THE CRETACEOUS–TERTIARY MASS EXTINCTION: THEORIES AND CONTROVERSIES

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Abstract: The Cretaceous–Tertiary boundary (KTB) mass extinction is primarily known for the demise of the dinosaurs, the Chicxulub impact, and the frequently rancorous thirty-years-old controversy over the cause of this mass extinction. Since 1980 the impact hypothesis has steadily gained support, which culminated in 1990 with the discovery of the Chicxulub crater on Yucatán claimed as the KTB impact site and "smoking gun" that virtually proved this hypothesis. In a perverse twist of fate, this discovery also began the decline of the impact hypothesis, because for the first time it could be tested directly based on the impact crater and impact ejecta in sediments throughout the Caribbean, Central America, and North America. Two decades of multidisciplinary studies amassed a database with a sum total that overwhelmingly reveals the Chicxulub impact as predating the KTB mass extinction in the impact-crater cores, in sections throughout northeastern Mexico and in Brazos River sections of Texas, U.S.A. This paper recounts the highlights of the KTB controversy, the discovery of facts inconsistent with the impact hypothesis, and the resurgence of the Deccan volcanism hypothesis as the most likely cause for the mass extinction.

Key words: Cretaceous–Tertiary, KTB, Mass Extinction, Chicxulub Impact, Deccan Volcanism, Impact-tsunami, Age of Chicxulub impact

INTRODUCTION

Most mass extinctions over the past 500 million years in Earth's history occurred during times of major volcanic eruptions; some occurred at times of multiple impacts (Fig. 1), and all were accompanied by major changes in climate, sea level, and oxygenation levels of the water column (Hallam and Wignall, 1997; Courtillot et al., 2000; Wignall, 2001; Courtillot and Renne, 2003; Keller, 2005, 2008a). This consistent association is a first-order test favoring some direct or indirect causal relationship between mass extinctions, volcanism, large impacts, and environmental changes. But among the five major mass extinctions, only the Cretaceous–Tertiary boundary (KTB) mass extinction can be shown to have a close correspondence between an iridium anomaly that is commonly assumed to represent an impact, an impact crater (Chicxulub), a large igneous province (Deccan Traps), and major changes in climate and sea level (Fig. 2).

The KTB mass extinction differs from the other four major mass extinctions in that it occurred after the longest period (145–65.5 Ma) with the lowest background extinctions ($<$ 10%), except for minor increases associated with the oceanic anoxic events in the Aptian (12%) and the late Cenomanian ($\sim$ 17%; Fig. 2). Throughout the Cretaceous, generic diversity steadily increased, accelerating during the Campanian and reaching its maximum during the late Maastrichtian prior to the mass extinction (Fig. 2; Li and Keller, 1998; Keller, 2001). Although the reason for this rapid rise in overall diversity is beyond the scope of this paper, the likely cause is a major increase in nutrients as a result of long-term climate change and possibly volcanic activity. The cause(s) for the end-Cretaceous mass extinction following this long period of globally increasing diversity must be related to the twin catastrophes of Deccan volcanism and a large meteorite impact.

Volcanologists and many paleontologists have long advocated global devastation by continental flood-basalt provinces (CFBPs) and large igneous provinces (LIPs) causing extinctions by poisoning (SO_2, acid rain) and eutrophication, exacerbated by climate change (McLean, l985; Courtillot et al., l986; Officer et al., l987; Courtillot and Gaudemer, 1996; Courtillot, l999; Kerr, l998; Racki, l999a,1999b; Ray and Pande, l999; Wignall, 2001; Courtillot and Renne, 2003; Vermeij, 1995, 2004; Mather et al., 2004; Chenet et al., 2007; Chenet et al., 2008; Chenet et al., 2009; Keller et al., 2008a; Keller et al., 2009a; Keller et al., 2009b). Similar effects are predicted as a result of a large impact. Hybrid hypotheses have tried to link mass extinctions, volcanism, and impacts, with the latter triggering large-scale magmatism (Stothers et al., 1986; Rampino and Stothers, l988; Stothers and Rampino, l990; Jones et al., 2002; Alvarez, 2003). However, no evidence links Deccan eruptions to the Chicxulub impact, and Ivanov and Melosh (2003) concluded that large impacts could not initiate volcanic eruptions. Consequently, the most popular hypothesis since 1980 is that a large meteorite impact was the sole cause for the KTB mass extinction (e.g., Alvarez et al., 1980; Alvarez, 2003).

Neither the impact nor the volcanism hypothesis has been entirely convincing as cause for the KTB mass extinction. This is partly because critical aspects of the empirical record, such as the selective nature and variable rates of extinctions, the appearance of gradual or stepwise extinctions, and the timing between impacts, volcanism, and mass extinctions could not be reconciled with either of these hypotheses. A most vexing problem has been that of determining the correspondence between the KTB mass extinctions and the Chicxulub impact, or between the KTB mass extinction and Deccan volcanism. This is largely due to the fact that markers for mass extinction, impact, and volcanism are never observed in the same stratigraphic sequences, for several reasons, including an incomplete sedimentary record, nonpreservation of impact and/or volcanism signals, or because these events are not coeval.

Frequently, the correspondence between impact and mass extinction must be inferred from stratigraphic correlations that often lack the necessary time resolution, or by radiometric dating with large (1%) error bars, or even merely the assumption that the mass extinction must be due to the Chicxulub impact (Schulte et al., 2010). In practice, this has led some workers to claim cause-and-effect between impacts and mass extinctions where the close stratigraphic proximity is merely the result of an incomplete stratigraphic record, or where disparate time scales suggest overlap (see review in Keller, 2008b). Conversely, a strong belief in the cause–effect scenario (or "strong expectations syndrome" of Tsujita, 2001), has led some workers to ignore the stratigraphically separated mass-extinction and impact signals, claiming them to be one and the same.

For the past three decades proponents and doubters of the impact-kill hypothesis have often heatedly argued over the cause of the KTB mass

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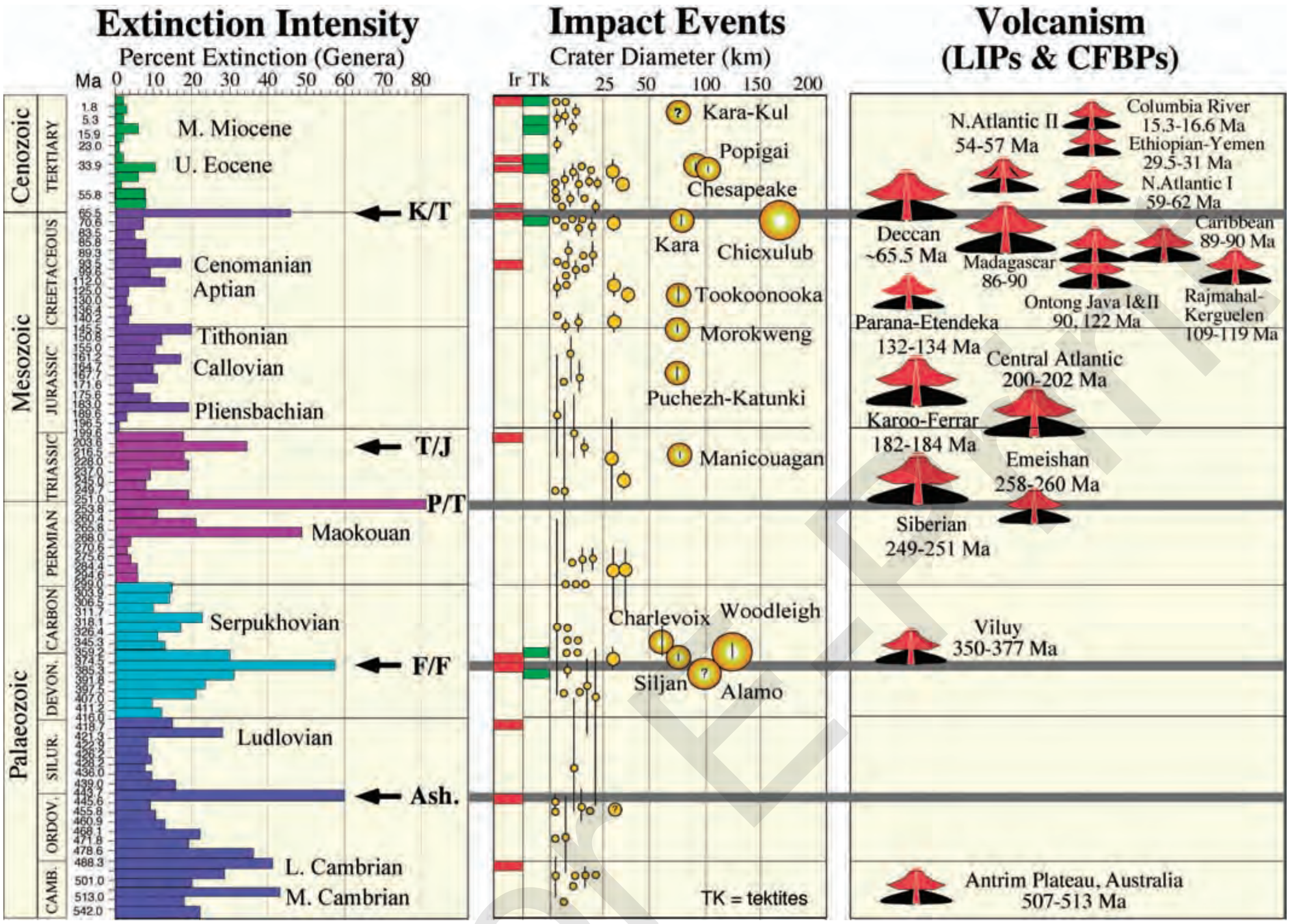

FIGURE 1.—Mass extinctions, impacts, and large igneous provinces during the Phanerozoic. Stratigraphic subdivisions and numerical ages are from the 2004 International Stratigraphy Chart (ICS) of Gradstein and Ogg (2004); genera compilation is from Sepkoski (l996), Hallam and Wignall (1997), and MacLeod (2003); impact database is from Grieve (1997, 2004) and Glikson et al. (2005); LIPS and CFBP database is from Courtillot and Renne (2003). Note that the Chicxulub impact predates the KT boundary by 300 ky. (Modified after Keller, 2005.)

extinction and in particular the cause of the demise of the dinosaurs. Although numerous hypotheses have been advanced to explain this mass extinction, some ranging from arcane to ludicrous, death by a large extraterrestrial bolide impact (Alvarez et al., 1980) has remained the most popular and dominant scenario. The runner-up hypothesis is death by massive volcanic eruptions in India known as the Deccan Traps (McLean, 1985; Courtillot et al., 1986). This chapter reviews the major controversies surrounding the impact-kill hypothesis, and in particular the evidence that does not fit this beautiful scenario and, in fact, proves it wrong. A brief review of the volcanism-kill hypothesis and the recent advances that point to Deccan volcanism demonstrates that this is the most likely cause for the KTB mass extinction.

IMPACT CONTROVERSY: 1980–2010

The Introduction to the Field Guide of 1994 to Northeastern Mexico's Cretaceous–Tertiary (KT) sequences with impact ejecta deposits is as current in 2010 as it was then. In that introduction, Keller et al. (1994a) wrote: **"*The controversy over the nature of the KT transition and the causes of the associated global faunal and floral changes was altered fundamentally in 1980 with the discovery of the now-famous iridium anomaly at the KT boundary at Gubio, Italy (Alvarez et al., 1980). The discovery of similar anomalies elsewhere and the proposition that these anomalies and the KT extinctions resulted from the impact of a large extraterrestrial bolide have spurred over a decade of unparalleled research on the physical and biological events at and near the KT boundary. Within a short time, the controversy resolved itself into two contrasting schools of thought: (1) the KT events reflect the catastrophic effects of a large (10-km) bolide colliding with the earth, and (2) the KT extinctions were the culmination of long-term changes in the earth's biota reflecting major changes in the global climatic system and resulted from extreme, but still normal terrestrial processes, mainly volcanism, which may have been accelerated by a bolide impact at KT boundary time.*"**

We expressed the hope that "***some issues of basic geology might be resolved by discussions on the outcrops and that an interdisciplinary approach might be taken towards some of the contentious issues of their interpretations***." Unfortunately, that did not happen either during the 1994 field trip attended by about seventy scientists, or in the years since. Instead, interpretations of the KTB age of the Chicxulub impact, Chicxulub as the single cause for the KTB mass extinction, and the

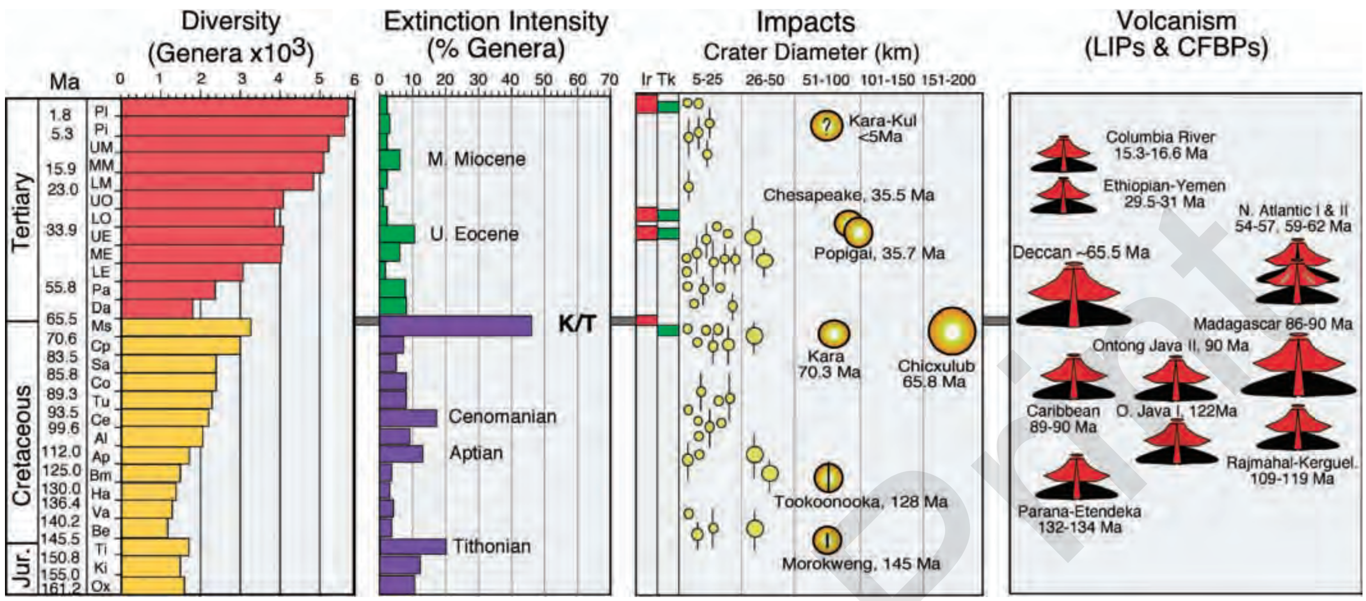

FIGURE 2.—Diversity and extinction intensity correlated with the impact crater record and large igneous provinces during the Cretaceous and Cenozoic. Note that the Chicxulub impact predates the KT boundary by about 300 ky (Keller et al., 2003a; Keller et al., 2004a; Keller et al., 2004b; Keller et al., 2007). The main phase (80%) of the Deccan volcanic province occurred at the end of the Maastrichtian (Chenet et al., 2007; Chenet et al., 2009) and ended at the KT mass extinction (Keller et al., 2008a). (Modified after Keller, 2008a.)

tsunami scenario to explain any discrepancies became entrenched in the public minds as well as in part of the scientific community.

Despite a virtual taboo on questioning the KTB impact hypothesis, pesky little facts that could not be reconciled with this hypothesis surfaced in the literature. The evidence was multidisciplinary and ranged from the extinction records of dinosaur to microfossils, from sedimentology to geochemistry, including stable isotopes, trace elements, and platinum group elements (PGEs). Though at first largely ignored by the scientific community, they eventually added up to a sizeable and irrefutable body of evidence that was incompatible with the KTB impact hypothesis. Today, this body of evidence is the source of contentious arguments regarding the age of the Chicxulub impact on Yucatán and whether this impact did or did not cause the KTB mass extinction. It is this body of evidence that calls for a long-overdue re-evaluation of the KTB impact-kill hypothesis and a new look at the other catastrophe: Deccan volcanism as potential cause for the KTB mass extinction.

Persistent arguments about the Chicxulub impact hypothesis include:

(1) Whether the sandstone complex between the spherule layer and the KT boundary represents tsunami deposition (Smit, 1999; Soria et al., 2001; Arenillas et al., 2006), or submarine channel infill by current transport, gravity flows, and slumps associated with slope conditions and a sea-level fall (Adatte et al., l996; Bohor, l996; Stinnesbeck et al., l996; Keller et al., l997; Keller et al., 2003a; Keller et al., 2003b; Keller et al., 2007; Keller et al., 2009c; Keller et al., 2009d; Schulte et al., 2003).

(2) Whether the stratigraphically oldest spherule layer discovered in upper Maastrichtian sediments in northeastern Mexico and Texas is due to slumps and large-scale tectonic disturbance triggered by the impact, despite the absence of major slumps or significant tectonic disturbance (Smit et al., 2004; Schulte et al., 2003; Schulte et al., 2006; Schulte et al., 2008; Schulte et al., 2010), or represents the time of the impact about 300 ky prior to the mass extinction (Keller et al., 2002; Keller et al., 2003a; Keller et al., 2003b; Keller et al., 2007; Keller et al., 2008b; Keller et al., 2009c; Keller et al., 2009d).

(3) Whether the impact breccia in the Chicxulub impact crater core Yaxcopoil-1 marks the KT boundary and therefore sediments up to the KTB should be interpreted as backwash and crater infill despite absence of high-energy deposits and exotic clasts (Arz et al., 2004; Smit et al., 2004; Schulte et al., 2010), or whether evidence of normal sedimentation, repeated glauconite deposition, followed by characteristic KTB criteria well above the impact breccia indicate a pre-KTB age for the impact breccia (Keller et al., 2004a; Keller et al., 2004b).

(4) Whether the Chicxulub impact caused the KTB mass extinction as commonly assumed, or caused no extinctions or significant environmental effects (Keller et al., 2009c; Keller et al., 2009d).

(5) Whether the placement of the KT boundary should be redefined based solely on the the presence of an Ir anomaly and/or any impact ejecta, including melt rock spherules and breccia (Smit et al., 1992; Smit et al., 1996; Smit, 1999; Schulte et al., 2006; Schulte et al., 2008; Schulte et al., 2010; Arenillas et al., 2006; Molina et al., 2006), rather than the standard global KTB defining criteria that include the mass extinction of planktic foraminifera, first appearances of Danian species, $\delta^{13}C$ shift, and coincident Ir anomaly (Keller et al., 1995; Keller et al., 2008b; review in Keller, 2008b). These and other arguments are discussed below, except for the KTB defining criteria, which is discussed in Keller (this volume, 2).

IMPACT-KILL HYPOTHESIS

No debate has been more contentious during the past thirty years, or has more captured the imagination of scientists and public alike, than the hypothesis that an extraterrestrial bolide impact was the sole cause for the KTB mass extinction (Alvarez et al., l980). How did this hypothesis evolve so quickly into a virtually unassailable "truth" where questioning could be dismissed by phrases such as ***"everybody knows***

***that an impact caused the mass extinction*", "*only old fashioned Darwinian paleontologists can't accept that the mass extinction was instantaneous*", "*paleontologists are just bad scientists, more like stamp collectors*",** and it must be true because **"*how could so many scientists be so wrong for so long*"**. A closer look at the factual evidence underlying reasoning and development of this hypothesis into an almost unassailable bulwark reveals an interaction between scientific investigations, exuberant belief in the rightness of the impact hypothesis, and public media fascination.

It all began with the discovery of a sharp peak of anomalous iridium concentrations in a thin clay layer at the KT boundary near Gubbio, Italy, by Walter Alvarez, Luis Alvarez, his physicist father and Nobel Prize winner, and their collaborators Frank Asaro and Helen Michel in 1979. Iridium occurs in concentrations in some meteorites and deep within the Earth, where it is brought to the surface by volcanic eruptions. Assuming that volcanic eruptions occurred over a long time interval, it was reasoned that a volcanic Ir source could not have resulted in a sharply peaked concentration, whereas a meteorite crashing into Earth could leave this telltale anomaly in a single instant. Today, this assumption is questioned with new data from Deccan volcanism that suggests that eruptions could have occurred rapidly enough and in sufficient volumes to account for the Ir anomalies (Chenet et al., 2007; Chenet et al., 2008; Chenet et al., 2009).

Back in the early 1980s, the coincidence of the Ir anomaly and mass extinction of planktic foraminifera in the thin Gubbio KTB clay layer made a convincing case that a giant meteorite caused the mass extinction (Alvarez et al., 1980). Although the idea of a meteorite impact causing mass extinctions had been proposed earlier, this was the first time that actual supporting evidence was found, lending it substance and credence. It was no longer a wild guess, but a testable hypothesis. Anyone could look for the impact signal and evaluate the tempo and severity of extinctions. This was an exciting and major breakthrough for science, and it began to attract scientists from diverse fields, including astrophysicists, geophysicists, geochemists, mineralogists, sedimentologists, and, of course, paleontologists.

Unfortunately, this wide interest rarely resulted in integrated interdisciplinary studies or joint discussions to search for common solutions to conflicting results. Increasingly, in a perverse twist of science new results became to be judged by how well they supported the impact hypothesis, rather than how well they tested it. An unhealthy US versus THEM culture developed where those who dared to question the impact hypothesis, regardless of the solidity of the empirical data, were derided, dismissed as poor scientists, or simply ignored. Despite this adverse scientific environment the controversy persisted and thrived over time as more detailed investigations revealed the nature and timing of the mass extinction and its stratigraphic separation from the Chicxulub impact.

Studying an instantaneous event in time required the development of a new set of investigative tools and methods. Where formerly samples taken at 1 m intervals were considered adequate for detailed studies, it now required sampling resolution at 1 cm or even a few millimeters to home in on the impact and extinction signals. The new tool kit carried over into other fields, and applied to other problems it led to advances and breakthroughs for all mass-extinction events and major catastrophes in Earth's history. This unintended consequence of the impact hypothesis is a lasting achievement and is now routinely applied across geological sciences. Back in the impact exuberance of the 1980s only the impact crater, the smoking gun, was still missing for complete confirmation, and the search was on.

The Smoking Gun?

After a ten-year search the smoking gun was hailed to be the circular magnetic and gravity anomaly subsurface structure on the northwestern margin of the Yucatán peninsula, Mexico (Hildebrand et al., 1991). This circular structure was first identified as an impact crater by Penfield and Camargo (1981) a decade earlier but failed to garner much attention. The crater diameter was first announced as 180–200 km, then expanded to up to 300 km (Sharpton et al., 1992; Urrutia Fucugauchi et al., 1996; Morgan and Warner, 1999) and subsequently reduced to 150–170 km wide (Bell et al., 2004). Sharpton et al. (1992) linked Chicxulub to the KT boundary based on shocked quartz and an Ir anomaly within the impact breccia, though the latter was never confirmed. Impact glass spherules from KT boundary sections in Haiti and northeastern Mexico and melt rock from the crater breccia yielded $^{40}Ar/^{39}Ar$ ages with reported error margins of ± 200 ky of the KT boundary (Izett et al., 1991; Swisher et al., 1992; Smit et al., 1992; Dalrymple et al., 1993), although the recognized error margin for $^{40}Ar/^{39}Ar$ ages today is 1% or 600 ky (Chenet et al., 2007). Back in the early 1990s the case seemed sealed; Chicxulub was the long-sought KTB impact crater and the cause of the end-Cretaceous mass extinction. Many scientists believed that the smoking gun had been found.

One critical element was still missing—the age of the sediments overlying the impact breccia in wells from the Chicxulub crater taken by Mexico's oil company PEMEX. Without this age control, all that could be said with confidence was that the breccia was deposited sometime within the rather large error margin of $^{40}Ar/^{39}Ar$ ages spanning the KTB. This was insufficient to claim a cause-and-effect scenario with the KTB mass extinction. But in the irrational impact exuberance that prevailed at the time, this critical detail was considered inconsequential.

Only in the first announcement of the Chicxulub crater rediscovery was it acknowledged that determining the precise age of the crater was impossible from available stratigraphic data (Hildebrand et al., 1991). Indeed, Lopez Ramos (1973, 1975) had previously determined a late Maastrichtian age for the 60–170 m of limestone above the impact breccia in Chicxulub wells C1 and Y6 (Fig. 3). This clearly presented a problem for declaring this impact the smoking gun. Alan Hildebrand sent a single sample from well Y6 N12 at 1000–1003 m depth and about 70 m above the impact breccia to G. Keller, who shared it with W. Sliter for age determination. Both reported a late Paleocene zone P3 age. Based on this age, Hildebrand et al. (1991, p. 870) erroneously reported that a KTB age is indicated for the impact breccia and that the earlier age assignment of Lopez Ramos (1975) was probably invalid.

The Lopez Ramos (1975) biostratigraphic age report could not be verified because no samples were available. Likewise, Hildebrand had no samples for the 70 m between the impact breccia and sample Y6 N12. It was rumored that the PEMEX warehouse that stored the cores had burned down, destroying all cores, except for the few samples analyzed by the small group that announced the 'smoking gun studies'. When Chicxulub cores reappeared a few years later, a biostratigraphic study of all existing PEMEX wells of the Chicxulub crater area by Ward et al. (1995) revealed that at a minimum 18 m of undisturbed late Maastrichtian limestones overlie the impact breccia in wells Y6 and C1 (Fig. 3). Ward et al. (1995, p. 875) cautioned that it was impossible to substantiate Chicxulub as the KTB impact crater based on biostratigraphy of existing PEMEX well samples.

The warning signal had been raised to no avail. Chicxulub had become the KTB impact crater. Evidence to substantiate the KTB age now rested on the stratigraphic position of the impact-spherule layer in Haiti (Lamolda et al., 1997; Maurasse et al., 2005), though this proved difficult because impact spherules and two PGE anomalies are in early Danian zone P1a sediments (Keller et al., 2001; Stueben et al., 2002). Similarly in southern Mexico and Guatemala spherule-rich layers were reported from early Danian sediments overlying the KTB unconformity (review in Keller et al., 2003a; Keller et al., 2003b; Stueben et al., 2005). But in northeastern Mexico and Texas impact spherules were first reported from late Maastrichtian sediments near the base of thick sandstone deposits that underlie the KTB (Bourgeois et al., 1988; Smit et al., 1992). Consequently, the KTB was placed at the impact-spherule layer in the belief that the Chicxulub impact caused the mass extinction

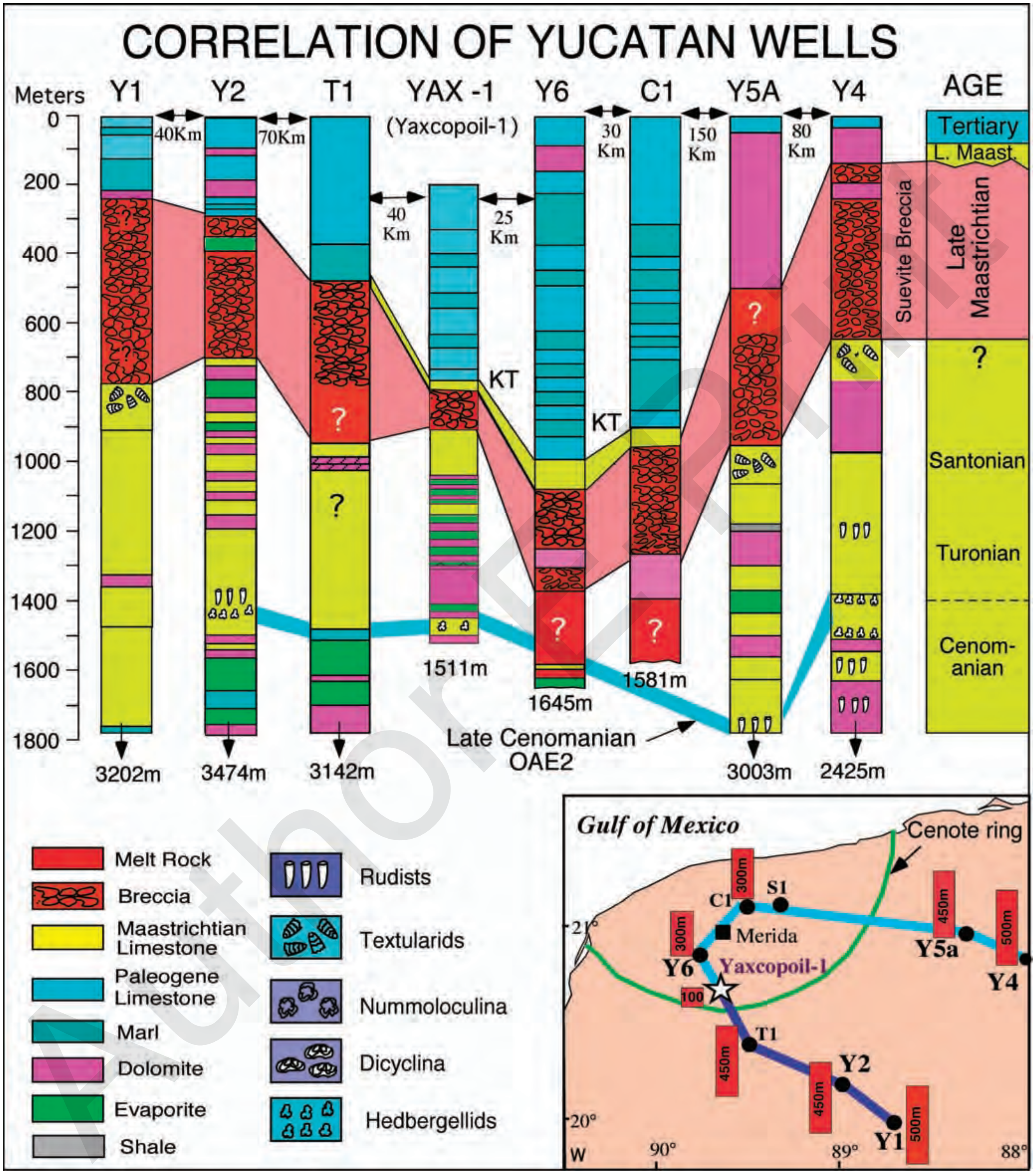

Figure 3.—Stratigraphic correlation of wells Yaxcopoil-1 (Yax-1) and PEMEX wells across northern Yucatán. Correlation based on lithology, biostratigraphy, and electric logs. Note the Maastrichtian limestone layer overlying the impact breccia in Yax-1, Y6 and C1. (Modified after Ward et al., 1995.)

FIGURE 4.—Locations of KTB localities with impact-spherule deposits.

and that the sandstone complex was the result of an impact-generated mega-tsunami event. This interpretation was widely accepted, but it also fueled its own impact-tsunami controversy.

Impact-Tsunami Deposits?

The inconclusive age control of the Chicxulub crater in the early 1990s placed the burden of proof on sections with impact ejecta (e.g., iridium, impact glass spherules) surrounding the Gulf of Mexico and Caribbean (Fig. 4). But here too, problems were apparent from the very beginning. The first discovery of impact glass spherules in northeastern Mexico came from El Mimbral and subsequently from El Peñon. In both localities a 1 m thick glauconite and spherule-rich unit containing a sandy 20–25 cm thick limestone was discovered at the base of a sandstone complex that infills submarine channels (Fig. 5) (Smit et al., 1992, Stinnesbeck et al., 1993). Above the sandstone complex, an Ir anomaly was detected at El Mimbral coincident with the mass extinction of planktic foraminifera (Keller et al., 1994b). If the Chicxulub impact caused the mass extinction and the Ir anomaly, then impact spherules should be in close stratigraphic proximity. How could this stratigraphic separation be reconciled?

It was simple. Assuming that the spherules, the Ir anomaly, and the mass extinction originated from the same event, then the sandstone complex could be interpreted as an impact-generated tsunami deposit (Smit et al., 1992; Smit et al., 1996; Smit, 1999). By this scenario, the spherules rained from the sky within minutes to hours of the impact and settled on the ocean floor (unit 1 of Fig. 5). Within hours, impact-generated tsunami waves caused tremendous destruction, margin collapse, and slumps around the Gulf of Mexico, depositing the massive sandstone (unit 2). Within a few days the waning waves of the tsunami deposited alternating sand, silt, and shale layers (unit 3). At last the settling of fines and iridium marked the KTB and return to normal conditions. This interpretation had already been proposed for the sandstone complex and the Ir anomaly that underlie the mass extinction along the Brazos River in Texas (Bourgeois et al., 1988). It was all beautifully simple, and intuitively it made sense.

But it could not account for the ground truth. Too many facts contradicted tsunami deposition for the sandstone complex in northeastern Mexico, including multiple spherule layers separated by a sandy limestone (unit 1) 20–25 cm thick with J-shaped burrows infilled with spherules. Two ash layers (zeolites) and several horizons of bioturbation (*Chondrites, Thalassinoides,* and *Ophiomorpha)* within the alternating sand–shale layers of unit 3, all indicate deposition over an extended period of time (exceeding a tsunami event) marked by repeated colonization of the sea floor (Fig. 5; Adatte et al., 1996; Stinnesbeck et al., 1996; Stinnesbeck et al., 2001; Keller et al., l997; Ekdale and Stinnesbeck, l998). At El Mimbral and several other northeastern Mexico localities (e.g., El Peñon, La Lajilla) spherule deposition (unit 1) thus occurred in two events separated by a long period of limestone sedimentation, whereas unit 3 was also deposited over an extended time period marked by repeated colonization of the seafloor. These spherule layers could not have rained from the impact cloud, as also evident by the abundant reworked shallow-water debris transported from near-shore areas at El Mimbral (e.g., plants, wood, shallow-water benthic foraminifers, Smit et al., 1992; Stinnesbeck et al., 1993; Smit 1999; Alegret et al., 2001). Recently, Schulte et al. (2010) argued that the presence of shallow-water benthic foraminifera "contradicts a long-term depositional sequence … because their presence requires unrealistically rapid relative sea-level changes of > 500 m." Therefore, they argued the sandstone complex could be explained only by impact tsunami deposition. Posing an absurd alternative may be one way of arguing one's favored position, but it does not substitute for evidence or ignoring existing evidence that contradicts that position.

The well-documented trace-fossil horizons, zeolite layers, and multiple spherule layers separated by limestone indicate sediment deposition over an extended time interval that is likely related to the latest Maastrichtian sea-level fall that scoured submarine channels (Fig. 5; Keller et al., 1994a; Keller and Stinnesbeck, 1996; Adatte et al., 1996). In the subsequent low sea level, spherule debris was eroded from near-shore areas, transported seaward, and deposited in the channels during repeated episodes (unit 1). Gravity slumps led to a massive unsorted influx of sand (unit 2). With rising sea level, coarse and fine layers of unit 3 were deposited, marking periods of rapid sediment influx alternating with normal sedimentation and colonization of the ocean floor (burrows in fine-grained layers; Fig. 5). The iridium anomaly (Rocchia et al., 1996) and the KTB mass extinction (Keller et al., 1994b) at El Mimbral in the clay layer above the sandstone complex mark a condensed interval (surface of maximum starvation) followed by the continued rise in sea level (Adatte et al.,

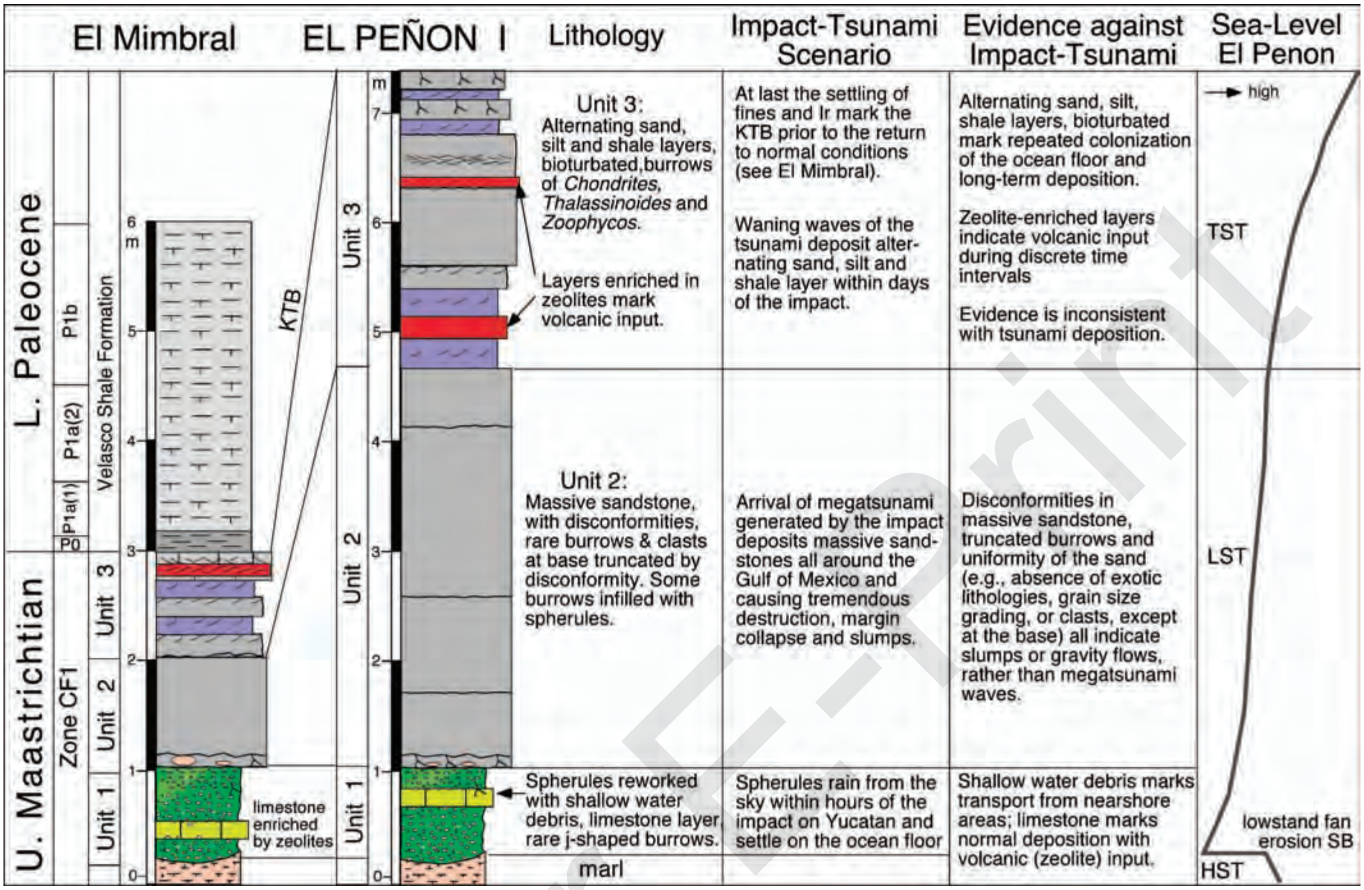

FIGURE 5.—The sandstone complex and lithologic description at El Mimbral and El Peñon in northeastern Mexico (Keller et al., 2003a), along with sea-level changes inferred from lithology and paleontology, the impact-tsunami interpretation (e.g., Smit et al., 1992; Smit et al., 1996), and the evidence that is inconsistent with this scenario.

1996). The same lithological, faunal, and geochemical characteristics are observed in dozens of outcrops throughout northeastern Mexico (Keller et al., 2003a).

Critics have generally countered these lithological observations by claiming that the limestone layer separating the spherule unit 1 is due to large-scale tectonic disturbance (none has been documented), that there are too few burrows in this limestone to be of significance, that the J-shaped spherule-filled burrows are nothing but fluid-escape structures, and that bioturbation in the alternating layers of unit 3 does not exist or is the result of downward burrowing from the KT boundary (e.g., Smit et al., 1992; Smit el al., 1996; Smit, 1999; Soria et al., 2001; Lawton et al., 2005; Schulte et al., 2006; Schulte et al., 2008; Schulte et al., 2010; Arenillas et al., 2006). None of these *ad hoc* arguments have been supported by evidence, nor can these explanations account for the evidence based on field and laboratory observations. Nevertheless, a recent review by Schulte et al. (2010, p. 1215) claims "***A range of sedimentary structures and lack of evidence for ocean floor colonization within the clastic unit in northeastern Mexico indicate rapid deposition***." By denying documented evidence of trace fossils (e.g., Keller et al., 1997; Ekdale and Stinnesbeck, 1998) and asserting a range of undocumented sedimentary structures they reaffirmed the original 1992 conclusion of Smit et al. (1992) that the sandstone complex represents a tsunami deposit generated by the Chicxulub impact at the KT boundary.

Age of Chicxulub Impact

The trace fossils and sedimentological features of the sandstone complex raised initial doubts that these deposits are KTB in age. Further doubts were raised with the subsequent discovery of a 2-m-thick impact-spherule unit interbedded in upper Maastrichtian marls 4–5 m below the two reworked spherule layers at the base of the sandstone complex at El Peñon, 9 m below at Loma Cerca and 2 m below at Mesa Juan Pérez in northeastern Mexico (Figs. 4, 6; Keller et al., 2002; Keller et al., 2003a; Schulte et al., 2003). These stratigraphically older spherule layers revealed no evidence of reworking from shallow waters, such as wood, leaves, and shallow-water benthic foraminifera that are common in the spherule layers (unit 1) at the base of the sandstone complex (Smit et al., 1992; Stinnesbeck et al., 1993; Stinnesbeck et al., 2001; Keller et al., 2002; Keller et al., 2003a; Keller et al., 2009c). This oldest spherule layer predates the KT boundary by as much as 300,000 years as determined from its position near the base of planktic foraminiferal zone CF1, which spans the last 300,000 years of the Maastrichtian.

Proponents of an impact tsunami reconciled the older spherule evidence by explaining their presence by an impact-induced tectonic disturbance (Smit, 1999; Smit et al., 2004; Soria et al., 2001; Schulte et al., 2003), although no such disturbance is observed in northeastern Mexico, apart from rare, small (< 2 m), local gravity slumps often restricted to within the spherule layer (Soria et al., 2001; Keller et al.,

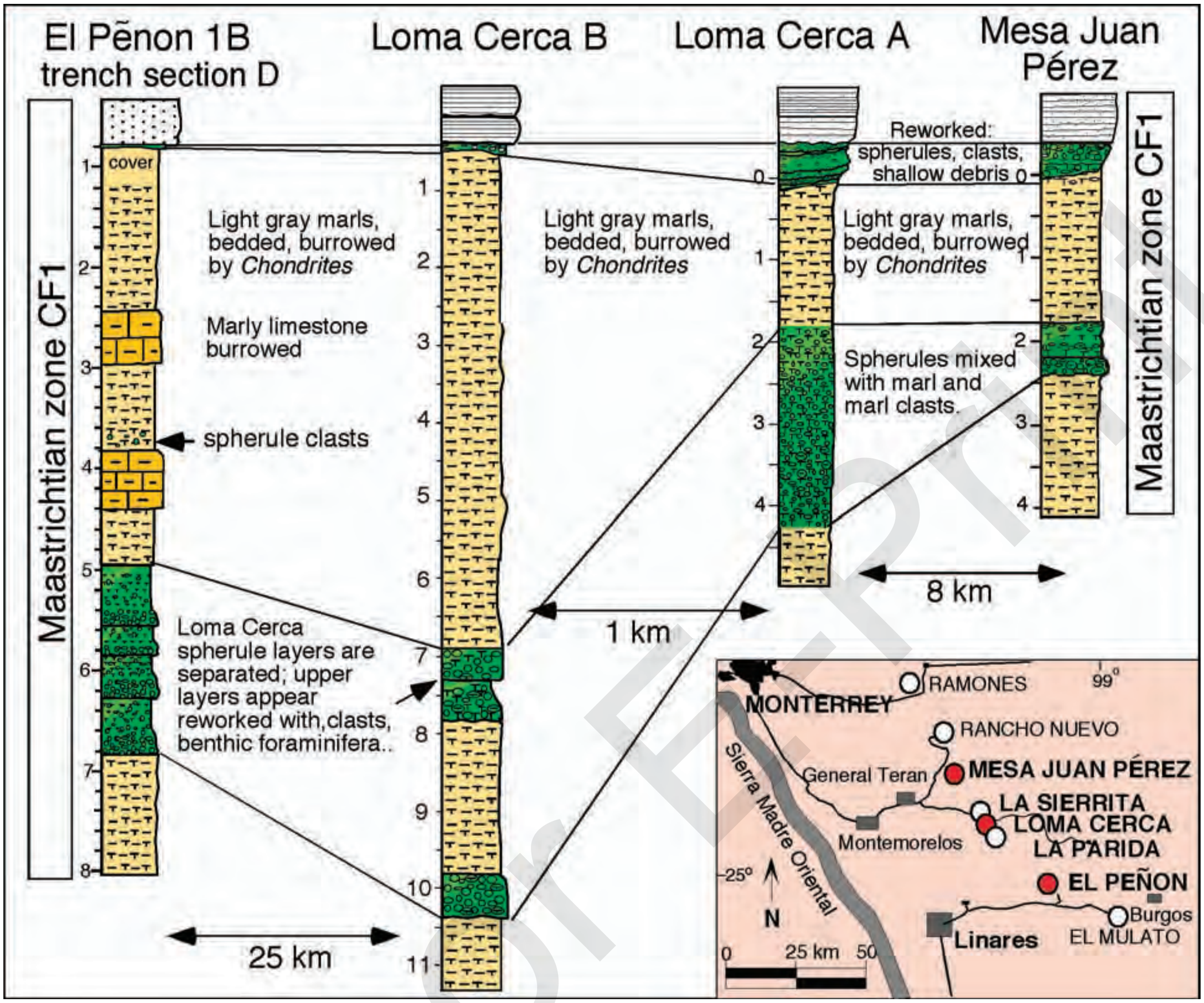

FIGURE 6.—Correlation of El Peñon 1 outcrops with Loma Cerca and Mesa Juan Pérez sections at 25 km and 35 km to the north, respectively. Variable erosion in submarine channels below the reworked spherule unit at the top accounts for the reduced marl layer at Loma Cerca A and Mesa Juan Pérez. (Data from Keller et al., 2003a; Keller et al., 2009c.)

2002; Keller et al., 2009c; Schulte et al., 2003). Others have pointed to the stratigraphic proximity of impact spherules to overlying Danian sediments in some deep-sea sections (e.g., Blake Nose, Bass River, Demerara Rise) as unequivocal evidence that the Chicxulub impact caused the KTB mass extinction (Olsson et al., l997; Norris et al., 1999; Norris et al., 2000; Klaus et al., 2000; MacLeod et al., 2007), although condensed sedimentation and disconformities rule out a complete record (Keller, 2008b). For example, MacLeod et al. (2007) argued that the 2-cm-thick spherule layer that underlies early Danian sediments is in “first-order agreement with the prediction of the impact hypothesis” recording history “within minutes of the impact.” This conclusion was reached despite the evidence of soft-sediment deformation and erosional contacts between the spherule layer, chalk, and white clay at Demerara Site 1259 (Keller, 2008b). High-resolution biostratigraphic, quantitative faunal and chemostratigraphic analyses of deep-sea sections remain to be done to evaluate the completeness of the KTB transition.

The implication that the Chicxulub impact may not have been the KTB killer was almost inconceivable. “How could so many be so wrong for so long?” is a frequently asked rhetorical question. How could a large impact that left a crater 170 km wide not have caused the mass extinction? But a better question is why an impact with a crater 170 km wide should cause one of Earth’s largest five mass extinctions when other large impacts, such as the late Triassic Manicouagan impact, with a crater 150 km wide, and the late Eocene Popigai and Chesapeake impacts, with craters about 100 km wide (Fig. 1) caused no extinctions and left no measurable environmental effects? Indeed, quantitative planktic foraminiferal analysis across the primary Chicxulub impact-spherule layer near the base of zone CF1 at El Peñon, Loma Cerca, and Mesa Juan Pérez shows that not a single species went extinct as a result of this impact (Keller et al., 2009c).

Chicxulub Drilling—Ultimate Proof of KTB Age?

The 2001–2002 drilling of the Chicxulub crater core Yaxcopoil-1 by DOSECC (Drilling, Observations and Sampling of the Earth’s Continental Crust) was supposed to resolve the age issue and show once and for all that Chicxulub is the KTB impact that caused the mass extinction (Dressler et al., 2003). Instead, the new crater core supported

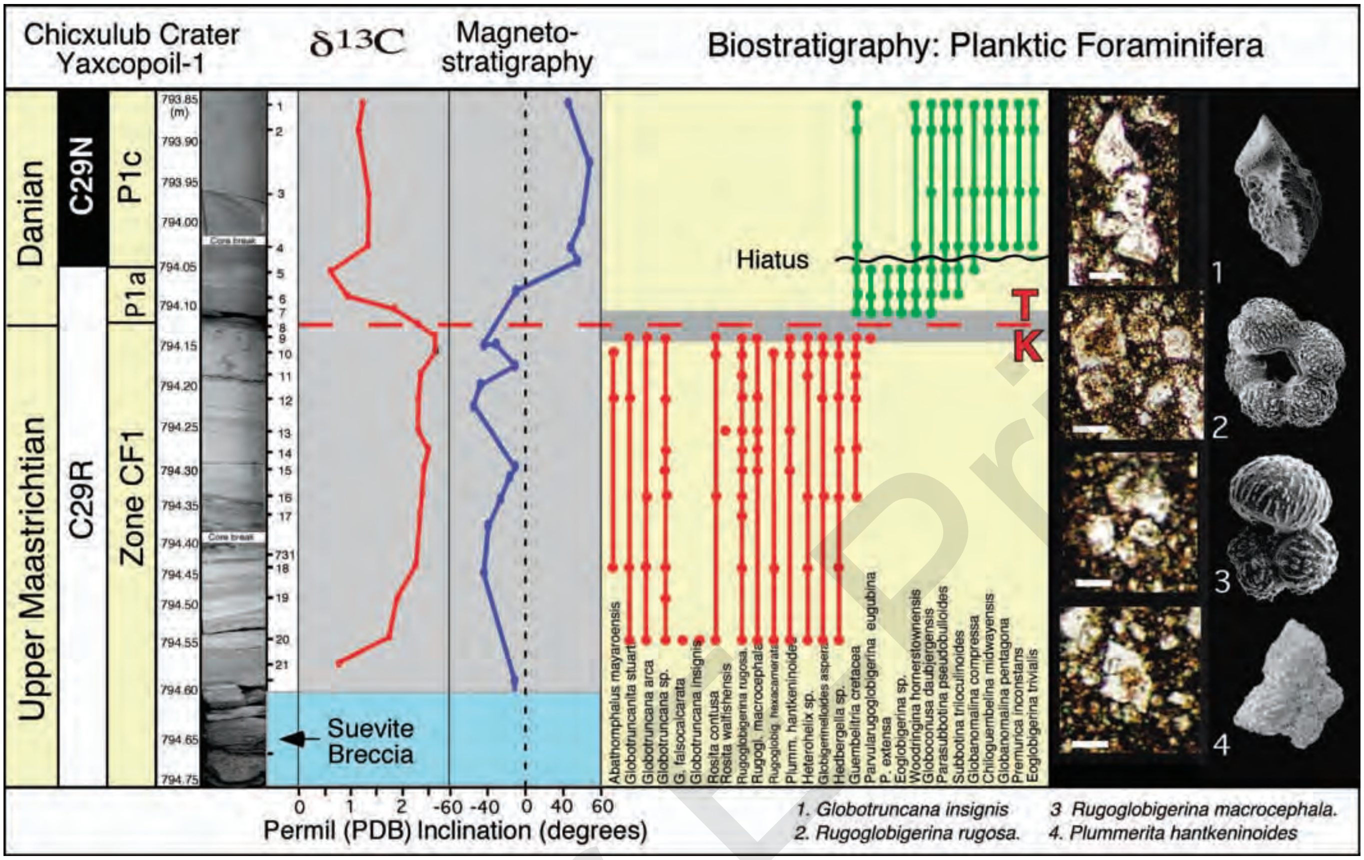

FIGURE 7.—Chicxulub impact crater core Yaxcopoil-1: Stratigraphy of the KTB transition from the impact (suevite) breccia to the KT boundary shows a 50-cm-thick limestone layer with five thin glauconite clay layers deposited over tens of thousands of years. Magnetostratigraphy and planktic foraminiferal assemblages indicate that sediment deposition above the impact breccia occurred during C29R and zone CF1, which spans the last 300 ky of the Maastrichtian. Foraminifera are illustrated from thin sections of the dolomitic limestone (left column). For comparison, SEM illustrations are shown of the same species (right column). (Modified from Keller et al., 2004a.)

the previous findings of a pre-KTB age and fueled a new controversy. The critical evidence is a laminated micritic and partially dolomitized limestone 50 cm thick between the top of the impact breccia and a green clay layer 1 cm thick that marks the KTB and mass extinction (Fig. 7). Above it, the first early Danian species of zone Pla (*Parvularugoglobigerina eugubina* zone) are observed coincident with the KTB characteristic $\delta^{13}C$ shift. In the limestone below, planktic foraminifera indicate deposition occurred during zone CF1 in magnetochron 29R (Keller et al., 2004a; Keller et al., 2004b). Sedimentologic and mineralogic analyses provided further support of normal slow deposition over an extended time period as indicated by five thin glauconite layers, bioturbation, and absence of high-energy deposition and exotic clasts.

All of these characteristics are incompatible with the tsunami backwash and crater infill interpretation. Moreover, the pre-KTB age of the Chicxulub impact breccia supported earlier observations by Lopez Ramos (1973, 1975) and Ward et al. (1995) based on the old PEMEX cores in the Chicxulub crater area, and also supported earlier observation of the pre-KTB age of the Chicxulub impact based on the stratigraphically oldest impact-spherule layer in northeastern Mexico (Figs. 3, 6; Keller et al., 2003a; Keller et al., 2009c).

The new Yaxcopoil-1 results met with fierce criticism and the controversy resulted in the 2004 BBC Horizon documentary *What killed the Dinosaurs*. Smit et al. (2004) interpreted the 50-cm-thick limestone as tsunami backwash and crater infill following the impact. By this interpretation the Chicxulub impact remains KTB in age and the cause for the mass extinction. Of particular concern to Jan Smit are the planktic foraminifera reported by Keller from the 50-cm-thick limestone; he claimed that they do not exist and the forms illustrated are nothing but dolomite crystals. He has maintained this view despite corroborating findings of planktic foraminifera in the same samples by his collaborator (Arz et al., 2004) and subsequently by Michelle Caron, whom he had asked to evaluate the samples. Both noted that in addition to the late Maastrichtian assemblage there are also some reworked earlier Cretaceous species present, which should be expected due to erosion of the crater walls. To this day (Geological Society of America (GSA), Annual Meeting 2009, Portland, and European Geophysical Union (EGU) meeting 2010) Jan Smit maintains that the 50-cm-thick limestone marks tsunami backwash and that no planktic foraminifera are present.

In contrast, Schulte et al. (2010) argue that the presence of some reworked foraminifera and grain-size data in the 50-cm-thick limestone of Yaxcopoil-1 indicate erosion and reworking rather than long-term deposition. However, neither the presence of rare reworked foraminifera nor grain-size data (which reflects the dolomitization of the limestone) have any bearing on either long-term or short-term deposition. More telling is what they ignore of the multi-proxy evidence for long-term deposition in the Yaxcopoil-1 crater core, particularly the presence of five glauconite layers, each of which took tens of thousands of years to accumulate, the bioturbation that reveals that it cannot be backwash and crater infill, the late Maastrichtian carbon isotope values, and deposition in chron 29r below the KTB, none of which can be accounted for by chaotic instantaneous deposition after the impact (Keller et al., 2004a).

Under any normal circumstances this extremely strong multi-proxy evidence together with the latest Maastrichtian index species (*Plummerita hantkeninoides*, zone CF1) would be considered unquestionably long-term deposition during the latest Maastrichtian. But these are not normal circumstances. The validity of the KTB impact theory necessitates that Chicxulub is KTB in age. Schulte et al. (2010, p. 1216) argue for a KTB age based on three points: (1) (unspecified) geochronologic data that correlates the KTB with the Chicxulub impact (note that to date there is no geochronologic data on the Chicxulub impact that is more accurate than within 600,000 years (1% error for K/Ar and Ar/Ar dating); (2) no other large impact besides Chicxulub occurred during the last million years of the Cretaceous, and (3) 'orbital cycles in deep-sea sites demonstrate that there is neither a 300,000 years gap nor hiatus between the Chicxulub impact and the KT boundary'. These arguments are puzzling in that they ignore the Chicxulub data in favor of presenting rather weak and insufficient evidence to support their conclusion of a KTB age.

Yaxcopoil-1 marks a critical turning point in the KTB debate. The critical crater drilling test that was hailed to prove once and for all that the Chicxulub impact is KTB in age and caused the mass extinction had failed. The once solid, nearly impenetrable wall surrounding the impact hypothesis had cracked. Were other findings that did not fit this scenario too easily dismissed?

IMPACT EVIDENCE IN TEXAS

Challenging a popular theory requires extraordinary proof. The controversy over the age of the Chicxulub impact led to charges that impact and tsunami disturbance made any age determination based on the impact crater, as well as any sections in Mexico with impact ejecta, unreliable and that real proof had to come from more distant sedimentary sequences (Smit et al., 2004). With this in mind, we turned our focus to the KTB sequences along the Brazos River in Texas located about 1300 km from the Yucatán impact crater. These sections contain the best preserved marine and terrestrial microfossil records of North America in essentially continuous KTB sequences similar to the El Kef stratotype section, but with the added advantage of Chicxulub impact evidence.

The Brazos sections were deposited near the entrance to the shallow Western Interior Seaway and experienced only minor tectonic activity during the last 65 My. They differ from the deep-water (outer shelf to upper slope) northeastern Mexico sections mainly by their shallow depositional environment and very high sedimentation rate. They share critical similarities, including the presence of a sandstone complex (also known as "event deposit") with reworked spherules at the base. This sandstone complex has long been interpreted as KTB impact-tsunami or related deposits and served as the type section for the impact-tsunami interpretation in northeastern Mexico (e.g., Bourgeois et al., 1988; Smit et al., 1992; Smit et al., 1996; Heymann et al., 1998; Schulte et al., 2006). In Texas, as in northeastern Mexico, this interpretation required placement of the KTB at the base of the sandstone complex based on the assumption that it was generated by the Chicxulub impact. Standard KTB-defining paleontological and stable isotope criteria contradicted this KTB placement, which resulted in controversy. Nevertheless, the Brazos sections are the ideal testing ground regarding the age of the Chicxulub impact and its biotic and environmental consequences.

In 2005 we set out to test the challenging results from northeastern Mexico and the Chicxulub crater core Yaxcopoil-1 based on new drilling and KTB outcrops along the Brazos River, Falls County, Texas, supported by the National Science Foundation through the Continental Dynamics Program and Sedimentary Geology and Paleobiology Program. Drilling of Brazos sections Mullinax-1 to Mullinax-3 was done by DOSECC (Drilling, Observations and Sampling of the Earth's Continental Crust) with each well spanning from the Danian through the Maastrichtian and recovering the KTB interval and the sandstone complex (Fig. 8). In addition, new outcrops exposing the KTB were sampled to obtain a broad regional distribution and sections were studied by an international team of scientists.

We chose the Brazos area for its undisturbed sedimentary record, complete stratigraphic sequences comparable to the El Kef stratotype, absence of significant tectonic activity, excellent preservation of microfossils, and the presence of a sandstone complex with impact spherules. In addition, the Brazos River area affords relatively simple and inexpensive coring of only 17–35 m to span the KTB transition and late Maastrichtian. These attributes make the Brazos sections the most important KTB locality outside Mexico and critical to resolving the current controversy regarding the age of the Chicxulub impact and its potential kill effect.

Early results of the Brazos sections show that the sandstone complex is separated from the KT boundary by up to 1 m of claystones (1.6 m reported by Schulte et al., 2006), which were deposited in a dysoxic environment. Deposition occurred during the latest Maastrichtian zone CF1 as indicated by planktic foraminiferal assemblages and stable isotope signals, and by claystone sediments that are burrowed and of the same mineralogical and geochemical compositions as below the sandstone complex (Keller et al., 2007).

Within the sandstone complex, the base is marked by an unconformity with lithified clasts, some of which contain impact spherules, and others contain mudcracks infilled with spherules. These clasts reveal the history of Chicxulub impact spherules, their deposition in a shallow environment, subaerial exposure during which mudcracks formed and were infilled with impact spherules eroded from a prior fallout deposit, the subsequent lithification (probably as hardground), followed by erosion, transport, and redeposition of clasts at the base of the sandstone complex. These clasts are thus unequivocal evidence that the Chicxulub impact predates the KTB. Above the clasts are two or three upward-fining impact-spherule-rich layers with abundant shell hash, glauconite, and sand. This is followed by one to several hummocky cross-bedded sandstone layers that contain truncated burrows, followed by laminated sand, a short interval (10 cm) of fining-upward sand prior to the resumption of uppermost Maastrichtian claystone deposition. The sandstone complex thus reveals that deposition occurred prior to the KTB and over an extended time period that is inconsistent with tsunami deposition (Gale, 2006; Keller et al., 2007; Keller et al., 2009d). Moreover, spherule deposition predates not only the KTB but also the sandstone complex.

About 40 to 60 cm below the sandstone complex, a 2–4 cm thick yellow clay layer was discovered that consists of altered impact glass (cheto smectite), identical to the altered impact glass in the two spherule layers at the base of the sandstone complex (Fig. 9). Brazos sections thus demonstrate that both the sandstone complex and the Chicxulub impact-spherule layer are stratigraphically separated and below the KTB.

Critique of these results has focused on the yellow clay layer and the placement of the KT boundary. Schulte et al. (2010) argued that high sanidine content in the yellow clay indicates a local volcanic origin. However, XRD analysis shows almost no sanidine in the yellow clay. Moreover, the presence of the same cheto smectite in the two spherule-rich layers of the sandstone complex argues for the same impact-glass origin. They ignore all other evidence, such as Maastrichtian faunal and floral assemblages, stable isotopes, mineralogy, and clasts with impact spherules. The second critique claims that the Chicxulub impact defines the KTB and therefore must be placed at the impact-spherule layer at the base of the sandstone complex (Schulte et al., 2008; Schulte et al., 2010). This is circular reasoning—one cannot evaluate the age of the Chicxulub impact by defining the impact as KTB in age. The

FIGURE 8.—New drilling of Brazos KT sections by DOSECC in 2005 and supported by the National Science Foundation through the Continental Dynamics Program and Sedimentary Geology and Paleobiology Program.

definition of the KT boundary must include independent criteria (see Keller, this volume).

VOLCANISM AND THE KTB MASS EXTINCTION: 1980–2010

Volcanism and Impact Hypotheses Collide

In 1980, when the impact hypothesis was proposed by Alvarez et al. (1980), McLean (1978) had previously advocated CO_2 emissions from Deccan volcanism as the most likely cause for the KTB mass extinction. This set the paleontologist Dewey McLean on a direct collision course with the father–son (physicist–geologist) team of Luis and Walter Alvarez. In addition, most dinosaur experts were highly skeptical and often critical of the impact hypothesis, because they could not reconcile the gradual decline evident in the fossil record with a sudden death by impact. This resulted in one of the most bizarre and acrimonious personal attacks on the integrity of Dewey McLean and paleontologists in general. In an interview with the New York Times' Malcolm Browne (January 19, 1988) Luis Alvarez said: ***"I don't like to say bad things about paleontologists, but they're really not very good scientists. They're more like stamp collectors."*** Of dinosaur expert Dr. William A. Clemens, his colleague at the University of California at Berkeley, he said his criticism can be dismissed on grounds of general incompetence. When asked about the charge that he had interfered with the academic promotion of Dr. McLean (http://filebox.vt.edu/artsci/geology/mclean/) Luis Alvarez denied it, but added:

"***If the president of the college had asked me what I thought about Dewey McLean, I'd say he's a weak sister. I thought he'd been knocked out of the ball game and had just disappeared, because nobody invites him to conferences anymore.***"

Luis Alvarez's personal attacks went beyond paleontologists to anyone who disagreed with the impact hypothesis and especially those who offered Deccan volcanism as the alternative killing mechanism. Special invective was also reserved for geologists Charles B. Officer and Charles L. Drake and physicist Robert Jastrow at Dartmouth College, who advocated intense volcanism and sea-level changes as likely cause for the KTB mass extinction (http://www.nytime.com/1988/01/19/science/the-debate-over-dinosaur-extinction). These personal attacks on opponents of the impact hypothesis during the 1980s scared away most scientists from contributing to the debate or entering the discussions. Deccan volcanism became one of the often unspoken elephants in the debate.

Deccan Volcanism—Real Cause for the KTB Mass Extinction?

Despite the rancorous debate of the 1980s, the study of Deccan volcanism continued to be pursued and most actively by geophysicist Vincent Courtillot and his collaborators at the Physique du Globe de

FIGURE 9.—Cottonmouth Creek waterfall drapes over the resistant sandstone complex with reworked Chicxulub impact spherules at the base. The original impact spherule layer is present in a 3-cm-thick yellow layer in claystones about 60 cm below the sandstone complex. Microfossils date the impact-spherule layer as near the base of zone CF1, or about 300 ky before the mass extinction.

Paris. At the beginning, Courtillot advocated Deccan volcanism not as the alternative hypothesis to an impact, but as a contributing factor in addition to the impact (Courtillot et al., 1986; Courtillot et al., 1988). As evidence accumulated, the discussions gradually shifted towards volcanism as having the dominant long-term role in the mass extinction and the impact as the last straw at the KTB (Vandamme and Courtillot, 1992; Courtillot, 1999).

Deccan volcanism as the principal cause for the KTB mass extinction faced daunting scientific hurdles. For over two decades the main Deccan eruptions were shown to have occurred over less than 0.8 My in magnetic polarity C29r spanning the Cretaceous–Tertiary boundary (Courtillot et al., 1986; Courtillot et al., 1988; Duncan and Pyle, 1988; Vandamme and Courtillot, 1992). Determining where within this major eruptive phase the KTB mass extinction occurred remained problematic. For this reason, models estimating the biotic and environmental consequences generally underestimated the duration, rate, and quantity of Deccan gas emissions by orders of magnitude, leading to conclusions that volcanism could not have been one of the major causes for the KTB mass extinction. Today, this view is rapidly and radically changing, principally due to three recent studies.

(1) Chenet et al. (2007), Chenet et al. (2008), and Chenet et al. (2009) estimated that the bulk (80%) of the 3500-m-thick Deccan traps was deposited over a very short time period—possibly less than 10,000 years, with most of this time represented by periods of quiescence between volcanic eruptions (e.g., intertrappean sedimentation). The entire Deccan lava pile erupted in three phases, with the first and smallest phase at 67.4 My, the main phase at or near the KTB, and the last smaller phase at the C29r–C29n transition in the early Danian. These conclusion were reached based on the largest single database (169 sites) employed to date and integrating paleomagnetic analysis, K-Ar and Ar/Ar dating, chemostratigraphy, and petrology.

(2) Self et al. (2008a) and Self et al. (2008b) measured concentrations of sulfur and chlorine gas in rare glass inclusions of crystals in Deccan lavas and determined that 1 km^3 of lava released between 3.5 to 5.4 teragrams of SO_2 and 1 teragram of HCL. In modern basaltic eruptions these two gases cause well-documented climatic and environmental effects (Self et al., 2008b; Chenet et al., 2008). The massive Deccan eruptions and huge amounts of S and Cl gases released over a very short time period at the end of the Cretaceous would have had severe environmental consequences.

(3) Keller et al. (2008a) discovered that the KTB mass extinction coincided with the end of the main phase of Deccan volcanism. Their results are based on sedimentologic, microfacies, and biostratigraphic data of intertrappean sediments 4–9 m thick in four quarry outcrops in the Rajahmundry area of the Krishna–Godavari Basin of southeastern India. In this area Deccan eruptions, known as the Rajahmundry traps, mark the end of the main phase of Deccan volcanism and the world's

longest lava flows, extending over 1500 km across the Indian continent and into the Bay of Bengal. Sediments immediately below mark the mass extinction in planktic foraminifera. Sediments directly overlying the lower trap basalts contain early Danian planktic foraminiferal assemblages of zone P1a, which mark the evolution in the aftermath of the KTB mass extinction. These results were corroborated in intertrappean sediments between C29r and the C29r–C29n transition in central India (Jhilmili, Chhindwara District, Madhya Pradesh; Keller et al., 2009a; Keller et al., 2009b; Keller et al., 2009e).

The results of these studies strongly suggest that Deccan volcanism played a critical role in the KTB mass extinction, which occurred after the last mega-pulse of the main phase of Deccan volcanism. Although the kill mechanism(s) and the precise nature of environmental catastrophes due to volcanic gas emissions remains to be determined, Deccan volcanism has emerged as a credible cause for the KTB mass extinction and the most serious challenge to the impact hypothesis. Moreover, the discovery of rapid and voluminous Deccan eruptions at KTB time suggests that Ir and other PGE contributions may have been far greater than originally assumed and could account for at least some Ir anomalies. In their "review" of KTB studies, Schulte et al. (2010) both ignored and misrepresented the new Deccan studies claiming 1 My duration of Deccan volcanism with only moderate climatic warming of ~ 2° C and no link to the KTB. They conclude that the Chicxulub impact was the sole cause of the KTB mass extinction.

DISCUSSION AND CONCLUSIONS

After thirty years of intense controversy and often unscholarly invective aimed at opponents of the impact hypothesis, KTB studies may have finally reached the turning point where the sum total of scientific evidence overwhelmingly points away from a KTB impact and strongly supports volcanism and associated climate and environmental changes as the likely cause for the mass extinction. But a thirty-year-old controversy dies hard no matter how strong the evidence disproving it. The recent Science review article by Schulte et al. (2010) claimed international consensus by 41 scientists that the Chicxulub impact was the sole cause for the KTB mass extinction.

To arrive at this conclusion, the authors used a rather selective review of data and interpretations by proponents of this viewpoint, but they ignored or misrepresented the vast body of evidence accumulated by scientists across disciplines (paleontology, stratigraphy, sedimentology, geochemistry, geophysics, volcanology) that documents a complex long-term scenario involving impacts, volcanism, and climate change that is inconsistent with their conclusion. Moreover, their claim that Chicxulub is the cause for the KTB mass extinction is based on the *assumption* that the global iridium anomaly at the KTB and Chicxulub are genetically linked and therefore of the same age. There is no evidence to support this assertion. No Ir anomaly has ever been identified in association with undisputed Chicxulub impact ejecta (impact glass spherules), and no impact spherules have ever been identified in the Ir-enriched KTB clay in Mexico or elsewhere (review in Keller, 2008a). In rare deep-sea sites where the Ir anomaly is just above impact spherules it is due to condensed sedimentation and/or nondeposition. Defining Chicxulub impact ejecta as the KTB is circular reasoning and *a prioi* excludes any assessment of the true age of the Chicxulub impact.

In retrospect, the most acrimonious and personal attacks were launched at a time when scientific evidence supporting the impact hypothesis was at its weakest. From the outset in 1980 to today the strongest evidence in favor of an extraterrestrial impact was the Ir anomaly. All corollary effects, such as global wildfire, nuclear winter, shutoff of photosynthesis, and mega-tsunamis have remained hypothetical with no unequivocal support and for the most part negative evidence.

Perhaps it is not surprising that under such conditions the strongest advocates of the impact hypothesis resorted to highly publicized personal invective. An US versus THEM culture was cultivated that provided easy access to favorable peer reviews and rapid publication of manuscripts claiming support for the impact hypothesis, invitations to lecture at conferences, and favorable peer reviews of grant proposals for impact supporters. This adverse academic climate and fear of personal attacks kept many scientists away from publishing data contradicting the impact hypothesis or even voicing doubt.

The discovery of the Chicxulub structure in 1990 and its claim as the smoking gun that proves the impact hypothesis was a boon that seemed to trump all previously raised doubts. The Chicxulub crater became widely accepted by scientists as the impact that caused the KTB mass extinction. In a perverse twist of fate, the discovery of the Chicxulub crater was also a boon to scientists who had raised questions. For the first time, the impact hypothesis could be tested directly based on the impact crater itself and impact ejecta throughout the Caribbean, Central America, and North America. Two decades of multidisciplinary studies amassed a solid database with a sum total that overwhelmingly reveals the Chicxulub impact as predating the KTB mass extinction and causing no species extinctions. In a triumvirate of studies testing the age of the Chicxulub impact, first in northeastern Mexico, then the impact crater on Yucatán, and finally in the Brazos River area in Texas, the same late Maastrichtian age was confirmed. This corroborating evidence in three different and widely separated areas could no longer be attributed to *ad hoc* disturbances: The Chicxulub impact was not KTB in age.

The final evidence, or "smoking gun", came from the Brazos sections in Texas, a shallow-water environment, devoid of slumps, that had undergone no significant tectonic disturbance since the late Maastrichtian. The Brazos sections boast one of the highest sedimentation rates in an inner-neritic environment of less than 20 m depth during the KTB transition and cut by incised valleys during the latest Maastrichtian sea-level fall. The high sediment accumulation rate in this environment preserved stratigraphically well separated records of (1) the original Chicxulub impact-spherule ejecta layer (altered to cheto smectite) in late Maastrichtian claystone of zone CF1 about 300,000 years before the KTB, (2) three fining-upward impact-spherule layers eroded from nearshore areas and redeposited at the base of a sandstone complex including clasts with impact spherules that record their own pre-KTB Chicxulub impact history, and (3) the KTB up to 90 cm above the sandstone complex (Keller et al., 2007). This volume is devoted to documenting the Brazos sections in terms of the age, depositional environment, sedimentology, mineralogy, sequence stratigraphy, geochemistry, including PGEs and trace elements, late Maastrichtian high-stress conditions, and the KTB mass extinction.

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