibly remagnetized) polarity. The strongest results came from core 32, section 2 and core catcher: one questionably reversed and three definite reversed samples. This part of unit 2 shows faint bedding and lacks limestone clasts; it may be a coherent slab within the mudflow. The reversed polarity is incompatible with mudflow emplacement in the Cenomanian (or elsewhere in the Cretaceous Long Normal Chron). The unit 2 samples are consistent with emplacement of the unit as a single mudflow at K-T boundary time, but the data cannot exclude emplacement or remagnetization in a Campanian-Paleocene reversed polarity chron.

Three samples from the current-bedded sandstone of unit 3 (section 31-1) gave inconclusive results (Fig. 1). Micropaleontology and the presence of glass and an Ir anomaly argue that this unit is a K-T boundary deposit, and the paleomagnetic results do not contradict this view.

GLASS

Buffler, Schlager, et al. (1984, p. 47, 554) inferred that the smectite of unit 3 was derived from alteration of volcanic glass. The high Ir levels we observed suggest an impact origin instead. This was confirmed by our recovery of altered spherules (Fig. 3A) and glass fragments (samples 536-9-cc, 1–2 cm; 536-9-cc, 10–12 cm; 540-31-1-, 141–142 cm) whose characteristics indicate origin by impact.

Glass fragments from Sites 536 and 540 are generally <50 μm in diameter (Fig. 3B); they are green, brown, amber, and clear in plane-polarized light and isotropic in cross-polarized light. Igneous magmas remain molten for tens to thousands of years, allowing crystallites and phenocrysts to grow. Impact ejecta is flash-melted and immediately quenched, with no time for crystals to grow (Glass, 1990; Izett, 1991).

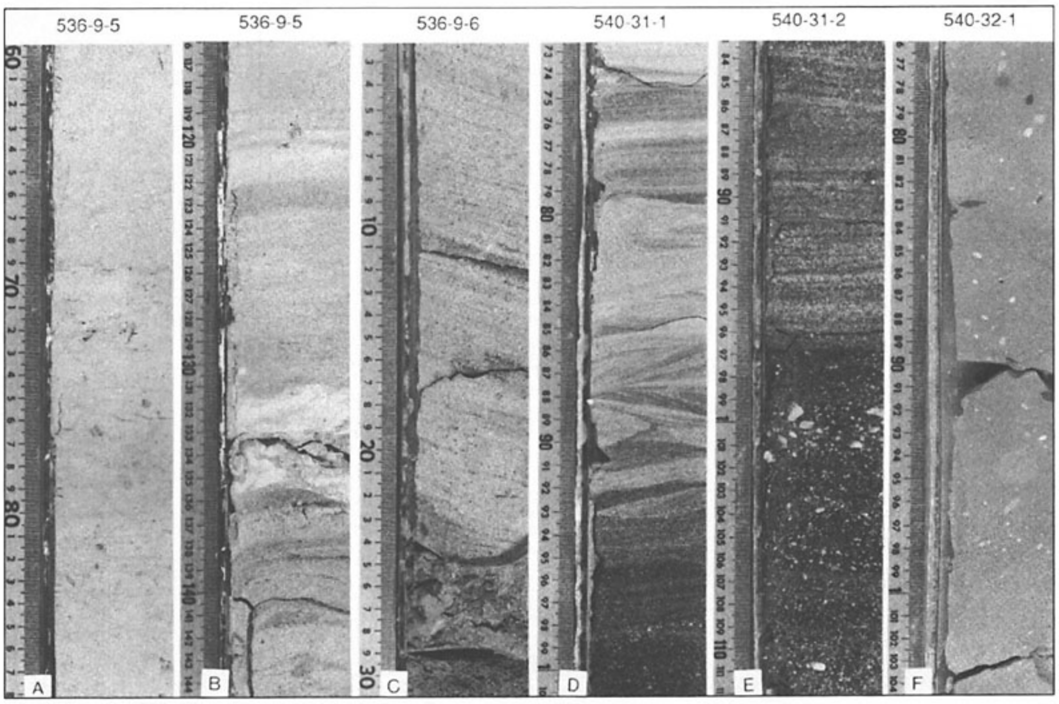

Figure 2. Important facies from K-T interval in DSDP Sites 536 and 540. A: Basal Paleocene (*eugubina* zone) ooze (unit 5) resting on top of Cretaceous ooze containing only small forams (unit 4), which is interpreted as redeposited mud suspended by large K-T wave (contact at 75 cm). B: Gradational transition downward (at 120–125 cm) from redeposited ooze of unit 4 to current-bedded sandstone of unit 3. C: Foreset bedding in sandstone of unit 3. D: Cross-bedding, in part bidirectional, in unit 3 sandstone. E: Unit 3 sandstone, rich in dark pyrite. F: Pebbly mudstone of unit 2.

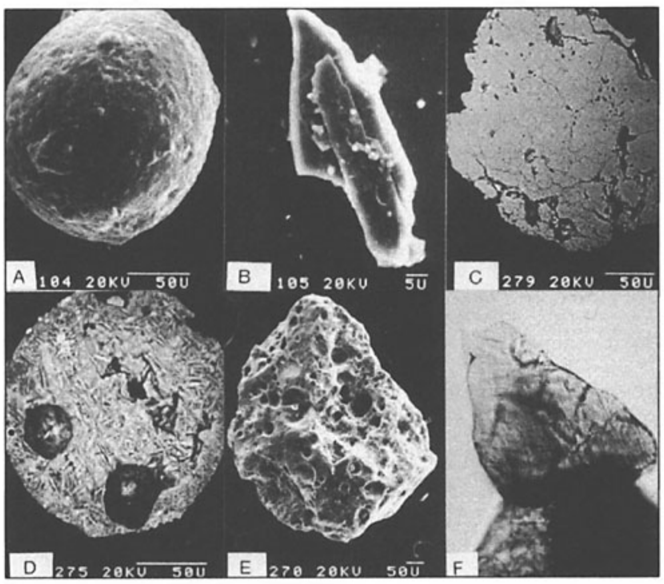

Figure 3. Spherules, glass, and shocked quartz from DSDP Leg 77 K-T interval. Scale-bar values are micrometres. A: Spherule partially altered to smectite; similar spherules when broken open are seen to contain glass remnants (scanning electron microscope [SEM]; 536-9-cc, 1–2 cm). B: Glass fragment from insoluble residue, probably spherule core (SEM; 536-9-cc, 11–12 cm). C: Polished section of pure SiO_2 glass grain (SEM; 536-9-cc, 1–2 cm). D: Polished section of spherule with K-feldspar crystals in matrix of glass with approximately K-feldspar composition (SEM; 536-9-cc, 1–2 cm). E: Partly altered vesicular glassy fragment (SEM; 540-31-2, 40–112 cm). F: Quartz grain, 0.21 mm in diameter, showing two strong sets of planar deformation features (plane-polarized light; spindle mount: 540-31-1, 53–55 cm).

The absence of crystals in the unit 3 glass thus argues for an origin as impact ejecta. Neither crystals of igneous minerals nor volcanic rock fragments were found anywhere in the unit 3 sandstone.

Impact-ejecta glass differs compositionally from volcanic glass in two ways. (1) Because the ejecta is only briefly molten there is insufficient time for mixing, so ejecta glasses from a single impact can be compositionally variable. (2) Shock melting of various target rocks gives exotic compositions unlike those of igneous rocks. K-T glasses from Beloc (Izett et al., 1990; Izett, 1991; Maurrasse and Sen, 1991; Sigurdsson et al., 1991), Mimbral (Smit et al., 1992), and Leg 77 show both these characteristics. Leg 77 glass samples (Table 1) are low in Fe (<1%) but high in Na (Table 1, analysis 1), K (analysis 2), and Ca (analyses 3 and 4). Nearly pure SiO_2 glass occurs as stringers, droplets, and shards (Fig. 3C) and may be shock-melted quartz.

The K-rich glass is associated with crystalline sanidine spherules <200 μm in diameter (Fig. 3D) that are similar in structure and composition to those described from K-T boundary sections in Europe and elsewhere as altered microtektites (Smit and Klaver, 1981; Montanari et al., 1983). Leg 77 for the first time yielded small amounts of glass preserved in K-T sanidine spherules, suggesting that marine diagenesis is responsible for the alteration of the glass to sanidine.

Several large (>200 μm) vesicular grains of partially altered glass were found in sample 540-31-2, 40–112 cm (Fig. 3E). The composition of the glass and associated smectitic clay is similar to Ca-rich glass from Mimbral, and like the Beloc glass, it has a high S content. These grains are morphologically similar to vesicular impact ejecta in deep-sea sediments of late Pliocene age (Margolis et al., 1991).

In summary, an impact origin for the Leg 77 glasses is indicated by (1) absence of crystals in the glass, (2) absence of crystals and volcanic rock fragments in the unit 3 sandstone, (3) heterogeneity of glass compositions, and (4) exotic glass chemistry.

SHOCKED MINERALS

Abundant shocked grains were recovered from site 540 (31-1, 29–30 cm and 53–55 cm). In each insoluble residue, grains larger than about 0.1 mm were examined by using a spindle stage on a petrographic microscope, and both shocked and unshocked grains of quartz, quartzite, and feldspar were found. Multiple planar deformation features (Fig. 3F), which are unambiguous evidence for shock metamorphism, were observed in 24% and 31% of the grains in the two samples, respectively. Using the technique of Hörz and Quaide (1973), Debye-Scherrer X-ray diffraction studies of a rotated single grain confirmed the visual identification of shock effects in the quartz grains from Site 540.

The largest shocked grains found were 0.21 mm in diameter, and single crystals of shocked quartz contain up to nine sets of lamellae. The average value for the two sites of 28% of grains

TABLE 1. MICROPROBE ANALYSES OF LEG 77 GLASS

	1	2	3	4
SiO_2	70.40	68.40	62.67	60.41
Al_2O_3	20.95	19.32	21.58	20.87
FeO	0.18	0.09	0.55	0.79
MgO	0.05	0.08	0.14	0.19
CaO	0.26	1.12	4.25	4.97
K_2O	2.96	10.21	8.12	6.66
Na_2O	4.32	0.84	2.60	2.77
TiO_2	0.04	0.04	0.13	0.01
MnO	0.06	0.03	-	-
CrO	0.03	-	-	-
NiO	0.03	-	-	-
CuO	0.03	-	-	-
S	0.01	-	-	-
Total	99.31	99.77	100.04	96.67

Note: Analysis 1 from Site 540, section 31-1, 141-142 cm depth; 2, 3, and 4 are from Site 536, section 9-cc; 2 is from 1-2 cm depth; 3 and 4 are from 10-12 cm depth.

showing shock features is within the range of 12%–47% (average about 30%) reported for K-T sites in western North America (Izett, 1990); it is similar to 27% and 31% reported for an intracrater breccia and proximal ejecta of the Chicxulub crater (Hildebrand et al., 1991) and 26% for the K-T spherule bed at Mimbral (Smit et al., 1992). Grain lithologies are similar to those of K-T sites in western North America and Mimbral. These observations suggest a common source at the Chicxulub crater.

IRIDIUM

The interpretation of units 3 and 4 as K-T boundary deposits containing impact ejecta is strengthened by Ir measurements (Fig. 1; also Table 2[1]). One sample from the top of unit 1 has very low Ir. Low Ir concentrations are also found in 12 samples from the mudstone matrix of unit 2. If unit 2 is a K-T mudflow, it must have been triggered by seismic or water waves, just before the arrival of Ir-bearing impact ejecta.

Ir values are well above background (50–250 ng/g) in unit 3, supporting the interpretation that this unit contains a component of impact ejecta. Ir peaks at 650 ±15 ng/g near the top of unit 4, tailing out upward into the very basal Paleocene, with an integrated column density of about 50 ng Ir/cm^2. This suggests that fine Ir-bearing dust settled out with the suspended carbonate ooze.

DISCUSSION

The glassy microtektites, shocked quartz, and high Ir values support an impact origin for the Sites 536 and 540 clastic deposits. Biostratigraphy localizes these deposits at or extremely near the K-T boundary. Coarse clastic deposits at the biostratigraphic K-T boundary in otherwise fine-grained, deep-water sedimentary units are known only at sites in and around the Gulf of Mexico and the Caribbean; they appear to be the signature of a gigantic tsunami, which argues for nearby impact. These observations on Sites 536 and 540, together with recent results on Beloc, Mimbral, and the Chicxulub crater strongly support the hypothesis that a major impact occurred at K-T time on the northern Yucatán Peninsula.

[1] Table 2, Iridium Analyses from DSDP 536 and 540, GSA Supplementary Data 9225, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

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