- The Society
- Publications
- Library and Information Services
- Events
- Education / Careers
- Our Views
- Geoscientist Online
  - Online Special - KT Mass Extinction: theories and controversies
    - KT Mass Extinction: theories and controversies - extended version
    - References
  - Down to a sunless sea
  - Slip-slidin' away
  - Glaciers - no nonsense science
  - All under heaven
  - Seepage-related stromatolites?
  - Glaciers - science and nonsense
  - Bridging the Energy Gap?
  - Earth's hottest place
  - Water, sandstone & climate change
  - Archive
- Specialist and Regional Groups

Home | Geoscientist Online | Features | Online Special - KT Mass Extinction: theories and controversies | KT Mass Extinction: theories and controversies - extended version

KT Mass Extinction: theories and controversies - extended version

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The Cretaceous-Tertiary (KT) mass extinction is primarily known for the demise of the dinosaurs, the Chicxulub impact and the frequently rancorous 30 year-old controversy over the cause of this mass extinction. Since 1980 the impact hypothesis steadily gained support that culminated in 1990 with the discovery of the Chicxulub crater on Yucatan as the KT impact site and 'smoking gun' that proved this hypothesis. In a perverse twist of fate this discovery also began the decline of this 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 and North America. Two decades of multidisciplinary studies amassed a database with a sum total that overwhelmingly reveals the Chicxulub impact as predating the KT mass extinction in the impact crater cores, in sections throughout NE Mexico and in Brazos River sections of Texas.

With the discovery of facts inconsistent with the impact hypothesis, we are now witnessing the resurgence of the Deccan volcanism hypothesis as the most likely fundamental cause for the KT mass extinction.

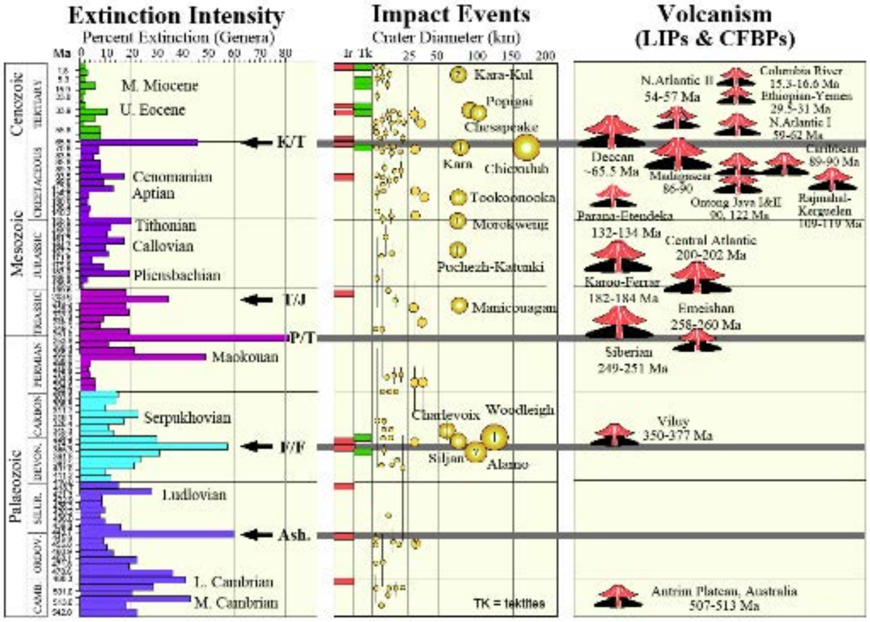


Figure 1. Mass extinctions, impacts and large igneous provinces during the Phanerozoic. Stratigraphic

subdivisions and numerical ages from the 2004 International Stratigraphy Chart (ICS) of Gradstein and Ogg (2004), Genera compilation from Sepkoski (l996), Hallam and Wignall (1997) and MacLeod (2003); impact database from Grieve (1997,2004) and Glikson et al. (2005), LIPS and CFBP database from Courtillot and Renne (2003). Note that the Chicxulub impact predates the K-T boundary by 300 ky. (Modified after Keller, 2005).

Introduction

Most mass extinctions over the past 500Ma 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. This first order test favours some direct or indirect causal relationship between mass extinctions, volcanism, large impacts, climate and sea-level changes. But among the five major mass extinctions, only the Cretaceous-Tertiary (KT) boundary mass extinction can be shown to have a close correspondence between an iridium anomaly commonly assumed to represent an impact, an impact crater (Chicxulub), a large igneous province (Deccan Traps) and major climate and sea level changes (Fig. 2).

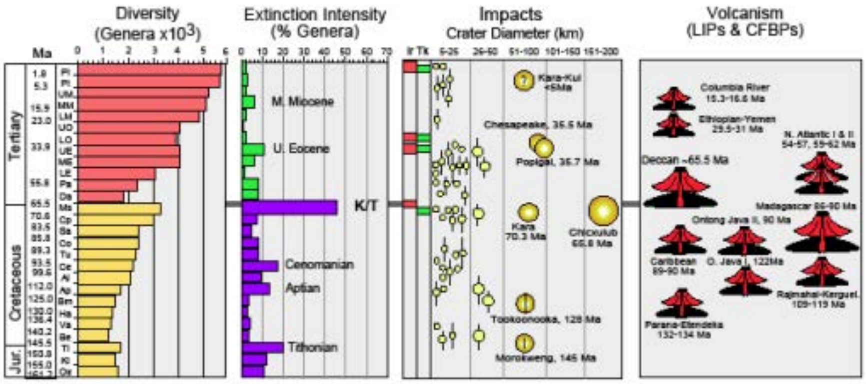


Figure 2. Diversity and extinction intensity correlated with the impact crater record and large igneous provinces during the Cretaceous and Cenozoic. Note that the Chicxulub impact predates the K-T boundary by about 300 ky (Keller et al., 2003a, 2004a,b, 2007), the main phase (80%) of the Deccan volcanic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

The KT mass extinction differs from the other four major mass extinctions in that it occurred after the longest period (145-65.5Ma) of lowest background extinction (<10%) (except for minor increases associated with the oceanic anoxic events in the Aptian (12%) and late Cenomanian (~17%, Fig. 2)). Throughout the Cretaceous, generic diversity steadily increased, accelerating during the Campanian and peaking during the late Maastrichtian, prior to the mass extinction (Fig. 2). The likely cause was a major increase in nutrients as a result of volcanic activity and associated climate change. Following this long period of globally increasing diversity the cause(s) of the end-Cretaceous mass extinction must be related to the twin catastrophes of Deccan volcanism and a large meteorite impact.

Volcanologists and palaeontologists 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. 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. However, no evidence links Deccan eruptions to the Chicxulub impact and in 2003 Ivanov and Melosh concluded that large impacts could not initiate volcanic eruptions.

Consequently, since 1980 the most popular hypothesis is that a large meteorite impact was the sole cause of the KT mass extinction. Neither the impact nor volcanism hypotheses have been entirely convincing however. This is partly because critical aspects of the empirical record (the selective nature and variable rates of extinctions, the appearance of gradual or stepwise extinctions, timing between impacts, volcanism and mass extinctions) could not be reconciled with either. A most vexing problem has been determining the correspondence between the KT mass extinction and either the Chicxulub impact or Deccan volcanism. This is largely due to the fact that mass extinction, impact and volcanism markers are never observed in the same stratigraphic sequences for several reasons, including an incomplete sedimentary record, non-preservation 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 resolution, or by radiometric dating with large (1%) error bars, or even merely the assumption that the mass extinction must have been due to the Chicxulub impact.

In practice, this has led some workers to claim cause-and-effect between impacts and mass extinctions where close stratigraphic proximity is merely the result of an incomplete stratigraphic record, or where disparate timescales suggest overlap. Conversely, a strong belief in the cause-effect scenario (or what Tsujita called the “strong expectations syndrome”), 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 argued heatedly over the cause of the KT mass extinction and in particular the demise of dinosaurs. Although numerous hypotheses have been advanced to explain this mass extinction, death by large extraterrestrial bolide impact has remained the most popular scenario, leaving death by massive volcanic eruptions in India as the runner-up.

Impact Controversy: 1980 – 2010

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 Gubbio, Italy. 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 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 extinction 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.

In a 1994 field guide to the crucial localities in Mexico I once 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 excursion (attended by about 70 scientists), or since. Instead, interpretations of the KT age of the Chicxulub impact, of Chicxulub as the single cause for the KT mass extinction, and the tsunami scenario to explain any discrepancies, became entrenched in the public mind as well as in part of the scientific community.

Yet, despite a virtual taboo on questioning the KT impact hypothesis, pesky little facts that could not be reconciled with it surfaced in the literature. The evidence was multi-disciplinary and ranged from the extinction records of dinosaur to microfossils, from sedimentology to geochemistry, including stable isotopes, trace elements and 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 KT impact hypothesis.

Today, this body of evidence is the source of contentious arguments regarding the age of the Chicxulub impact and impact crater on Yucatan and whether this impact did or did not cause the KT mass extinction. It is this body of evidence that calls for a long overdue re-evaluation of the KT impact-kill hypothesis and a new look at the other catastrophe - Deccan volcanism as potential cause.

Persistent arguments of the Chicxulub impact hypothesis include:

- 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 withslope conditions and a sea level fall (Adatte et al., l996; Bohor, l996; Stinnesbeck et al., l996; Keller et al., l997, 2003a,b, 2007, 2009c,d; Schulte et al., 2003).
- Whether the stratigraphically oldest spherule layer discovered in upper Maastrichtiansediments in NE Mexico and Texas is due to slumps despite the absence of major slumps(Smit et al., 2004; Schulte et al., 2003, 2006, 2008), or represents the time of the impactabout 300 ky prior to the mass extinction (Keller et al., 2002, 2003a, b, 2007, 2008b,2009c,d).
- 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), or whether evidence of normal sedimentation, repeated glauconite deposition followed by characteristic KT criteria well above the impact breccia indicate a pre-KT age for the impact breccia (Keller et al., 2004a,b).
- Whether the Chicxulub impact caused the KT mass extinction as commonly assumed, or caused no extinctions or significant environmental effects (Keller et al., 2009c,d).
- Whether the placement of the KT boundary should be re-defined based solely on the mass

extinction and the presence of an Ir anomaly and/or impact spherule ejecta (Smit et al., 1992, 1996, Smit, 1999; Schulte et al., 2006, 2008; Arenillas et al., 2006; Molina etal., 2006), rather than the standard global KT 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, 2008b; review in Keller, 2008b).

Impact-Kill Hypothesis

No debate has been more contentious during the past 30 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 KT 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 palaeontologists can’t accept that the mass extinction was instantaneous”, “palaeontologists 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.

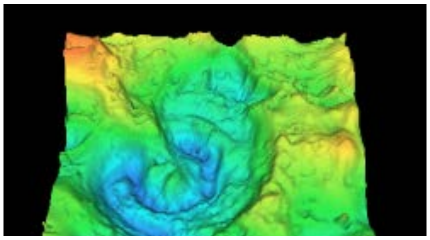
It all began with the discovery of a sharp peak of anomalous iridium concentrations in a thin clay layer at the KT boundary near Gubbio, Italy, by Walter Alvarez, Luis Alvarez, his physicist father and Nobel Prize winner and their collaborators Frank Asaro and Helen Michel in 1979. Iridium occurs in 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 eruptions occurred rapidly enough to deposit peak Ir anomalies (Chenet et al., 2007, 2008). Back in the early 1980s, the coincidence of the Ir anomaly and mass extinction of planktic foraminifera in the thin Gubbio KT 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, palaeontologists.

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.

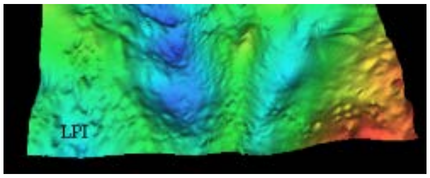
Despite this adverse scientific environment the controversy persisted and thrived over time as more detailed investigations revealed the nature and timing of the mass extinction and its stratigraphic separation from the Chicxulub impact. Studying an instantaneous event in time required the development of a new set of investigative tools and methods. Where formerly samples taken at 1m intervals were considered adequate for detailed studies, it now required sampling resolution at one centimetre or even a few millimetres to home in on the impact and extinction signals. The new tool kit carried over into other fields and applied to other problems lead 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 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 10-year search the smoking gun was hailed to be the circular magnetic and gravity anomaly subsurface structure on the north western margin of the Yucatan peninsula, Mexico (Hildebrand et al. (1991) (Fig. 3). 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 180-200km, then expanded to up to 300km (Sharpton et al., l992; Urrutia-Fucugauchi et al.,l996; Morgan and Warner, l999) 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 NE Mexico and melt rock from the crater breccia yielded ^{40}Ar/^{39}Ar ages with reported error margins of ±200ky of the K-T boundary (Izett, l99l; Swisher et al., l992; Smit et al., 1992; Dalrymple et al., l993), although the recognized error margin for 40Ar/39Ar ages today is 1% or 600ky (Chenet et al., 2007). Back in the early 1990s the case seemed sealed; Chicxulub was the long-sought KT impact crater and cause for the end-Cretaceous mass extinction. Many scientists believed 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 KT mass extinction. But in the irrational impact exuberance that prevailed at the time, this critical detail was considered inconsequential.

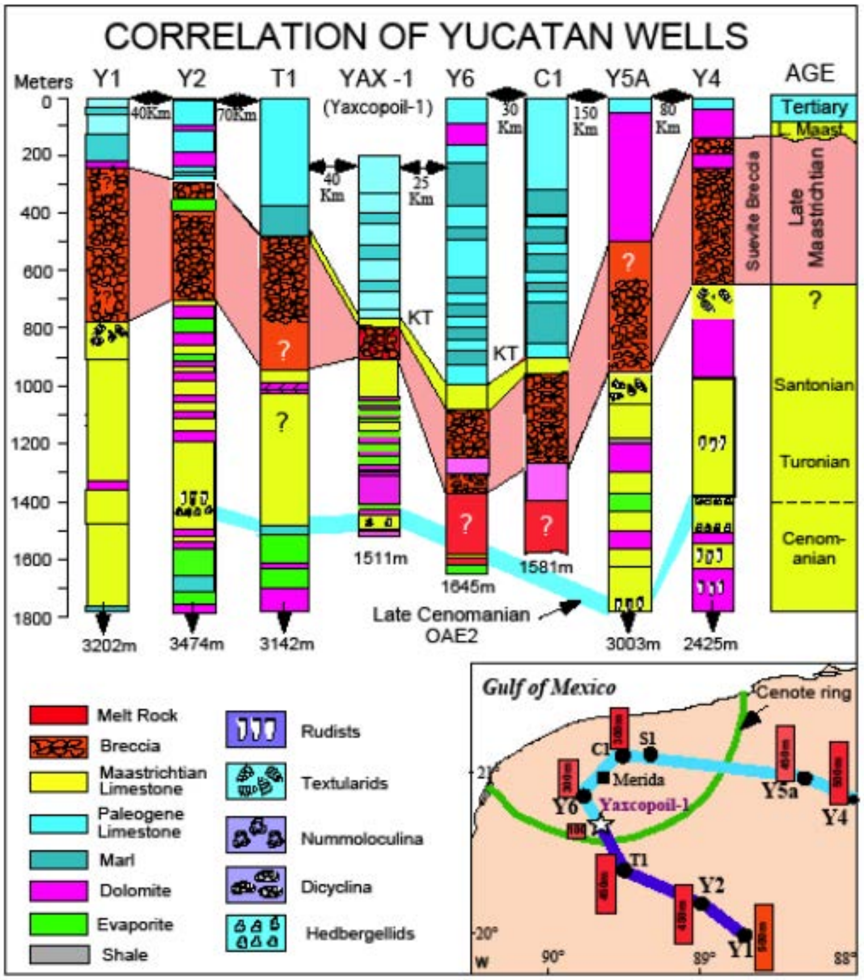


Figure 4. Stratigraphic correlation of wells Yaxcopoil-1 (Yax-1) and PEMEX wells across northern Yucatan. Correlation based on lithology, biostratigraphy and electric logs 45 (modified from Ward et al. 1995). Note the Maastrichtian age limestone layer overlying the impact breccia in Yax-1, Y6 and C1.

Only in the first announcement of the Chicxulub crater re-discovery 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 60-170m of limestone above the impact breccia in Chicxulub wells C1 and Y6 (Fig. 4). 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 concluded that a KT age is indicated for the impact breccia and that the earlier age assignment of Lopez Ramos (1975) was probably invalid.

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 rumoured that the PEMEX warehouse that stored the cores had burned down destroying all cores, except for the few samples analysed by the small group that announced the ‘smoking gun studies’.

When Chicxulub cores re-appeared 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 18m of undisturbed late Maastrichtian limestones overlie the impact breccia in wells Y6 and C1 (Fig. 4). Ward et al. (1995, p. 875) cautioned that it was impossible to substantiate Chicxulub as the KT impact crater based on biostratigraphy of existing PEMEX well samples.

The warning signal had been raised to no avail. Chicxulub had “become” the KT impact crater. Evidence to substantiate the KT 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, 2003a,b; Stueben et al., 2005). But in NE 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 and that the sandstone complex was the result of an impact-generated mega-tsunami event. This interpretation was widely accepted, but also fuelled its own impact-tsunami controversy.

Impact-Tsunami deposits?

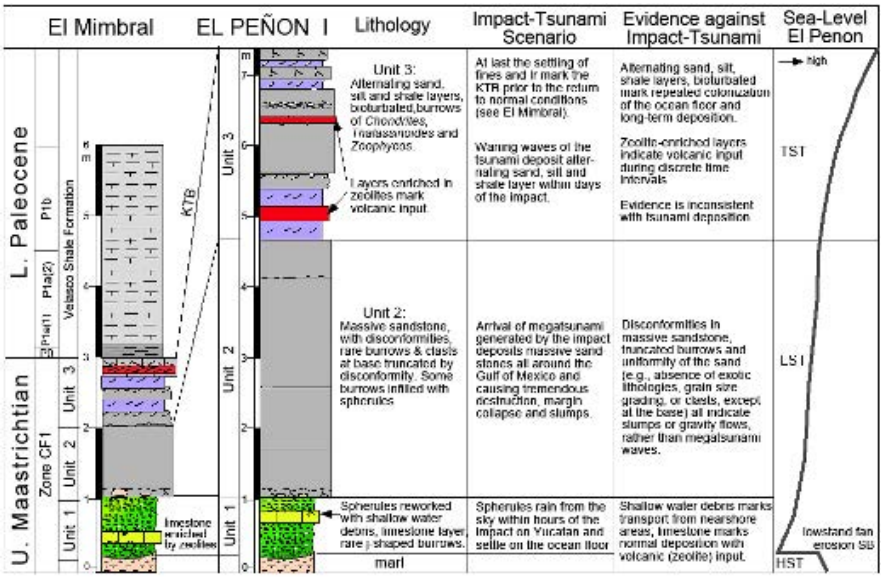
The inconclusive age control of the Chicxulub crater in the early 1990s placed the burden of proof on sections with impact ejecta (e.g., iridium, impact glass spherules) surrounding the Gulf of Mexico and Caribbean (Fig. 5). But here too, problems were apparent from the very beginning. The first discovery of impact glass spherules in northeastern Mexico came from El Mimbral and subsequently from El Peñon. In both localities a 1m-thickglauconite and spherule unit containing a 20-25cm-thick sandy limestone was discovered at the base of a sandstone complex that infills submarine channels (Fig. 6) (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 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, Ir anomaly and mass extinction originated from the same event, then the sandstone complex could be interpreted as impact-generated tsunami deposit (Smit et al., 1992, 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. 6). 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 Ir anomaly that underlies the mass extinction along the Brazos River in Texas (Bourgeois et al., 1988).

It was all beautifully simple and intuitively made sense. But it could not account for the ground truth. Too many facts contradicted tsunami deposition for the sandstone complex in NE Mexico, including multiple spherule layers separated by a 20-25 cm thick sandy limestone (unit 1) 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 indicating deposition over an extended period of time (exceeding a tsunami event) and marked discreet ash influx and repeated colonization of the sea floor (Adatte et al., 1996; Stinnesbeck et al., 1996, 2001; Keller et al., l997; Ekdale and Stinnesbeck,l998, Fig. 6). 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.

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). All these characteristics indicate sediment deposition over an extended time interval that is likely related to the latest Maastrichtian sea level fall that scoured submarine channels (Fig. 6, Keller and Stinnesbeck, 1996; Adatte et al., 1996). In the subsequent low sea level, erosion of spherule debris from near shore areas was transported seaward and deposited in the channels during repeated episodes (unit 1). Gravity slumps led to massive unsorted influx of sand (unit 2). With the rising sea level (TST) coarse and fine layers of unit 3 mark periods of rapid sediment influx alternating with normal sedimentation and colonization of the ocean floor (burrows in fine grained layers, Fig. 6). The iridium anomaly (Rocchia et al., 1996) and KT 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. The same lithological, faunal and geochemical characteristics are observed in dozens of outcrops throughout NE Mexico (Keller et al., 2003a).

Critics have 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, that bioturbation in the alternating layers of unit 3 doesn’t exist, or is the result of downward burrowing from the KT boundary (e.g., Smit et al., 1992, 1996; Smit, 1999; Soria et al.,2001; Lawton et al., 2005; Schulte et al., 2006, 2008, 2010; Arenillas et al., 2006). None of these ad hoc arguments has been supported by evidence, nor can these explanations account for the evidence based on field and laboratory observations.



Lithology	Impact-Tsunami Scenario	Evidence against Impact-Tsunami
Unit 3: Alternating sand, silt and shale layers, bioturbated, burrows of *Chondrites*, *Thalassinoides* and *Zoophycos*. Layers enriched in zeolites mark volcanic input.	At last the settling of fines and Ir mark the KTB prior to the return to normal conditions (see El Mimbral). Waning waves of the tsunami deposit alternating sand, silt and shale layer within days of the impact.	Alternating sand, silt, shale layers, bioturbated mark repeated colonization of the ocean floor and long-term deposition. Zeolite-enriched layers indicate volcanic input during discrete time intervals. Evidence is inconsistent with tsunami deposition.
Unit 2: Massive sandstone, with disconformities, rare burrows & clasts at base truncated by disconformity. Some burrows infilled with spherules	Arrival of megatsunami generated by the impact deposits massive sand stones all around the Gulf of Mexico and causing tremendous destruction, margin collapse and slumps.	Disconformities in massive sandstone, truncated burrows and uniformity of the sand (e.g., absence of exotic lithologies, grain size grading, or clasts, except at the base) all indicate slumps or gravity flows, rather than megatsunami waves.
Spherules reworked with shallow water debris, limestone layer, rare j-shaped burrows.	Spherules rain from the sky within hours of the impact on Yucatan and settle on the ocean floor	Shallow water debris marks transport from nearshore areas, limestone marks normal deposition with volcanic (zeolite) input.
marl		

Figure 6. The sandstone complex and lithologic description at El Mimbral and El Penon in NE Mexico along with the impact-tsunami interpretation (e.g., Smit et al., 1992, 1996), evidence that is inconsistent with this scenario and sea-level changes inferred from lithology and paleontology.

Age of Chicxulub Impact

The burrowing and sedimentological features of the sandstone complex raised initial doubts that these deposits are KT in age. Further doubts were raised with the subsequent discovery of a 2m-thick impact spherule unit interbedded in late Maastrichtian marls 4-5m below the two spherule layers at the base of the sandstone complex at El Peñon, 9m below at Loma Cerca, and 2m below at Mesa Juan Perez in NE Mexico (Figs. 5, 7, Keller et al., 2002, 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, 2001; Keller et al., 2002, 2003a, 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.

Impact tsunami proponents reconciled the older spherule evidence by explaining their presence as impact induced tectonic disturbance or slumps (Smit, 1999; Smit et al., 2004; Soria et al., 2001; Schulte et al., 2003, 2010), although no such disturbance is observed in NE Mexico, apart from rare small (<2m) local gravity slumps restricted to within the spherule layer (Soria et al., 2001; Keller et al., 2002, 2009c; Schulte et al., 2003). Others have pointed to the stratigraphic proximity of impact spherules with 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, 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 2cm-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 erosive 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 KT 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 170km-wide crater not have caused the mass extinction? But a better question is why should an impact with a 170km-wide crater cause one of Earth's largest five mass extinctions when other large impacts, such as the late Triassic Manicouagan impact with a 150km-wide crater, and the late Eocene Popigai and Chesapeake impacts with craters about 100km across (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 Perez shows that not a single species became extinct as a result of this impact (Keller et al., 2009c).

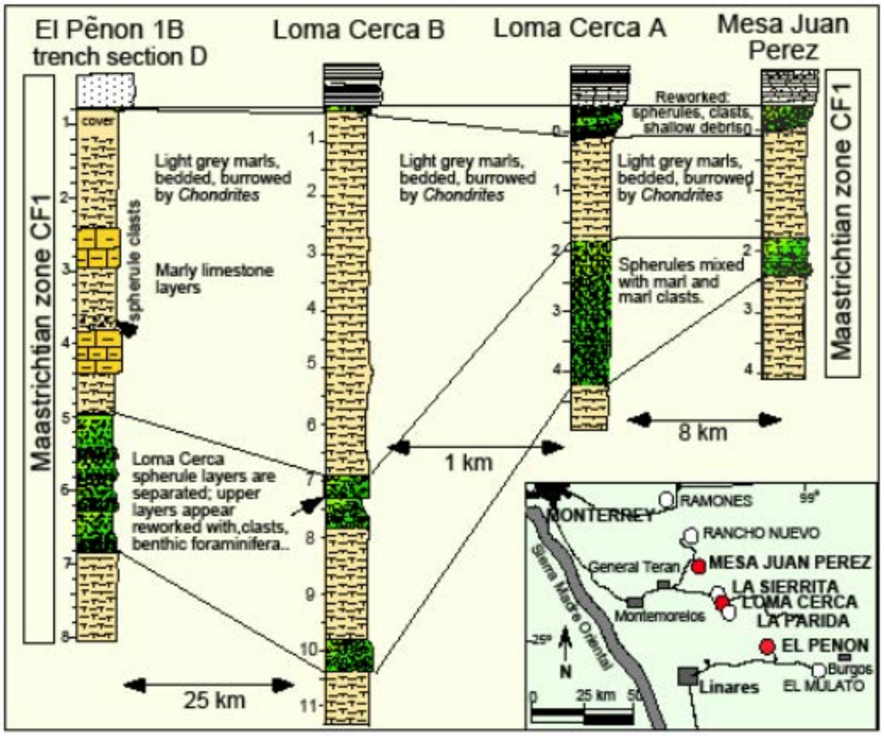


Figure 7. Correlation of El Peñon 1 outcrops with Loma Cerca and Mesa Juan Perez sections at 25 km and 35 km to the north, respectively. Variable erosion in submarine channels below the reworked spherule unit at the top accounts for the reduced marl layer at Loma Cerca A and Mesa Juan Perez.

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 was the KT impact (Dressler et al., 2003). Instead, the new crater core supported the previous findings of a pre-KT age and fuelled a new controversy. The critical evidence is in a 50cm-thick laminated micritic and partially dolomitised limestone between the top of the impact breccia and a 1 cm thick green clay layer that marks the KTB and mass extinction (Fig. 8). Above it, the first early Danian species of zone Pla (Parvularugoglobigerina eugubina) are observed coincident with the KTB characteristic δ13C shift. In the limestone below, planktic foraminifera indicate deposition occurred during zone CF1 in magnetochron 29R (Keller et al., 2004a,b).

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-KT age of the Chicxulub impact breccia supported earlier observations by Lopez Ramos (1973, 1975) and Ward (1995) based on the old PEMEX cores in the Chicxulub crater area, and also supported earlier observation of the pre-KT age of the Chicxulub impact based on the stratigraphically oldest impact spherule layer in NE Mexico (Figs. 4, 7, Keller et al., 2003a, 2009c).

The new Yaxcopoil-1 results met with fierce criticism. Smit et al. (2004) interpreted the 50cm-thick limestone as tsunami backwash and crater infill following the impact. By this interpretation the Chicxulub impact remains KT in age and the cause for the mass extinction. Of particular concern to Jan Smit are the planktic foraminifera reported by Keller from the 50cm-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. To this day (GSA 2009, Portland) Jan Smit maintains that the 50cm-thick limestone marks tsunami backwash and that no planktic foraminifera are present.

Yaxcopoil-1 marks a critical turning point in the KT debate. The critical crater drilling test that was expected to prove once and for all that the Chicxulub impact was KT 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 didn't fit this scenario too easily dismissed?

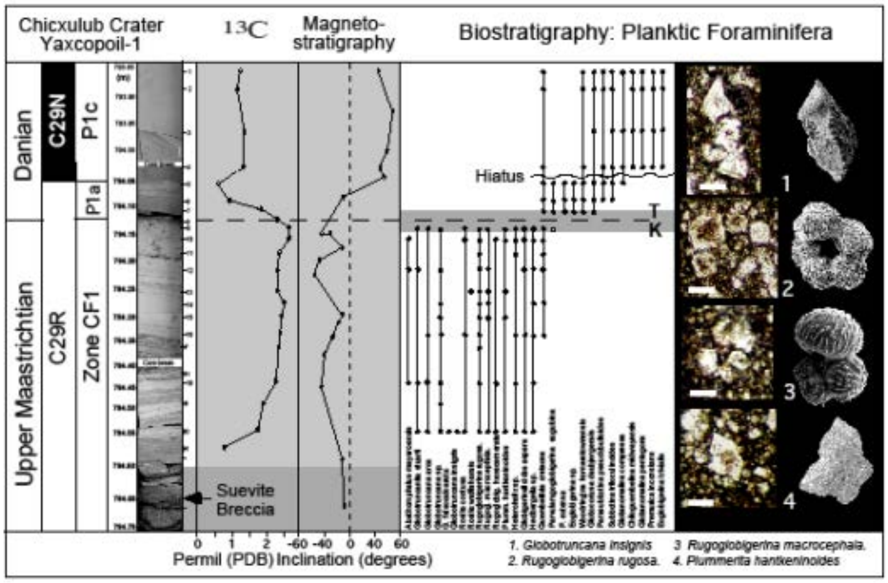


Figure 8. Chicxulub impact crater core Yaxcopoil-1: Stratigraphy of the KT transition from the impact (suevite) breccia to the KT boundary shows a 50 cm thick limestone layer with five thin glauconite clay layers deposited over tens of thousands of years. Magnetostratigraphy and planktic foraminiferal assemblages indicate 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.

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 K-T sequences along the Brazos River in Texas located about 1300km from the Yucatan impact crater.

These sections contain the best preserved marine and terrestrial microfossil records of North America in essentially continuous KT 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 million years. They differ from the deep-water (outer shelf to upper slope) north eastern 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 KT impact tsunami or related deposits and served as type section for the impact tsunami interpretation in NE Mexico (e.g., Bourgeois et al., 1988; Smit et al.,1992, 1996; Heymann et al., 1998; Schulte et al., 2006). In Texas as in NE 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 KT 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 NE Mexico and the Chicxulub crater core Yaxcopoil-1 based on new drilling and KT 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, with each well spanning from the Danian through the Maastrichtian and recovering the KT interval and sandstone complex (Fig. 9). In addition, new outcrops exposing the KTB were sampled to obtain a broad regional distribution and all 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, the 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 50-100 feet to recover the KT transition. These attributes make the Brazos sections the most important KT 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 1m of claystones (1.6m reported by Schulte et al., 2006), which were deposited in a dysoxic environment. Truncated burrows in the sandstone complex and up to three upward fining spherule layers near the base reveal deposition occurred over an extended time period inconsistent with tsunami deposition (Gale, 2006;Keller et al., 2007, 2009d). Betweeen 40 and 60cm below the unconformity at the base of the sandstone complex, the original spherule deposit was discovered in a yellow clay that consists of altered impact glass (cheto smectite), identical to the altered impact glass in the spherule layers at the base of the sandstone complex (Fig. 10). Brazos sections thus demonstrate that the sandstone and Chicxulub impact spherule layer are stratigraphically separated and below the KTB.

Critique of these results has centred on the placement of the KT boundary. Some workers have argued 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, 2010).

This is circular reasoning - one cannot evaluate the age of the Chicxulub impact by defining the impact as KT in age. The KT boundary definition must include independent criteria

Figure 9. New drilling of Brazos K-T sections by DOSECC in 2005 and supported by the National Science Foundation through the Continental Dynamics Program and Sedimentary Geology and Paleobiology Program.

Volcanism and KT Mass Extinction: 1980 – 2010

Before the impact hypothesis was proposed by Alvarez et al. (1980), McLean (1978) advocated CO_2 emissions from Deccan volcanism as the most likely cause for the KT mass extinction. This set the palaeontologist Dewey McLean on a direct collision course with the Luis and Walter Alvarez team. In addition, most dinosaur experts were highly sceptical and often critical of the impact hypothesis as 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 palaeontologists in general.

In an interview with the New York Times (January 19, 1988) Luis Alvarez said: “I don’t like to say bad things about palaeontologists, but they’re really not very good scientists. They’re more like stamp collectors.” Of criticism by dinosaur expert Dr William A Clemens, his colleague at the University of California at Berkeley, he said it could be dismissed on grounds of general incompetence. He denied that he had interfered with the academic promotion of Dr. McLean (http://filebox.vt.edu/artsci/geology/mclean/), 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. It 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 palaeontologists to anyone that disagreed with the impact hypothesis and especially those who offered Deccan volcanism as an 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 KT mass extinction (www.nytimes.com/1988/01/19/science/the-debate-over-dinosaurextinction).

These personal attacks on opponents of the impact hypothesis during the1980s scared away most scientists from contributing to the debate or entering the discussions. Deccan volcanism became the invisible elephant in the room.

Figure 10. 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 the base of zone CF1, or ~300 ky before the mass extinction.

Deccan Volcanism - Real Cause for the KT Mass Extinction?

Despite the rancorous debate of the 1980s, the study of Deccan volcanism continued to be most actively pursued by geophysicist Vincent Courtillot and his collaborators at the Institut de Physique du Globe in Paris. At the beginning, Courtillot advocated Deccan volcanism not as alternative hypothesis to an impact, but as contributing factor in addition to impact (Courtillot et al., 1986, 1988). As evidence accumulated the discussions gradually shifted towards volcanism as dominant long-term role in the mass extinction and the impact as the “last straw” at the KTB (Vandamme and Courtilot, 1992;Courtillot, 1999).

But demonstrating that Deccan volcanism was the principal cause of the KT mass extinction faced daunting scientific hurdles. For over two decades the main Deccan eruptions were shown to have occurred over less than 800,000 years in magnetic polarity C29r, spanning the Cretaceous-Tertiary boundary (Courtillot et al., 1986, 1988; Duncan and Pyle, 1988; Vandamme and Courtilot, 1992). Determining where within this major eruptive phase the KT 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 KT mass extinction.

Today, this view is rapidly and radically changing principally due to three recent studies. Chenet et al. (2007, 2008) 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 67.4Ma, 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 palaeomagnetic analysis, K-Ar and Ar/Ar dating, chemostratigraphy and petrology.

Self et al. (2008a,b) measured sulphur and chlorine gas concentrations in rare glass inclusions of crystals in Deccan lavas and determined that 1km3 of lava released between 3.5 to 5.4 teragrams of SO_2 and one teragram of HCl. In modern basaltic eruptions both these gases cause well documented climatic and environmental effects. The massive Deccan eruptions and huge amounts of S and Cl gases released over a very short period at the end of the Cretaceous would have had severe environmental consequences.

Keller et al. (2008a) discovered that the KT mass extinction coincided with the end of the main phase of Deccan volcanism. Their results are based on sedimentologic, microfacies and biostratigraphic data of 4-9m-thick intertrappean sediments 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 1300km across the Indian continent and into the Gulf 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 KT 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,b).

The results of these studies strongly suggest that Deccan volcanism played a critical role in the KT mass extinction, which occurred after the last mega-pulse of the main phase of Deccan volcanism. Although the kill mechanism(s) and precise nature of environmental catastrophes due volcanic gas emissions remains to be determined, Deccan volcanism has emerged as a credible cause for the KT mass extinction and the most serious challenge to the impact hypothesis. Moreover, the discovery of rapid and voluminous Deccan eruptions at KT 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.

Conclusion

After 30 years of intense controversy and often unscholarly invective aimed at opponents of the impact hypothesis, KT studies may have finally reached the turning point where the sum total of scientific evidence overwhelmingly points away from a KT impact and strongly supports volcanism and associated climate and environmental changes as the most likely cause for the mass extinction. 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 favour of an extraterrestrial impact was the Ir anomaly. All corollary effects, such as global wildfire, nuclear winter, shut off of photosynthesis and mega-tsunamis have remained hypothetical, enjoying 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 publicised personal invective. An US versus THEM culture was cultivated that provided easy access to favourable peer reviews and rapid publication of manuscripts claiming support for the impact hypothesis, invitations to lecture at conferences, and favourable peer reviews of grant proposals for impact supporters. This adverse climate and fear of personal attack kept many scientists away from KT studies, or 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 seemed to be a boon that trumped all doubts. The Chicxulub crater became widely accepted by scientists as the impact that caused the KT mass extinction. Yet, in a perverse twist of fate, the Chicxulub crater discovery was 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 and North America. Two decades of multi-disciplinary studies by both sides amassed a solid database with a sum total that overwhelmingly reveals the Chicxulub impact as predating the KT mass extinction and causing no species extinctions.

In a triumvirate of studies testing the age of the Chicxulub impact, first in NE Mexico, then the impact crater on Yucatan 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 KT in age. The final evidence 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 20m depth during the KT transition and cut by incised valleys during the latest Maastrichtian sea-level fall. The high sediment accumulation 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 300,000years before the KTB; (2) three upward-fining impact spherule layers eroded from nearshore areas and redeposited at the base of incised valleys; and (3) the KTB up to 90cm above the sandstone complex that infills the incised valleys (Keller et al., 2007).

Despite all this evidence, the KT controversy rages on. In their recent paper Chicxulub impact proponents redefined the KTB based on impact signals and claimed that the Chicxulub impact is the sole cause for the KT mass extinction (Schulte et al., 2010).

Acknowledgements

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