Meteoritics & Planetary Science 39, Nr 7, 1127–1144 (2004)
Abstract available online at http://meteoritics.org

More evidence that the Chicxulub impact predates the K/T mass extinction

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(Received 21 July 2003; revision accepted 21 May 2004)

Abstract–Yaxcopoil-1 (Yax-1), drilled within the Chicxulub crater, was expected to yield the final proof that this impact occurred precisely 65 Myr ago and caused the mass extinction at the Cretaceous-Tertiary (K/T) boundary. Instead, contrary evidence was discovered based on five independent proxies (sedimentologic, biostratigraphic, magnetostratigraphic, stable isotopic, and iridium) that revealed that the Chicxulub impact predates the K/T boundary by about 300,000 years and could not have caused the mass extinction. This is demonstrated by the presence of five bioturbated glauconite layers and planktic foraminiferal assemblages of the latest Maastrichtian zone CF1 and is corroborated by magnetostratigraphic chron 29r and characteristic late Maastrichtian stable isotope signals. These results were first presented in Keller et al. (2004). In this study, we present more detailed evidence of the presence of late Maastrichtian planktic foraminifera, sedimentologic, and mineralogic analyses that demonstrate that the Chicxulub impact breccia predates the K/T boundary and that the sediments between the breccia and the K/T boundary were deposited in a normal marine environment during the last 300,000 years of the Cretaceous.

INTRODUCTION

In the early 1990s, the Chicxulub crater on Yucatán, Mexico, was hailed as the smoking gun that proves the Alvarez et al. (1980) hypothesis that a single large asteroid killed the dinosaurs and caused the mass extinction of many other organisms at the Cretaceous-Tertiary (K/T) boundary 65 Myr ago. The impact crater size was estimated to be between 180 and 300 km (Hildebrand et al. 1991; Sharpton et al. 1992; Urrutia-Fucugauchi et al. 1996; Morgan and Warner 1999). Microspherule deposits surrounding the Gulf of Mexico were identified as impact ejecta (microtektites) and the frequently overlying siliciclastic deposits in northeastern Mexico as impact-generated megatsunami deposits (see review by Smit 1999). Microtektites and melt rock from the Chicxulub crater yielded $^{39}Ar/^{40}Ar$ ages within ±200 kyr of the K/T boundary (Izett 199l; Sigurdsson et al. 1991; Swisher et al. 1992; Dalrymple et al. 1993). These observations and interpretations made a convincing case for Chicxulub as the long-sought K/T boundary impact crater and the cause for the mass extinction at the end of the Cretaceous.

But doubts persisted regarding the precise age and size of the Chicxulub impact crater (review in Keller et al. 2003a) and the nature of the mass extinction (review in Keller 2001). Investigations of Chicxulub cores and logs drilled by Petróleos Mexicanos (PEMEX) in the 1960s revealed late Maastrichtian sediments overlying the impact breccia (Lopez-Ramos 1973, 1975), though confirmation proved difficult because critical samples were unavailable (Ward et al. 1995).

This left the burden of proof for a K/T age on sections with impact ejecta (e.g., glass spherules or microtektites) in northeastern Mexico (Fig. 1). However, from the very beginning, a K/T age of the Chicxulub impact in these sections was inconsistent with: i) the stratigraphic position of the impact ejecta at the base of a several m-thick massive sandstone and 1–2 m of alternating sand/silt/shale layers; ii) the several horizons of bioturbation within these sediments, which indicate repeated colonization of the ocean floor by invertebrates and, hence, deposition over an extended time period (Keller et al. 1997; Ekdale and Stinnesbeck 1998); iii) the presence of the iridium anomaly, which marks the K/T boundary impact and mass extinction worldwide, in the sediments above; and iv) the presence of a 20 cm-thick burrowed sandy limestone layer within the spherule deposit below the sandstone layer, which indicates that spherule deposition occurred in two phases separated by a period of

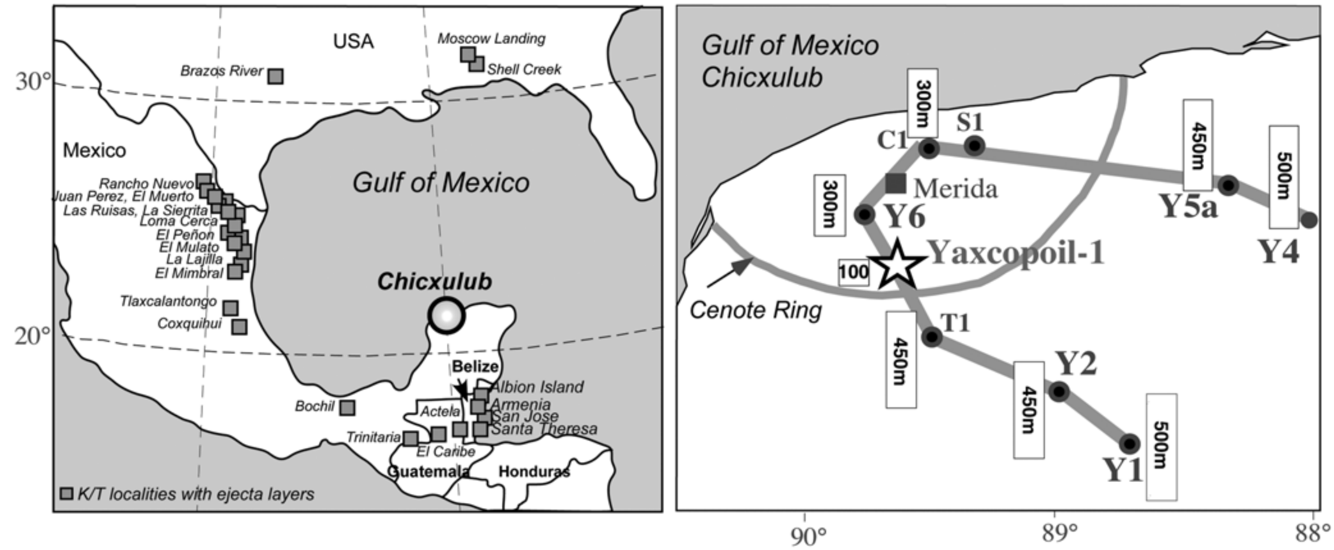

Fig. 1. Location map (a) showing localities with impact ejecta (microtektites) studied by the authors in the southern USA, Mexico, Guatemala, and Belize; b) localities studied on Yucatán within and outside the Chicxulub impact crater. The vertical bars mark the thickness of impact breccia at each locality. Note that, at Yaxcopoil-1, the impact breccia is only 100 m thick, compared with 300 m and 450 m inside and outside the crater, respectively.

time with no spherule deposition (review in Keller et al. 2003a). All these factors indicate that a megatsunami could not explain the separation of the spherule ejecta deposits below and the Ir anomaly and K/T mass extinction above the sandstone and sand/shale/silt layers as proposed by Smit et al. (1992, 1996; Smit 1999).

Recently, a K/T age for the Chicxulub crater was further placed in doubt with the discovery of glass spherule (microtektite) layers interbedded in up to 10 m of late Maastrichtian marls below the previously recognized spherule deposits in outcrops throughout northeastern Mexico, with particularly good outcrop exposures at Loma Cerca and El Peñon (Keller et al. 2002). The oldest and stratigraphically lowermost glass spherule layer occurs near the base of the planktic foraminiferal biozone CF1, which spans the last 300,000 years of the Maastrichtian. This indicates that the Chicxulub impact predates the K/T boundary by about 300,000 years; the younger microtektite layers are likely reworked (Stinnesbeck et al. 2001; Keller et al. 2002a, b, 2003a). In contrast, glass spherule deposits in Haiti, Guatemala, and Belize (Fig. 1) were found interbedded in early Danian sediments and evidently reworked from the original deposit (Keller et al. 2001, 2003b).

The new core drilled within the central basin of the Chicxulub crater was expected to resolve the controversy regarding the age of the Chicxulub impact. In 2001–2002 (Dec.–Feb.), the International Continental Scientific Drilling Program (ICDP) supported the drilling of a new core, Yaxcopoil-1 (Yax-1), within the Chicxulub crater with the stated objectives to: i) determine the precise age of the Chicxulub crater and its link to the global K/T boundary layer; ii) unravel Chicxulub's role in the K/T mass extinction; and iii) study the cratering event and size of the impact crater. Yax-1, drilled within the 60 km radius transient cavity of the impact structure, was expected to yield several hundred meters of impact breccia (suevite) overlying a coherent impact melt sheet (Dressler et al. 2003).

The new drill core, Yax-1, is located 40 km southwest of Mérida, Mexico and approximately 60 km from the center of the Chicxulub structure between the existing PEMEX wells Yucatán-6 (Y6) and Ticul-1 (T1) (Fig. 1). A continuous sequence of cores from 400 m to 1511 m subsurface was recovered. A 100 m-thick impact breccia was encountered between 794–894 m, overlying layered Cretaceous limestones, dolomites, and anhydrites between 894–1511 m (Stinnesbeck et al. Forthcoming). Preliminary investigation identified these Cretaceous sediments as large megablocks displaced into the crater as a result of impact-induced shaking (Dressler et al. 2003). Subsequent stratigraphic examinations revealed para-autochthonous sediments with correlatable horizons over several hundred kilometers in northern and southern Yucatán, which indicates that they represent relatively undisturbed in situ deposition rather than displaced megablocks (Stinnesbeck et al. 2003, Forthcoming).

New Controversy Over the Age of Chicxulub

Instead of settling once and for all a K/T age for the Chicxulub impact, the evidence from the new crater core Yax-1 supported the previous findings of a pre-K/T age and fueled a new controversy (Keller et al. 2004). The critical evidence is within a 50 cm-thick laminated micritic and partially dolomitized limestone between the top of the impact breccia and a 1 cm-thick green clay layer that marks the K/T

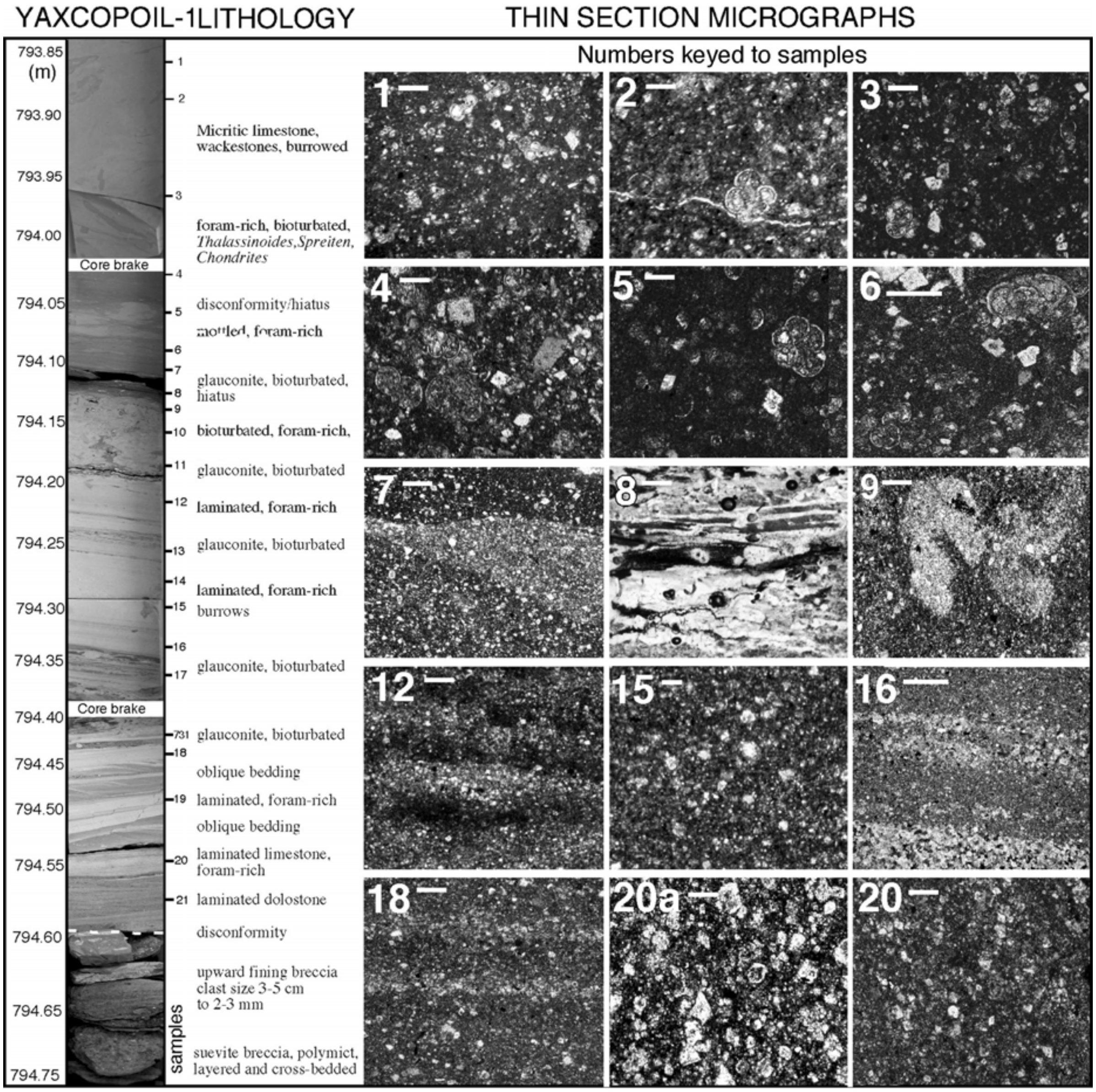

Fig. 2. Litholog of the 50 cm interval between the disconformities at the top of the impact breccia and the K/T boundary. (Scale bar = 0.1 mm for samples 16, 8, and 20a and 1 mm for all other samples.) Sedimentary features of samples are shown in thin section micrographs with the numbers keyed to the sample location in the litholog.

transition. Above this green clay, the first early Danian species of zone Pla (*Parvularugoglobigerina eugubina*) are observed.

If Chicxulub is the impact crater that caused the mass extinction, then this 50 cm-thick layer must be part of the impact as crater infill, backwash, or slumping from the crater walls, and the sediments should reflect this in a jumble of diverse rock types, breccia clasts, faunal elements of different ages, and high energy deposition. But if this 50 cm-thick layer shows none of these characteristics and instead reveals finely laminated sediments, glauconite layers, bioturbation, and hardgrounds indicative of low energy environments, and these sediments also contain planktic foraminiferal assemblages characteristic of very late Maastrichtian age, and the magnetostratigraphy reveals that deposition occurred within the latest Maastrichtian chron 29r, then the conclusion is inescapable that Chicxulub is not the long-sought K/T impact but an earlier impact.

In an earlier paper (Keller et al. 2004), we presented evidence from five different and independent proxies (sedimentology, magnetostratigraphy, ^{13}C data, planktic foraminiferal biostratigraphy, and iridium analysis) that the Chicxulub impact predates the K/T boundary by about 300,000 years and that this age is consistent with earlier results reported from K/T sections throughout northeastern Mexico (review in Keller et al. 2003a). Some have criticized these findings claiming that the foraminiferal images we

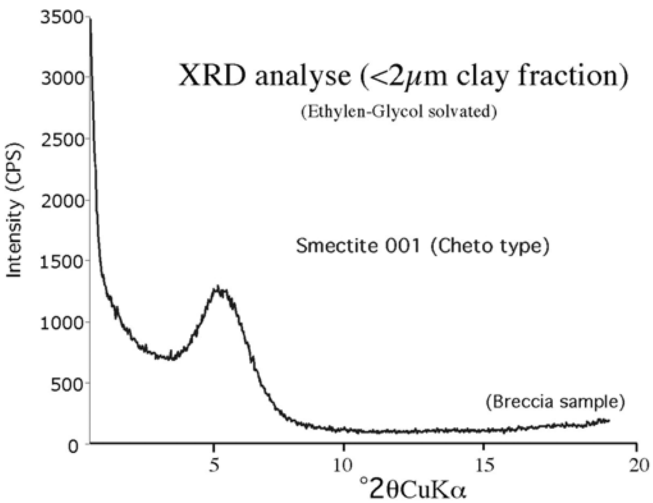

Fig. 3. XRD diffractogram of clay from the impact breccia shows well-crystallized Cheto smectite, which is a typical altered glass product.

presented are nothing more than dolomite rhombs (Smit et al. 2004; Arz et al. 2004) and that the 50 cm-thick interval represents high energy sedimentation consistent with backwash and crater infill (Smit et al. 2004). In this paper, we present further evidence in support of our original findings and demonstrate the presence of late Maastrichtian planktic foraminifera and normal sedimentation above the impact breccia.

Specifically, we focus on: 1) the nature and age of the impact breccia; 2) the nature of sediment deposition above the impact breccia; 3) the age proxies above the impact breccia; 4) biostratigraphy of planktic foraminifera; 5) the position of the K/T boundary and evidence for a K/T hiatus; and 5) the paleoenvironment. In addition, the Yax-1 results are compared and correlated with impact ejecta layers in northeastern Mexico.

Methods

The Yax-1 core was visually examined for lithological changes, sedimentary structures, macrofossils, trace fossils, bioturbation, erosion surfaces, and disconformities for the interval from the impact breccia through the early Tertiary. For the first 70 cm above the impact breccia, samples were collected at 3–5 cm intervals and at 10–20 cm intervals in the early Tertiary. Samples were analyzed for microfacies, microfossils, and mineralogical analyses as reported here.

For each sample, one or more thin sections were made and analyzed for microfacies and microfossils. A fraction of the samples was processed for foraminiferal studies and washed through a 63 micron screen, with the smaller (36–63 μm) size fraction separated and oven dried for examination of tiny specimens. Only the early Danian washed residues yielded tiny, poorly preserved species in 3D. In the micritic limestone between the top of the impact breccia and the K/T boundary, foraminifera are strongly recrystallized and cannot be freed from the enclosing sediments. Microfossils in these samples were, therefore, analyzed in thin sections with the petrographic microscope as well as cathodoluminescence.

For geochemical and mineralogical analyses, selected samples were dried, crushed, finely ground in an agate mill, and dried. Clay mineral analyses were conducted at the Geological Institute of the University of Neuchatel, Switzerland, based on XRD analyses (SCINTAG XRD 2000 Diffractometer). Sample processing followed the procedure outlined by Kübler (1987) and Adatte et al. (1996). For selected samples, wavelength dispersive (WDS) and energy-dispersive (ESEM, EDS) electron microprobe analyses were performed at the University of Neuchatel, Switzerland. All quantitative major element analyses were calibrated with common standards. Detection limits are in the range between 0.5 and 1 wt‰.

Platinum group elements (PGE) (analyzed by isotope dilution mass spectrometry ICP-MS, Axiom from VG Elemental, UK) and stable isotope analysis of bulk rock samples (by MultiPrep and Optima, both from Micromass UK Ltd.) were conducted at the Institute for Mineralogy and Geochemistry, University of Karlsruhe.

RESULTS

Impact Breccia

A 100 m-thick impact breccia is present between 794.65–895 m subsurface depth, and two small suevitic dykes are present at 915 m and 909 m, but there is no impact melt sheet. The breccia contains angular to subrounded clasts of dolomite, anhydrite, limestone with miliolids, and rare sandstone. There is also a minor component of melt rock and crystalline rocks of continental basement origin, such as granodiorite, gneiss, quartzite, and micaschist. Gray-green altered glass fragments and spherules are common along with quartz and feldspar xenocrysts with planar deformation lamellae (Stinnesbeck et al. Forthcoming). The upper 15 m of the breccia are stratified and show upward fining of clasts from 3–5 cm at the base to 2–5 mm at the top (Fig. 2). Coarse cross-bedding structures, alternating breccia layers of upward fining clasts, interbedded with gray friable sand layers in the top meter indicate reworking and current transport after deposition of the breccia. Devitrified glass fragments and spherules are common in the breccia and indicate alteration of glass.

Clay Fraction

Four samples were analyzed from the breccia at depths of 827.81, 851.02, 861.74, and 876.37 m. XRD analyses of these samples indicate the presence of Cheto smectite derived from altered glass in the Yaxcopoil breccia (Fig. 3). Smectite forms 90–100% of the clay fraction in this breccia and is

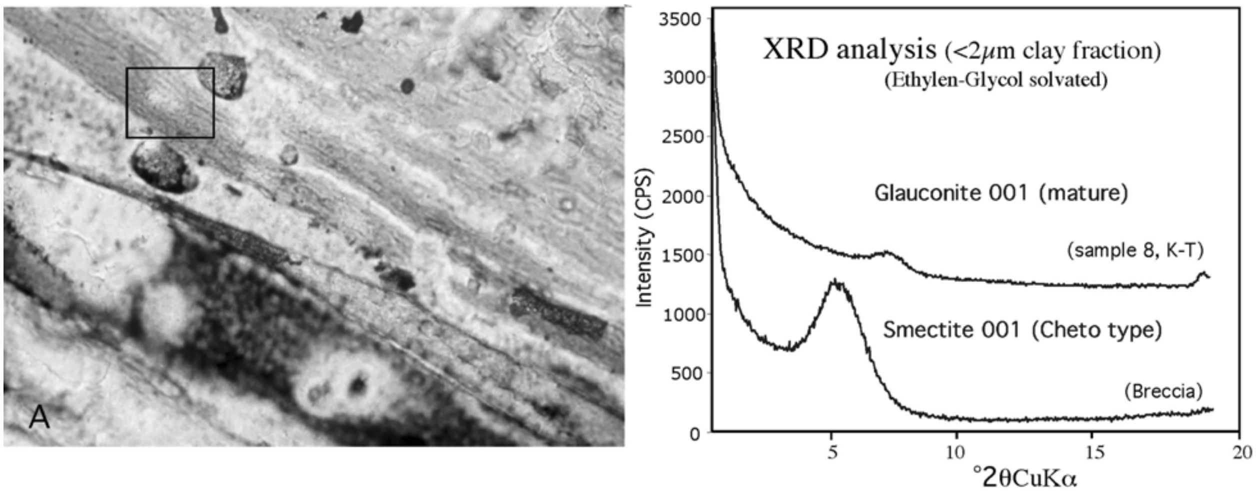

Fig. 4. Thin section micrograph of the green K/T clay layer (sample 8) with insert marking location of analysis. The XRD diffractogram of this green clay indicates the presence of mature glauconite. In contrast, XRD analysis of breccia samples shows the presence of well-crystallized Cheto smectite, which is a typical alteration product of glass.

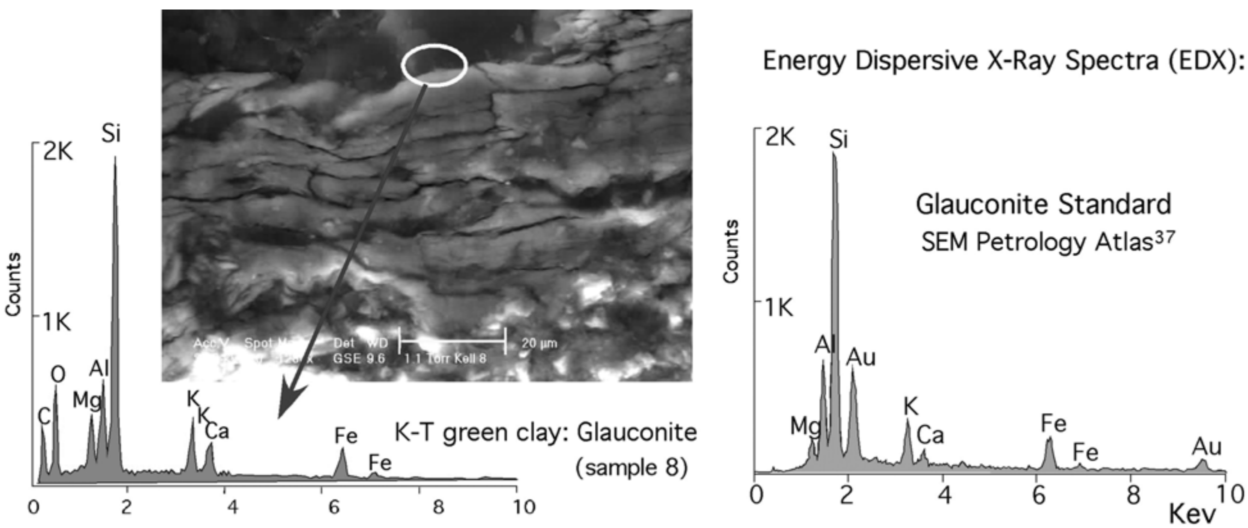

Fig. 5. Environmental SEM micrograph of the K/T green clay (sample 8) with electron diffractometer X-ray analysis that indicates a glauconite composition. The glauconite reference standard from the *SEM petrology atlas* (Welton 1984) is shown for comparison.

characterized by excellent crystallinity and a high intensity of the 001 reflection. After heating, the 9.66 Å reflection is very reduced compared with the ethylen-glycol solvated preparation, implying a particular cationic configuration of the interlayer as observed in bentonites derived from volcanic glass (Caillère et al. 1982; Debrabant et al. 1999). Based on XRD and thermoanalytic (DTA) techniques, Debrabant et al. (1999) interpreted such smectites at El Caribe in Guatemala and Ceibo (also called Tlaxcalantongo) in central Mexico as Na-Mg bentonite (Cheto type) derived from weathering of an impact glass spherule layer. Keller et al. (2003b) documented similar Cheto smectites in altered glass spherule and spheroid layers at Albion Island, Armenia, Santa Theresa and San Jose in Belize, Actela in Guatemala, Beloc in Haiti, Coxquihui in central Mexico, and Bochil and Trinitaria in central and southern Mexico (Fig. 1). In all of these localities, except Haiti, glass spherule deposition occurred on a confined carbonate platform that favored weathering in a pure smectite phase. Although these Cheto Mg-smectite clays may also be derived from volcanic glass (Elliot et al. 1989; Elliot 1993), their consistent association with altered glass spherule layers in Central America and with the impact breccia in Yax-1 strongly indictes a Chicxulub tektite origin.

Nature of Sediment Deposition above Impact Breccia

Laminated Limestones

The contact between the top of the reworked breccia and the overlying limestone is abrupt and erosional. About 50 cm of laminated micritic limestone separates this current bedded

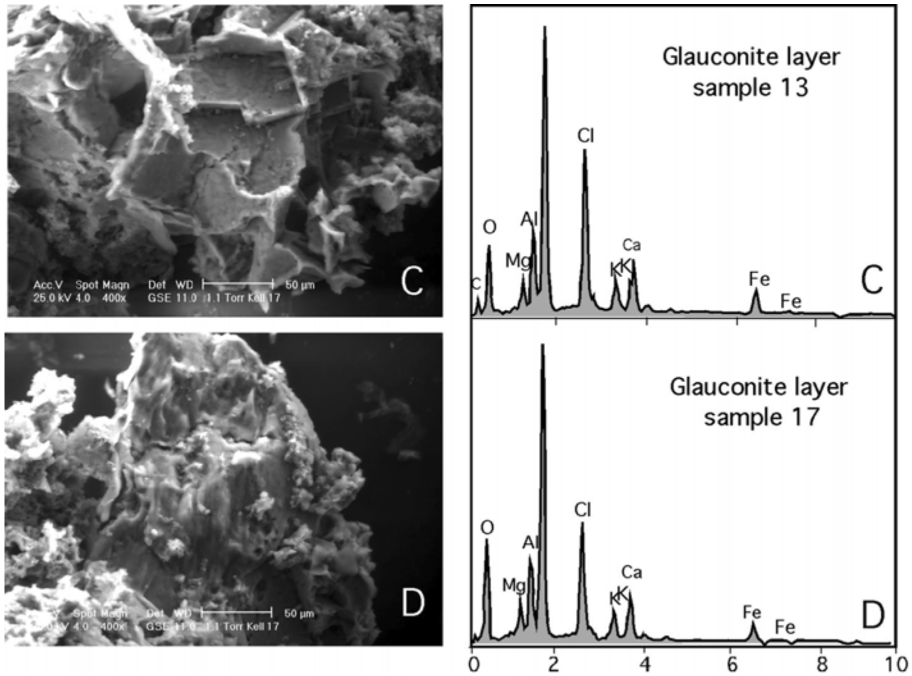

Fig. 6. Environmental SEM micrographs of insoluble residue grains from two green glauconite layers (samples 13 and 17) with electron diffractometer X-ray analysis that indicate a glauconite composition. (Note that the Cl peak is is due to the chlorhydric acid used in preparation of insoluble residues.) The two glauconite layers are between the K/T boundary and the impact breccia.

breccia from the K/T boundary (794.60–794.11 m; Fig. 2). The nature and depositional environment of this 50 cm-thick interval provides a critical test of in situ versus backwash and crater infill and, hence, the age of the impact. The lowermost 5 cm of this interval consist of coarse dolostone. Above it is a finely laminated micritic limestone with microlayers and patches of anhedral dolomite crystals. The laminated limestone indicates that deposition occurred in a quiet, low energy environment, while the dolomite crystals formed by diagenetic replacement of the precursor limestone with the original laminated texture still visible (Fig. 2).

Various sedimentary structures within the laminated limestone reveal a variable sedimentary history. Oblique bedding in three 1 cm-thick layers between 794.45 and 794.53 m likely formed by slightly agitated waters. However, Smit et al. (2003, written communication, 2004) claim these features represent cross-bedded, fine-grained sands and, hence, evidence of high-energy, post-impact backwash and basin infill. Moreover, they interpret the entire 50 cm-thick laminated interval as a cross-bedded unit that reflects the post-impact basin infill. These interpretations are curious as the glauconite layers represent very slow sedimentation in low energy environments, which is inconsistent with the formation of cross-beds, and no sand could be detected in the limestone. It is possible that the more crystalline layers, which consist of diagenetically altered dolomite rhombs, might have been mistaken for sand. Given the sedimentological and clay mineralogical contents of these sediments, high-energy cross-bedding and basin infill can be ruled out as depositional mechanisms. The evidence is consistent with relatively low-energy quiet water sedimentation interrupted by long pauses during which glauconite formed.

Glauconite

The most significant evidence of deposition in low-energy environments is revealed by five green clayey glauconite layers embedded within the laminated limestone at 794.43, 794.34–794.35, 794.24, 794.19, and 794.11 m, with the latter at the K/T boundary (Fig. 2). The microclasts of these layers are of glauconite origin and/or have in situ glauconite coating, as revealed by environmental scanning electron microscope (ESEM) and XRD analyses (Figs. 4 and 5). Odom (1984) and Odin (1988) demonstrated that the initial (immature) glauconite is characterized by a smectite-like XRD pattern. As glauconite matures (still at the sediment water-interface), it gains K and becomes more ordered as it transforms toward an illite-like mineral. The XRD pattern of this mature glauconite is characterized by a large peak located close to 10.1 Å, similar to an illite XRD pattern (Fig. 4). Compared to illite, glauconite has a higher 001/003 ratio, but the main difference is the non-existing 002 reflection due to heavy scattering of octahedral iron. The presence of the 060 reflection located at 1.51 Å is also a good criterion.

The glauconite layer observed at the discontinuity in the fifth glauconite layer, which marks the K/T transition (see below), is characterized by such an XRD pattern with no evidence of altered impact glass similar to the breccia (Fig. 4).

Environmental scanning electron microscope (ESEM) and electron diffractometer X-ray (EDX) analysis of this green clay indicates a glauconite composition (see comparison with glauconite standard (Fig. 5). These data indicate that the green glauconite clay at the K/T boundary is highly evolved or mature and requires at least 50 kyr to form (Chamley 1989; Odin 1988; Hillier 1995). Similarly, XRD patterns of insoluble residue grains from two glauconite layers within the micritic limestone (samples 13 and 17; Fig. 2) also show standard glauconite patterns (Fig. 6). Clay mineralogy, thus, indicates major periods of non-deposition as well as erosion at the K/T boundary and at the other four glauconite layers.

It can clearly be shown by the XRD diffractograms that these five green layers consist of mature glauconite (Chamley 1989), as shown in comparison with the glauconite standard in Fig. 5. Though it cannot be ruled out that some glauconite layers, except for the K/T layer, also contain some smectite derived from reworked and altered glass, this does not change the origin of the glauconite itself. Smit et al. (2003, personal communication, 2004) claim that the glauconite layers below the K/T boundary formed by the alteration of impact glass to glauconite, though no evidence is provided in support of this claim. Such alteration, even if theoretically possible, has never been observed or credibly demonstrated, and we would assert that Smit et al.'s (2004) own XRF core scanning data refute this argument. These data show all five glauconite layers to be enriched in Fe, which confirms the presence of glauconite. Such elevated Fe content is not compatible with alteration of impact glass. Moreover, increased K, Ti, Al, and Zr minerals in each of the five glauconite layers point toward reduced sedimentation rates and are inconsistent with Smit et al.'s backwash and crater infill interpretation.

Glauconite forms at the sediment-water interface in relatively shallow water environments (100–300 m, Hillier 1995) with very slow sediment accumulation due to sediment winnowing by gently agitated waters over a long time interval. These glauconite surfaces, therefore, represent long pauses in sedimentation and frequently indicate hardgrounds, which are invariably burrowed by marine benthos. This is also observed at Yax-1 where each of the five green glauconite clay layers is heavily burrowed as evident in Fig. 2. The glauconite layers, therefore, provide strong evidence in support of long-term deposition in a relatively low energy environment and reduced sedimentation. This means that deposition of the 50 cm-thick laminated limestone occurred over a long time period interrupted by five periods of glauconite formation.

Age Proxies above the Impact Breccia

The age of the 50 cm-thick laminated limestone between the impact breccia and the K/T boundary can be determined based on three independent non-biotic proxies: magnetostratigraphy, stable isotopes, and iridium (Fig. 7). Each of these proxies has a unique distribution across the K/T transition that identifies it as part of the latest Maastrichtian or earliest Danian.

Magnetostratigraphy

Magnetostratigraphy shows the interval between the breccia and 6 cm above the K/T boundary as the reversed interval chron 29r (Keller et al. 2004; Rebolledo-Vieyra et al. 2004), which spans the last 580 kyr of the Cretaceous and first 300 kyr of the early Paleocene (Berggren et al. 1995). The relatively steady reversed signals within the 50 cm-thick laminated limestone and glauconite layers indicate sediment deposition occurred within the last 580 kyr of the Maastrichtian. If these sediments consisted of crater infill and backwash as argued by Smit et al. (2004) and Dressler et al. (2003), one would expect chaotic signals reflecting the various ages of the sediments. Clearly, this is not the case.

Carbon Isotopes

$\delta^{13}C$ signals are another useful proxy for late Maastrichtian, K/T, and early Danian sediments. During the late Maastrichtian, bulk carbonate measurements are characteristically in the range of 2–3‰, the K/T boundary is marked by a 2–3‰ negative excursion, and low values prevailed in the early Danian (Keller and Lindinger 1989; Zachos et al. 1989; Barrera 1994). This characteristic pattern is evident in bulk carbonate measurements of Yax-1, which show consistently high $\delta^{13}C$ values characteristic of the late Maastrichtian, followed by the signature 2‰ negative excursion at the K/T boundary (Fig. 7). Only sample 21 shows anomalously low $\delta^{13}C$ values as a result of diagenesis in this coarse-grained dolostone. The $\delta^{13}C$ data, thus, show the expected pattern of a normal K/T transition. If the sediments consisted of chaotic backwash and crater infill of various ages, the $\delta^{13}C$ pattern would reflect this in highly variable signals.

Iridium

High iridium concentrations are another potential proxy for K/T age sediments. In general, anomalously high Ir concentrations mark this boundary worldwide. However, no Ir anomaly has been identified to date with the Chicxulub impact and spherule ejecta layer(s) (Keller et al. 2002), which suggests that this meteorite was not iridium-rich. The Ir anomalies measured at El Mimbral, La Sierrita, and Coxquihui in northeastern and central Mexico are associated with the K/T boundary red layer and tail upward into the early Danian zone Pla (Keller et al. 1994; Stinnesbeck et al. 2002; Keller et al. 2003a).

At Yax-1, the iridium anomaly at the K/T boundary is missing due to a hiatus, though slightly elevated values of 0.29 ng/g are present (Fig. 7). Similarly, low Ir values across the K/T boundary hiatus have been observed in sections with a significant hiatus in Guatemala (Fourcade et al. 1998; Keller

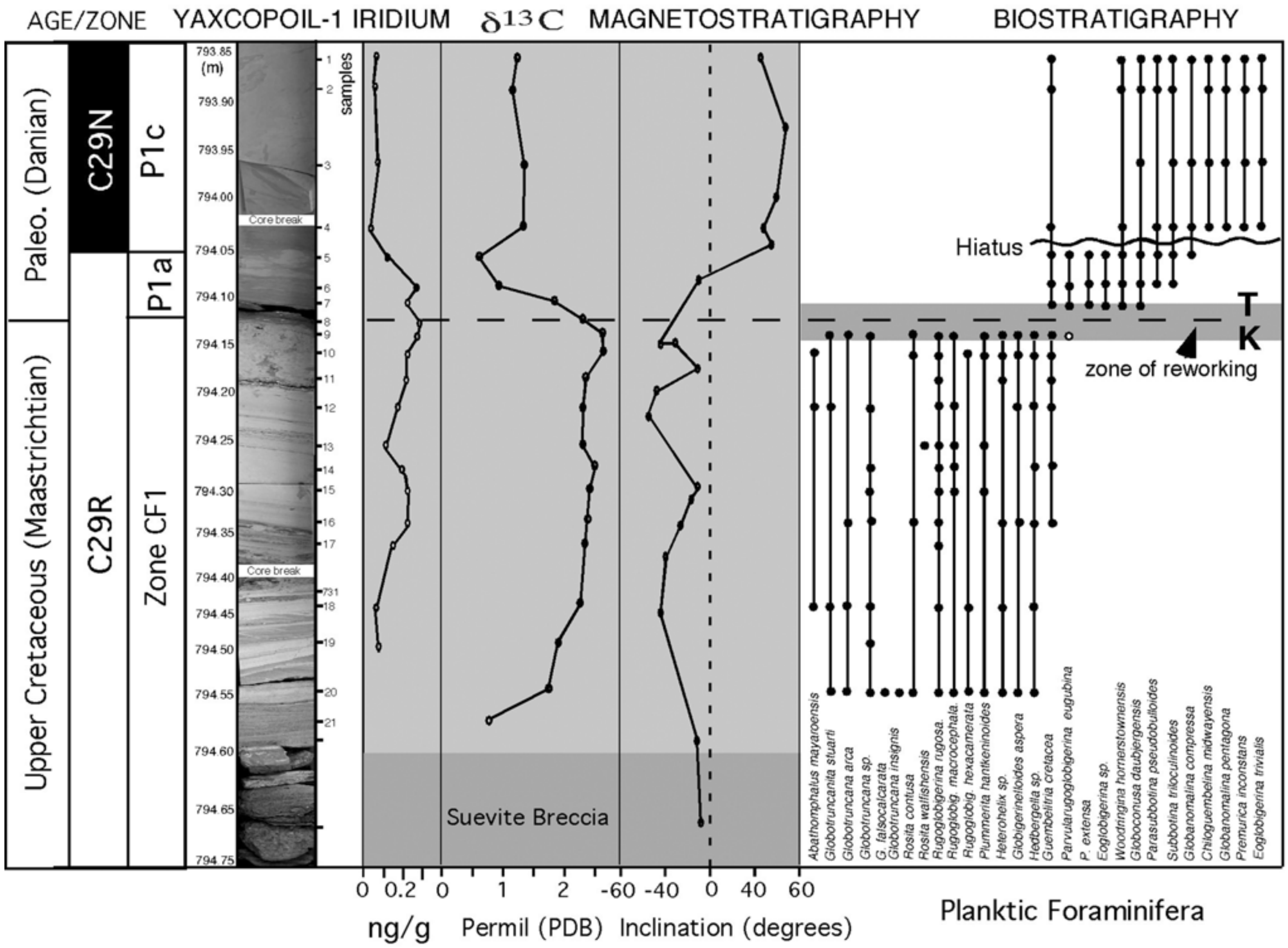

Fig. 7. Five sediment- and age-related proxies reveal late Maastrichtian pelagic sediments overlying the impact breccia in the Chicxulub core Yax-1. The K/T boundary is marked by a glauconite layer and a hiatus with zones P0 and most of P1a missing and probably also part of the uppermost Maastrichtian zone CF1. The second hiatus at 794.05 m marks the loss of zone Plb and the lower part of zone Plc. The absence of an Ir anomaly is likely due to the hiatus that spans the K/T boundary.

and Stinnesbeck 2000). Within the laminated limestone, iridium concentrations are very low, ranging from 0.06–0.08 ng/g in the 20 cm interval above the breccia and from 0.1 to 0.22 ng/g in the following 27 cm interval. These Ir concentrations are within the range of background values and lend no support for impact-generated deposition. The absence of an Ir anomaly at the K/T boundary is likely due to a hiatus (see below).

Biostratigraphy of Planktic Foraminifera

Biostratigraphy based on species ranges and characteristic assemblages, is the most common tool to determine the age of marine sediments. When employed in combination with magnetostratigraphy and stable isotopes, this yields the most powerful method for age control. At Yax-1, this multidisciplinary method is used to determine the age of the 50 cm-thick critical interval between the impact breccia and the K/T boundary.

Cathodoluminescence

At first glance, optical examination of the 15 thin sections from this 50 cm interval revealed no obvious microfossils. The finely laminated limestones reveal thin layers of diagenetic dolomite rhombs characterized by larger crystals (Fig. 8a; see also Fig. 2, numbers 12, 16, and 18), which have been identified as sand grains by Smit et al. (2004), and laminated micritic limestone with partial replacement by dolomite rhombs (Figs. 2, numbers 15 and 20; Fig. 8b). We tried to see whether foraminifera can be more easily recognized by using the cathodoluminescence method. This method is commonly used to determine how much of the original foraminiferal test calcite is preserved versus the amount that was recrystallized. The foraminiferal calcite will be highlighted with respect to the surrounding dolomite or limestone, which has a higher Fe content. The caveat of this method is that when foraminiferal test calcite is completely diagenetically altered and recrystallized, nothing is highlighted, even though the recrystallized foraminiferal tests

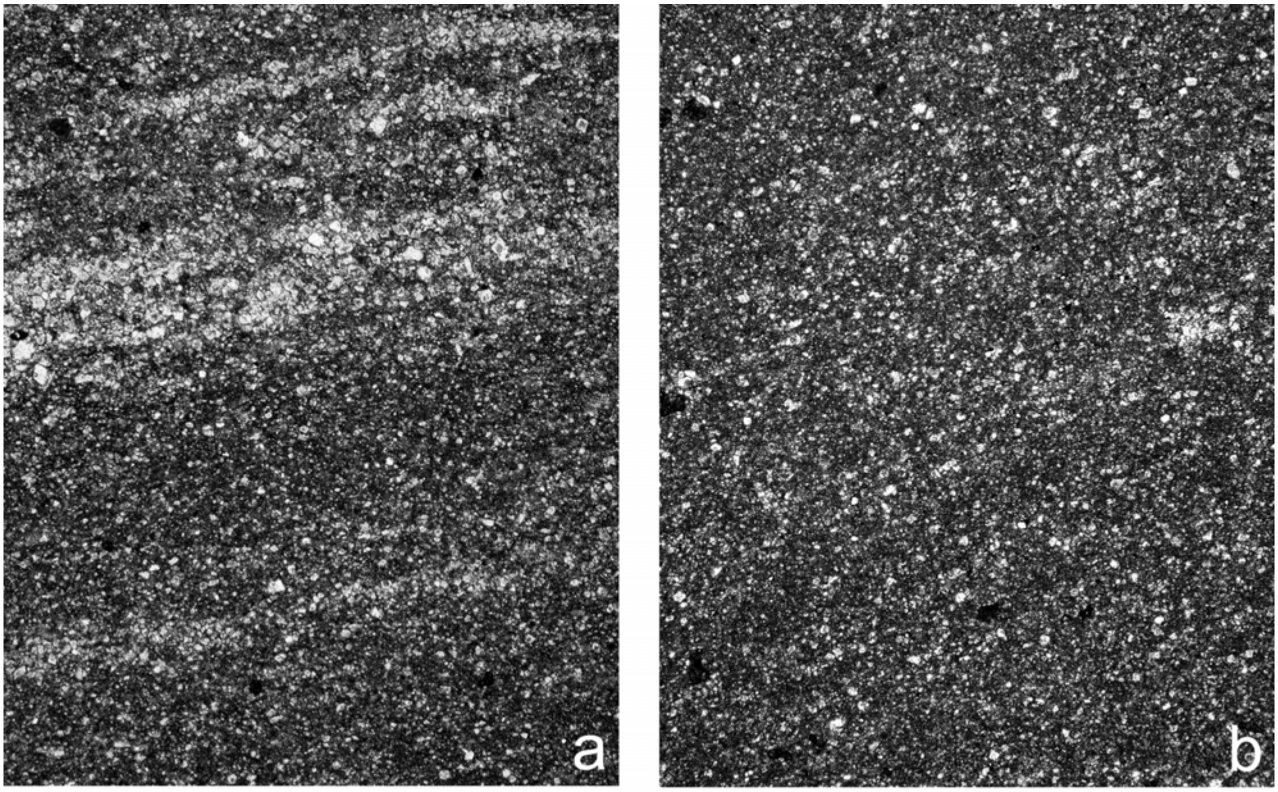

Fig. 8. a) Thin section micrograph of the laminated limestone (sample 16) showing layers of larger dolomite rhombs that might be mistaken for sand. No foraminifera are preserved in these recrystallized sediment layers; b) thin section micrograph of the laminated limestone (sample 14) showing partial replacement by dolomite rhombs, but some planktic foraminifera can still be recognized.

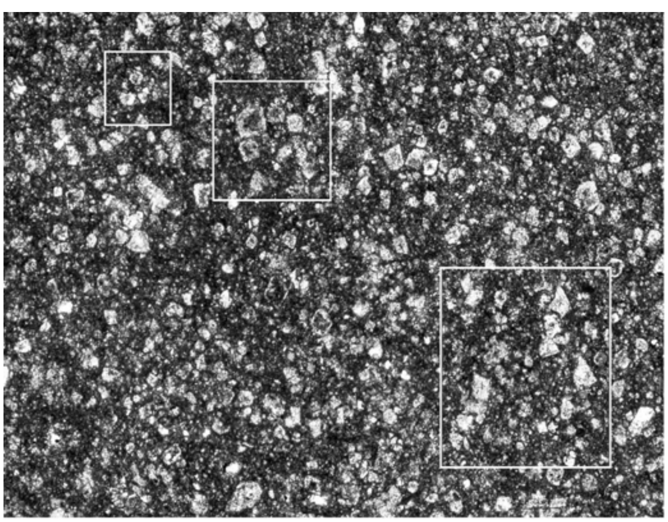

Fig. 9. Thin section micrograph of Yax-1 (sample 20) 6 cm above the impact breccia. This sample shows an abundance of planktic foraminifera in the micritic limestone. The foraminiferal tests are recrystrallized and the chambers infilled with calcite. Easily recognized species are shown in squares.

are present. Our analyses revealed no clear images of foraminifera because the original test calcite has been replaced. The cathodoluminescence method, therefore, cannot be used to determine the presence or absence of foraminifera in these sediments, but only the absence of preserved foraminiferal test calcite, contrary to Smit's claim.

Thin Section Analysis: Foraminifera or Crystals?

A careful thin section analyses of the laminated limestone revealed a diverse late Maastrichtian planktic foraminiferal assemblage and few low oxygen tolerant benthic foraminifera (mostly buliminellids). The species are invariably recrystallized and poorly preserved, as would be expected in micritic limestones. But, the recrystallization process generally retained the original species morphology, and lighter colored chamber infillings make them clearly recognizable with respect to the surrounding micrite (Fig. 9).

Preservation and recognition of foraminifera in these samples is largely dependent on the degree of diagenetic alteration. In the better preserved intervals, specimens can be identified at the species level as shown in the thin section photo of Fig. 9, though because of poor preservation and non-diagnostic cross sections of species, only few species can be identified with confidence. Nevertheless, foraminifera are abundant in this interval, and some easily recognizable species are marked in three squares, showing *Rugoblobigerina rugosa* and three specimens of *Globotruncana* (*G. insignis* and one unidentified). These and other species are shown in Fig. 10.

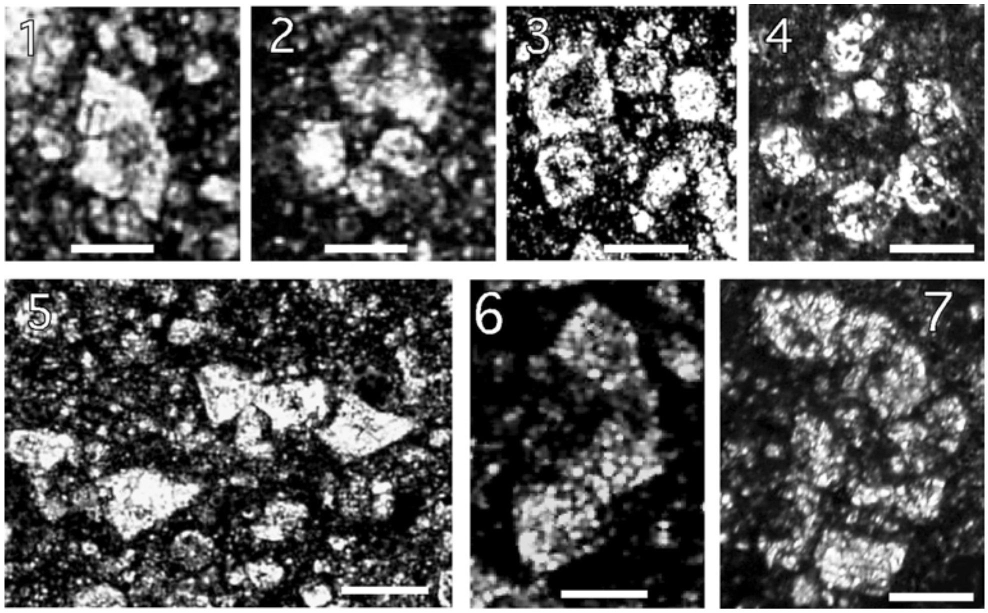

Fig. 10. Thin section micrographs of late Maastrichtian zone CF1 planktic foraminifera from Yax-1 (scale bar = 200 μm for all images): 1) *Plummerita hantkeninoides* (sample 20); 2) *Rugoglobigerina macrocephala* (sample 9); 3–4) *R. rugosa* (samples 19, 20); 5) *Globotruncana insignis* (sample 20); 6) *G. arca* (sample 9); 7) *Rosita contusa* (sample 9).

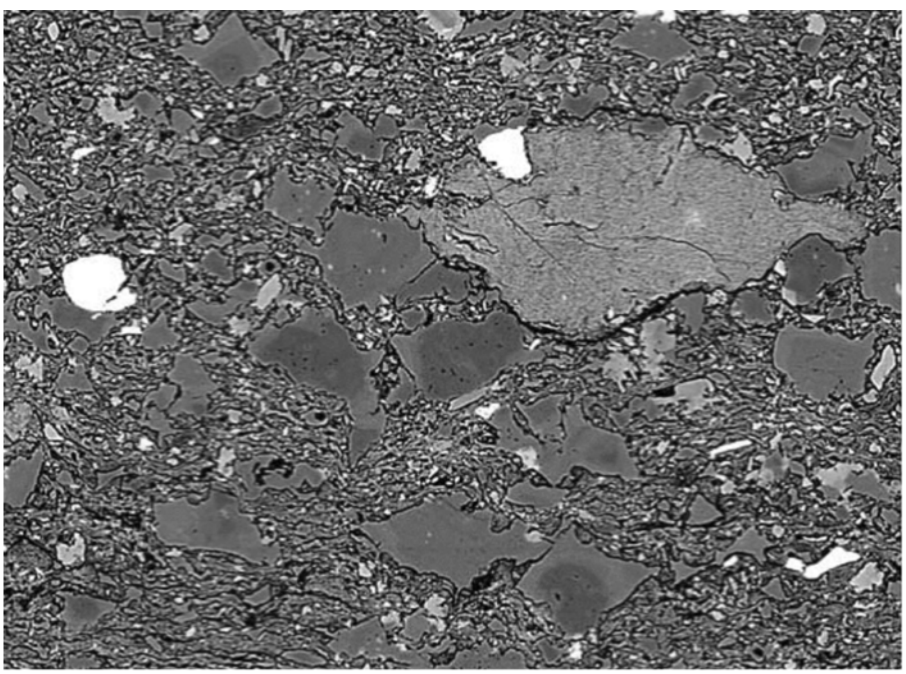

Fig. 11. Thin ection micrograph of Yax-1 dolomite rhomb by Jan Smit who claims that the planktic foraminifera shown in Figs. 10 and 12 are really dolomite rhombs that have been mistaken for foramifera. Note that there are no similarities between the foraminifera and the dolomite rhombs, which are much smaller in size, lack the overall morphology of foraminifera, and do not show the number and shape of chambers, orderly chamber arrangements, coiling direction, and apertures.

Smit et al. (2004) and Arz et al. (2004) have argued that because they did not find any images of planktic foraminifera in the 50 cm interval between the breccia and K/T boundary at Yax-1, they do not exist and that the images shown by us are just dolomite rhombs with overgrowth. In the Chicxulub debate sponsored by the Geological Society of London (http://www.geolsoc.org.uk/template.cfm?name=NSG95478345) (November 2003–January 2004), Smit illustrated dolomite rhombs he believes could be mistaken for foraminifera (Fig. 11). But, a comparison of the foraminiferal images in Fig. 10 and Smit's dolomite rhombs clearly shows the latter to be crystals and the former foraminifera with a complex series

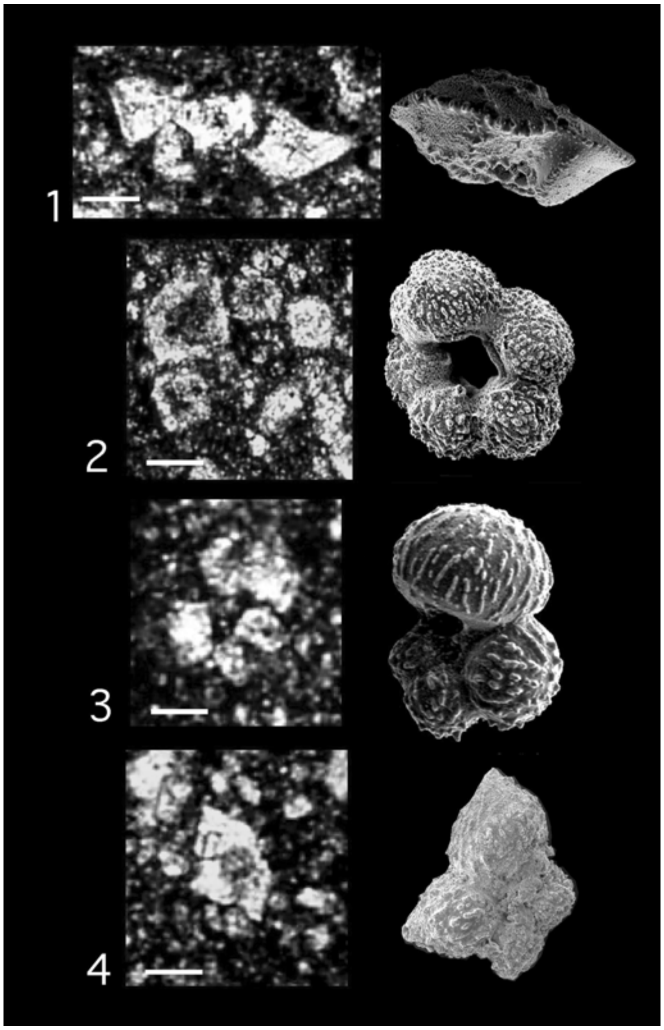

Fig. 12. Thin section micrographs of late Maastrichtian zone CF1 planktic foraminifera from Yax-1 compared with pristine 3D images of the same species from the El Kef, Tunisia, stratotype section. (Scale bar = 200 μm for all images): 1) *Globotruncana insignis* (sample 20); 2) *Rugoglobigerina rugosa* (sample 20); 3) *Rugoglobigerina macrocephala* (sample 9); 4) *Plummerita hantkeninoides* (sample 20).

of chambers with definite shapes and chamber arrangements that are not found in crystals.

We can further demonstrate that these images are foraminifera by comparing the Yax-1 thin section images with pristine 3D images of the same species. Figure 12 illustrates four species *(Globotruncana insignis, Rugoglobigerina rugosa, R. macrocephala, Plummerita hantkeninoides)*. Each 3D image shows the same view as the thin section image. For each species, the shape of the chambers, the number of chambers, chamber arrangement, and the apertural views and coiling views are the same. No random dolomite rhombs with overgrowth could have formed these images. These morphologies are identical to those of late Maastrichtian planktic foraminifera.

Species Ranges and Age Control

The first diverse and abundant planktic foraminiferal assemblage is present 5 cm above the impact breccia (Fig. 7; sample 20, 794.55–794.56 m) and includes species of *Globotruncana (G. stuarti, G. insignis), Rosita contusa, Abathomphalus mayaroensis, Rugoglobigerina (R. rugosa, R. macrocephala), Plummerita hantkeninoides, Globotruncanella petaloidea, Heterohelix, Hedbergella,* and *Globigerinelloides*. Most of these species can also be identified in the other laminated intervals, including sample 9 (794.13–794.14 m) at 2 cm below the green clay that marks the K/T boundary but not above it. Planktic foraminiferal assemblages are, thus, of high diversity with large and small, fragile and robust species present, and all are characteristic of the late Maastrichtian. Such uniform assemblages and the absence of older reworked species cannot be explained by backwash and crater infill, but they are consistent with in situ deposition in a normal low energy marine environment.

The age of this late Maastrichtian assemblage can be further narrowed based on the presence of the biozone CF1 marker *Plummerita hantkeninoides,* which spans the last 300 kyr of the Cretaceous, or the upper part of magnetochron 29r (Pardo et al. 1996). This is consistent with the magnetostratigraphic results at Yax-1 and indicates that the laminated limestone and glauconite layers between the breccia and K/T were deposited sometime during the last 300 kyr of the Maastrichtian. The Chicxulub impact, therefore, must predate the K/T boundary and was not associated with the mass extinction.

These results are corroborated in northeastern Mexico, where impact glass spherules are interbedded in late Maastrichtian marls up to 10 m below the K/T boundary (review in Keller et al. 2003a). In these sections, the age of the Chicxulub impact can be further narrowed based on the stratigraphic position of the lowermost and oldest spherule layer near the base of biozone CF1. The age of the Chicxulub impact can, therefore, be estimated at about 300,000 yr before the K/T boundary.

K/T Boundary and Early Paleocene

At Yax-1, the K/T boundary is marked by a 2–3 cm-thick dark gray-green marly limestone with a 3 to 4 mm-thick green glauconite clay that marks an erosional disconformity. Most Cretaceous planktic foraminifera disappear at this interval. Only very rare early Danian foraminifera are preserved in the green clay that marks the K/T hiatus. Ir concentrations reach only 0.29 ng/g in this interval, probably due to the hiatus (Fig. 7). $\delta^{13}C$ values begin the 2‰ decrease that characterizes the K/T boundary in low to middle latitudes globally. There is a significant amount of burrowing across the K/T interval. The underlying mottled and bioturbated 2 cm interval (sample 9; Fig. 2) contains rare early Danian planktic foraminifera (*Parvularugoglobigerina eugubina*) as a result of downward reworking.

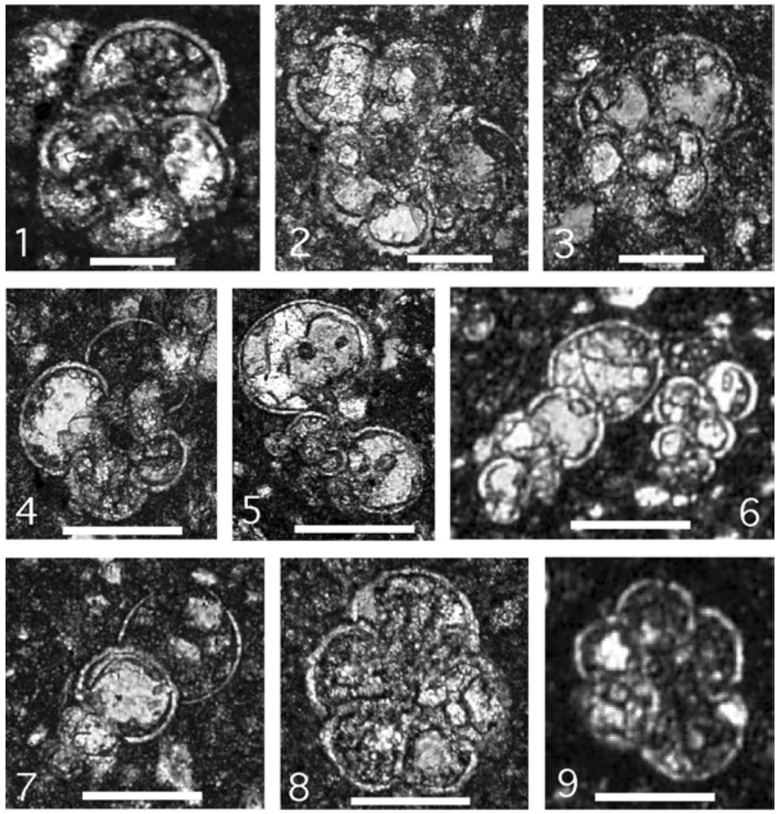

Fig. 13. Thin section micrographs of early Danian (Paleocene) zones P1a-P1c planktic foraminifera from Yax-1 (scale bar = 200 μm for images 1–3; scale bar = 100 μm for images 4–9): 1) *Planorotaloides compressa* (sample 3); 2) *Morozovella inconstans* (sample 4); 3–5) *Parasubbotina pseudobulloides* (samples 5–7); 6–7) *Woodringina hornerstownensis* (samples 1, 7); 8–9) *Parvularugoglobigerina eugubina* (samples 5, 6).

The first good Danian assemblage is present 2 cm above the boundary green clay and includes *P. eugubina, P. extensa, Eoglobigerina* sp., *Woodringina hornerstownensis* and *Globoconusa daubjergensis* (Figs. 7 and 13). Rare reworked Cretaceous species (*Rugoglobigerina, Globotruncana*) are also present. In the mottled, bioturbated 5 cm above this interval (samples 5 and 6) *Parasubbotina pseudobulloides, Subbotina triloculinoides,* and *Globorotalia compressa* (Fig. 13) are common, large and well-developed, characteristic of an upper Pla(2) assemblage.

This indicates a K/T hiatus with the early Danian zone P0 and most of the *P. eugubina* zone Pla is missing. These two zones characterize the early Danian interval of C29r above the K/T boundary, or about the first 300 kyr of the Paleocene (MacLeod and Keller 1994; Berggren et al. 1995; Pardo et al. 1996). Since this interval at Yax-1 is only 6 cm thick, the hiatus spans nearly 300 kyr at the base of the Tertiary and probably part of the uppermost Maastrichtian, which could explain the absence of a K/T iridium anomaly and the short sediment interval for biozone CF1. A K/T hiatus of this magnitude is widespread and observed throughout the Caribbean, Gulf of Mexico, and North Atlantic (Macleod and Keller 1991; Keller et al. 1993; 2003a) and is likely related to early Paleocene changes in climate, sea level, and intensified current circulation.

Another early Paleocene hiatus is indicated by planktic foraminifera at 6 cm above the K/T boundary, where species abruptly change to larger sizes and subzone Plc(2) marker species appear (e.g., *Morozovella inconstans, E. trivialis, Globorotalia pentagona*) (Figs. 7 and 13). This indicates another major hiatus with biozones Plb and Plc(1) missing. This faunal change and hiatus coincides with a change from C29r to normal polarity C29n (794.05 m) (Rebolledo Vieyra et al. 2004). The K/T boundary transition and early Danian are, therefore, largely missing due to non-deposition and erosion.

Paleoenvironment

Shallow water benthic foraminifera (e.g., lenticulinids, miliolids), bivalve fragments, and ostracods are common in the limestones, peloidal grainstones, and packstones below the impact breccia. This indicates a shallow water platform environment in an intertidal to subtidal setting, which could not support planktic foraminifera (Stinnesbeck et al. Forthcoming) (Fig. 14). The impact breccia contains limestone clasts with rare miliolids and lenticulinids from the underlying lithologies but no evidence of a deeper water

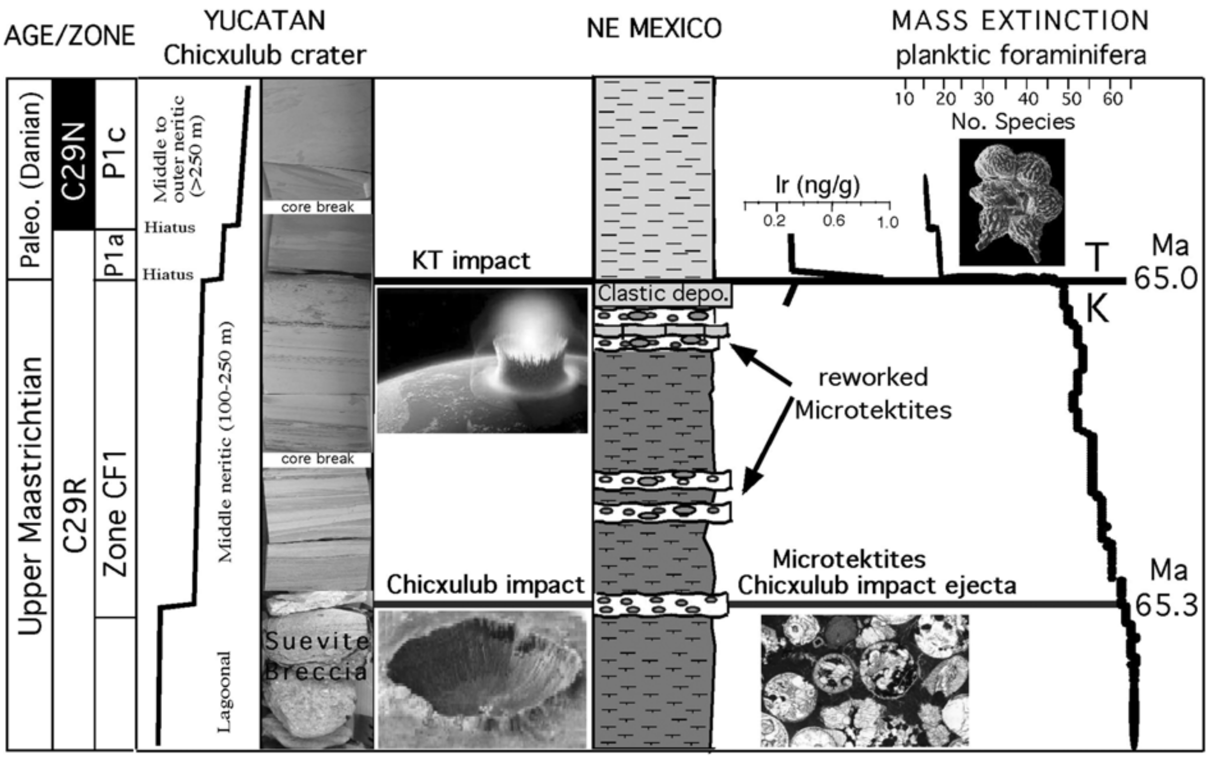

Fig. 14. Proposed correlation of Chicxulub impact breccia in the Yax-1 core with the oldest glass spherule (microtektite) layer in late Maastrichtian marls of northeastern Mexico (El Penon and Loma Cerca). The younger spherule layers are likely reworked. The Ir anomaly in northeastern Mexico is at the K/T boundary and marks the K/T impact and mass extinction. The paleodepth of the Chicxulub crater area deepens from lagoonal (pre-impact) to 100–250 m after the impact and gradually deepens to >250 m in the Danian.

environment. In the micritic limestone above it, benthic foraminifera are rare, but diverse planktic assemblages, including the deeper dwelling globotruncanids, indicate an open marine environment (middle neritic 100–250 m depth). Similar depth is also indicated by the five glauconite layers, which formed at 100–300 m depths (Hillier 1995). Above the K/T boundary, benthic species suggest further deepening to middle-outer neritic depths (250–500 m) (e.g. *Tristix* sp., *Praebuliminella, Cibicidoides, Bolivinoides*). Microfossils and sediments provide no evidence that the Chicxulub formed a very deep crater (a depth of 800 m was estimated by Bell et al. [2004] and Smit et al. [2004]).

DISCUSSION

Age of the Chicxulub Impact

The K/T controversy over the age of the Chicxulub impact is, in part, due to confusion and misunderstanding about the definition of the K/T boundary. Many have come to believe that the Chicxulub impact defines the K/T boundary and, therefore, must be of K/T age. For example, Smit et al. (2004) unequivocally state that, according to the definition of the global stratotype, the K/T boundary should be placed below the ejecta of the Chicxulub impact. They cite Cowrie et al. (1989) and Smit (1999) as sources for this definition. In our view, this cannot be correct. Cowrie et al. (1989) could not be the source for this definition because the Chicxulub crater was not discovered until after that publication. Furthermore, the global stratotype was not ratified by the IUGS until 1991, and Cowrie et al. (1989) guidelines for boundary definitions were revised in 1996 and accepted by the ICS (Remane et al. 1996).

According to the GSSP, a geochronologic boundary is defined by a point in the rocks, the so called "golden spike," which represents some event in Earth's history that can be recognized outside the type section (Remane 2003, p. 12). For the K/T boundary, this point is the lithological change between the Cretaceous and the Tertiary and usually consists of a dark clay layer with a thin red layer at the base, which may or may not contain anomalous concentrations of iridium. But the iridium is not a defining criterion by itself. The defining criteria, or primary markers, include, first and foremost, fossils and unique geochemical signals, such as the $\delta^{13}C$ shift and iridium anomaly, and magnetic reversals. For the K/T boundary, the primary markers are the mass extinction of tropical planktic foraminifera, the first appearance of Danian species above the boundary, the $\delta^{13}C$ negative excursion, the iridium anomaly in the red layer at the base of the clay, and the position of the boundary within the upper third of magnetochron C29r (Keller et al. 1995; Remane et al. 1996; Remane 2003).

These criteria do not include the Chicxulub ejecta glass spherules as a defining criterion for the K/T boundary nor should they. An iridium anomaly has been demonstrated to occur in the K/T boundary clay and coincides with the mass extinction and $\delta^{13}C$ shift within the upper part of C29r in complete sections worldwide. Some clay-altered spherules are sometimes present (e.g., Spain, Tunisia, Egypt, Israel), but these are very different from the Chicxulub spherule deposits in Central America, and no relationship between them has been demonstrated to date. Throughout Central America, the Chicxulub glass spherules have never been observed together with the iridium anomaly or the mass extinction but always well below it (Keller et al. 2003a), which excludes these as a criterion for the K/T boundary definition according to the GSSP guidelines.

Smit et al.'s (2004) assertion that Chicxulub glass spherules define the K/T boundary is not only incorrect, in our opinion, but also leads to circular reasoning: Chicxulub ejecta defines the K/T boundary, therefore, by definition Chicxulub must be K/T age (see also Smit 1999). The true age of the Chicxulub impact can only be determined by excluding the a priori assumption that it is of K/T age and by using the primary markers for this boundary, which provide independent age criteria (e.g., magnetostratigraphy, stable isotopes, and biostratigraphy). This was the main objective of this study on the Yax-1 core and of earlier studies in northeastern Mexico, and the results indicate that Chicxulub predates the K/T boundary mass extinction (Keller et al. 2004).

Pre-K/T Age of the Chicxulub Impact

The age of the laminated limestone above the impact breccia can be determined based on three independent proxies: planktic foraminifera, magnetostratigraphy, and carbon isotope stratigraphy. Planktic foraminiferal assemblages are diverse and include the zone CF1 index species *Plummerita hantkeninoides* (Figs. 7 and 12), which spans the last 300 kyr of the Maastrichtian (Pardo et al. 1996; Keller et al. 2002a; 2003a). Magnetostratigraphy marks this interval as C29r below the K/T boundary in agreement with planktic foraminifera. $\delta^{13}C$ data show the characteristic high values of the late Maastrichtian before the negative excursion at the K/T boundary. Thus, all three age related proxies indicate that the Chicxulub impact predates the K/T boundary and occurred sometime during zone CF1 and C29r below the K/T boundary. This adds to the accumulating evidence of a pre-K/T age for the Chicxulub impact based on impact glass spherule layers (microtektites) in northeastern Mexico (Keller et al. 2003a).

Pre-K/T Age of Impact Ejecta in Northeastern Mexico

Chicxulub impact glass spherule layers are present in late Maastrichtian marls throughout northeastern Mexico and are commonly assumed to be of K/T boundary age, and the overlying siliciclastic sediments are interpreted as impact-generated tsunami deposits (Smit et al. 1992, 1996; Smit 1999). However, the presence of multiple horizons of bioturbation within the siliciclastic unit indicates that deposition occurred over a longer time interval, probably by repeated sediment gravity flows separated by periods of normal sedimentation during which invertebrates colonized the ocean floor (Keller et al. 1997; Ekdale and Stinnesbeck 1998). The K/T boundary and Ir anomaly are above this siliciclastic deposit (Fig. 14).

Recent examination of sediments below these deposits have revealed up to four additional impact glass spherule layers interbedded in late Maastrichtian marls in numerous sections (Keller et al. 2002a, 2003a). No major faults, folds, or slumps have been observed, though some small-scale slumps are occasionally present within a spherule layer (Soria et al. 2001; Keller et al. 2002b; Schulte et al. 2003). There is no evidence of large slumps, folding, or any other structural deformation in northeastern Mexico. Spherule layers in Maastrichtian marls can be traced for several hundred meters in outcrops and correlated across the region (e.g., 25 km from El Peñon to Loma Cerca) (Stinnesbeck et al. 2001; Keller et al. 2002a, 2003a). The lowermost spherule layer is separated from the siliciclastic unit and overlying K/T boundary by up to 10 m of marls with planktic foraminifera of biozone CF1 age.

We assume that the lowermost spherule layer represents the original ejecta fallout based on its stratigraphic position and near absence of clasts and foraminifera. Other layers are likely reworked from the original ejecta deposit by currents probably related to sea level changes, as indicted by the presence of shallow water benthic foraminifera, common clasts, and the unusual abundance of robust globotruncanid species indicating sorting and transport (Stinnesbeck et al. 2001; Keller et al. 2002a).

The age of deposition of the original spherule layer can be determined from its stratigraphic position near the base of biozone CF1, which spans the last 300 kyr of the Maastrichtian. Based on the average sediment accumulation rate for biozone CF1, the age of the impact ejecta was determined at 65.27 ± 0.03 Myr, or about 300,000 years before the K/T boundary (Keller et al. 2002a, 2003a). This currently provides the best age estimate for the Chicxulub impact event and is supported by the CF1 assemblage overlying the impact breccia at Yax-1, the C29r magnetostratigraphy, and the late Maastrichtian carbon isotope signals.

Backwash and Crater Infill? Or Normal Marine Sedimentation?

The Yucatán well Yax-1 drilled in the Chicxulub crater yields the first crater evidence of the age of this impact event (critical K/T samples from earlier Yucatán cores have not been available for study; see Ward et al. 1995). The age of the Chicxulub impact can be determined based on the oldest sediments directly overlying the impact breccia and deposited in a normal marine environment. At Yax-1, these are the

50 cm-thick laminated limestones and five glauconite layers between the disconformities on top of the impact breccia and the K/T boundary. Five independent proxies (lithology, biostratigraphy, magnetostratigraphy, carbon isotope stratigraphy, iridium) indicate that deposition occurred in a normal marine environment near the end of the Cretaceous and preceding the K/T boundary.

Alternatively, it has been argued that the foraminifera are not present (Smit et al. 2004; Arz et al. 2004) or that the laminated limestone and late Maastrichtian foraminifera were reworked by backwash after deposition of the impact breccia and that the impact is of K/T age (Dressler et al. 2003: Smit et al. 2003, 2004). The evidence from sedimentation, geochemistry, and biostratigraphy indicates that this is not the case for the reasons summarized below:

1. Planktic foraminifera are demonstrably present in these laminated limestones, and the assemblages between the breccia and the K/T boundary are of high diversity with small and large, fragile and robust species, and all are characteristic of the latest Maastrichtian biozone CF1 age, which spans the last 300,000 yr of the Cretaceous. Such uniform assemblages and the absence of older reworked species cannot be explained by backwash and crater infill but are consistent with in situ deposition in a normal marine environment. These faunas could not have been reworked from older Yucatán platform sediments because the shallow subtidal Maastrichtian environment did not support planktic foraminifera.
2. Backwash and crater infill after the impact event would result in large-scale cross-bedding and upward fining sequences consisting of diverse clasts and faunal elements (e.g., shallow water benthic foraminifera of different ages) from the underlying breccia and lithologies surrounding the impact crater. No such sedimentary features are observed, and no clasts from shallow water lithologies and platform benthic foraminifera are present in the 50 cm interval between the impact breccia and the K/T boundary.
3. Sediments between the breccia and K/T boundary consist of laminated limestone and five glauconite layers. Only very minor sedimentary structures are apparent in the lower part of the 50 cm interval (794.45 to 794.53 m) where three 1 cm-thick layers with oblique bedding are present. This change in the dip angle may be due to compaction/settling of the underlying seafloor, which locally changed the seabed slope. In contrast, Smit et al. (2004) interpret these minor structures, the laminated sediments, and the five glauconite layers as a cross-bedded unit that represents backwash and crater infill.
4. The presence of five thin green glauconite layers in the 50 cm interval between the breccia and the K/T boundary (the fifth glauconite marks the K/T boundary) indicates repeated interruption of sedimentation for prolonged time periods (up to 50 kyr). These green layers are high in Fe, which is not compatible with alteration of impact glass, as interpreted by Smit et al. (2004). In addition, all five layers are characterized by reduced sedimentation, as indicated by increased K, Ti, Al, and Zr minerals, as shown by Smit et al. (2004). Each glauconite layer is also strongly bioturbated. This indicates that all five layers represent in situ formation and are unrelated to Chicxulub impact backwash and crater infill.
5. The age of the Chicxulub impact is estimated at 300,000 yr before the K/T boundary based on five independent proxies: 1) magnetostratigraphy indicates that deposition occurred within chron 29r below the K/T boundary; 2) planktic foraminifera indicate that deposition occurred during biozone CF1, which spans the last 300,000 yr of the late Maastrichtian, in agreement with magnetostratigraphy; 3) steady high $\delta^{13}C$ values also indicate deposition in the late Maastrichtian; 4) sedimentology (laminated limestones and glauconite layers) indicates a normal marine environment consistent with deposition over a long time period; 5) iridium concentrations are in the range of background values and lend no support for a K/T age.
6. Before the impact, the Yucatán shelf around Chicxulub was a shallow subtidal environment that did not support planktic foraminiferal assemblages. After the impact, these microfossils are abundantly present. If they were eroded and transported from great distances into the crater, there should be evidence of high-energy currents, diverse clasts, and species of diverse ages. No such evidence exists. The diverse assemblages indicate in situ deposition.

For all these reasons, the laminated limestone overlying the impact breccia must have been deposited in a normal pelagic environment over a long time period and interrupted five times by glauconite formation. All age proxies indicate that deposition occurred during the late Maastrichtian after the impact event and before the K/T mass extinction.

Multiple Impact Scenario

Investigation of the new Yax-1 well demonstrates that the Chicxulub impact predates the K/T boundary and is stratigraphically separated from the global K/T impact layer and mass extinction by about 300,000 yr.

Current evidence indicates that the end of the Cretaceous experienced multiple impacts (comet shower) rather than a single large impact as generally hypothesized (Keller et al. 2003a). Chicxulub appears to have been one of these impacts during the late Maastrichtian. Other smaller late Maastrichtian craters have been reported: Silverpit crater from the North Sea (Stewart and Allen 2002) and Boltysh crater from Ukraine (Kelley and Gurov 2003). In addition, K/T and late Maastrichtian Ir and PGE anomalies have been reported from Oman (Ellwood et al. 2003). Another impact may have occurred in the early Danian (*P. eugubina* (Pla) zone, approximately 64.9 Myr) as suggested by Ir and PGE anomaly patterns in sections from Mexico, Guatemala, and Haiti (Fig. 14; Stüben et al. 2002; Stinnesbeck et al. 2002; Keller et al. 2003a). Thus, there is increasing evidence that the end of the Cretaceous experienced multiple impacts (e.g., comet shower) rather than a single large impact, as generally hypothesized. The K/T boundary impact (65 Myr ago) appears to have been the largest impact, as indicated by the global Ir distribution. Though, with the discovery of a pre-K/T age for the Chicxulub impact, its location is still unknown. The Shiva crater of India has been proposed as a possible impact location (Chatterjee 1997).

K/T Mass Extinction

The mass extinction coincides with the K/T boundary event. Planktic foraminifera suffered total extinction of tropical and subtropical species, as documented worldwide, including Mexico (review by Keller 2001). At Yax-1, the incomplete K/T record, with nearly 300 kyr of the basal Tertiary and part of the underlying Maastrichtian missing, prevents precise evaluation of the biotic effects associated with the K/T event. However, the presence of diverse tropical and subtropical assemblages above the impact breccia at Yax-1 and throughout northeastern Mexico sections demonstrates that the Chicxulub impact was not responsible for the K/T mass extinction. Poor preservation of species in the micritic limestone above the breccia at Yax-1 prevents evaluation of the biotic effects of the Chicxulub impact at ground zero. Evaluation of the biotic effects of this impact will have to be done in well-preserved pelagic sequences based on species population statistics and assemblage changes reflecting ecologic tolerance.

Evidence from numerous late Maastrichtian sediment sequences indicate a gradual decrease in species diversity during the last 500 kyr associated with climate change including greenhouse warming between 65.4–65.2 Myr ago (Li and Keller 1998; Abramovich and Keller 2003) and intense Deccan Trap volcanic activity. Guembelitria-dominated assemblages in the Indian Ocean, Madagascar, and eastern Tethys during this time indicate high stress conditions related to intense volcanism (Keller 2003). No evidence of similar high stress conditions has been observed associated with the pre-K/T Chicxulub impact in Central America and the Caribbean, though a gradual decrease in diversity and abundance is evident in low to middle latitude planktic foraminifera (Fig. 14) and most other faunal groups (MacLeod et al. 1997). This suggests that the K/T boundary impact may have been the straw that broke the camel's back rather than the catastrophic kill of a healthy thriving community.

CONCLUSIONS

Determining the precise age of the Chicxulub impact crater is of paramount importance because in the current K/T mass extinction hypothesis, this impact event is the sole responsible agent for the demise of organisms ranging from the microscopic to dinosaurs. If the Chicxulub impact can be determined to have occurred at the K/T boundary 65 Myr ago, this hypothesis gains its strongest support to date. But if the impact is not of K/T age and is not associated with any mass extinction, as strongly indicated by this study of the new Chicxulub crater core Yax-1, the entire impact-kill hypothesis is in doubt, not just for the K/T boundary, but for all major mass extinctions.

Large impacts are credited with the most devastating mass extinctions in Earth's history, and the K/T boundary impact and mass extinction is the strongest and sole direct support for this view. But, if a large impact at Chicxulub did not cause the K/T mass extinction, as indicated by this and earlier studies, there is little support to argue that other large impacts did. Of course, one might argue that the real K/T killer impact has yet to be found. But this begs the question: How many impacts are necessary to cause a mass extinction and over what time interval? It also raises the question: What role did Deccan volcanism play in the end-Cretaceous mass extinction?

There is increasing evidence for multiple impacts across the K/T transition (Keller et al. 2003a), but their biotic effects have yet to be examined. If impacts are a primary or necessary cause for mass extinctions, what other environmental factors are involved, such as volcanism and climate change? What effects did these have on faunal communities? Can multiple impacts and environmental changes support instantaneous mass extinctions? Or, is the often ridiculed gradual or progressive mass extinction seen in the fossil record ultimately a more accurate portrayal of these environmental changes? The Chicxulub crater well Yax-1 provides a tantalizing glimpse of multiple impacts and necessitates a review of current impact and mass extinction theories.

Acknowledgments–We thank the reviewers R. Buffler and V. Luciani for their helpful comments, A. Villard for ultrapolished thin section preparation, M. Dadras (Institut de Microtechnique, Neuchatel, Switzerland) for environmental scanning electron microscope analysis, and V. Zibat (Laboratory of Electron-Microscopy, University of Karlsruhe) for electron microscope analysis. This study was supported by grants from the US National Science Foundation (EAR-0207407 to G. Keller), the German Science Foundation (STI 128/7 and Stu 169/22), and the Swiss National Fund (No. 8220–028367 and 21–67702.02 to T. Adatte).

Editorial Handling—Dr. Jaime Urrutia and Dr. Timothy Jull

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