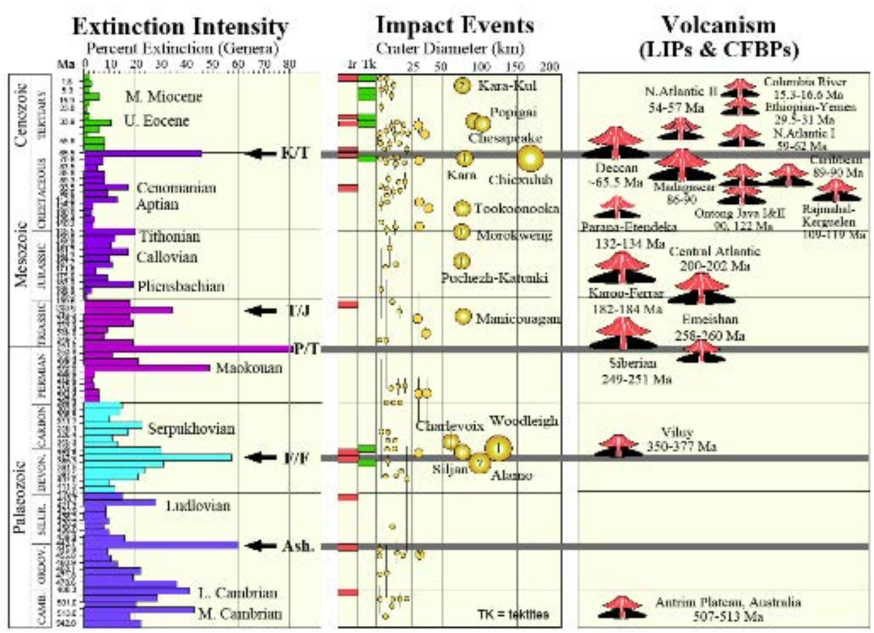
Online Special - KT Mass Extinction: theories and controversies

Recent attempts by the pro-Chicxulub lobby to pretend that meteorite impacts are the only game in town when it comes to explaining the Cretaceous-Tertiary (KT) mass extinction raise a smile from Gerta Keller* who here gives her view of the rise and fall of a theory.

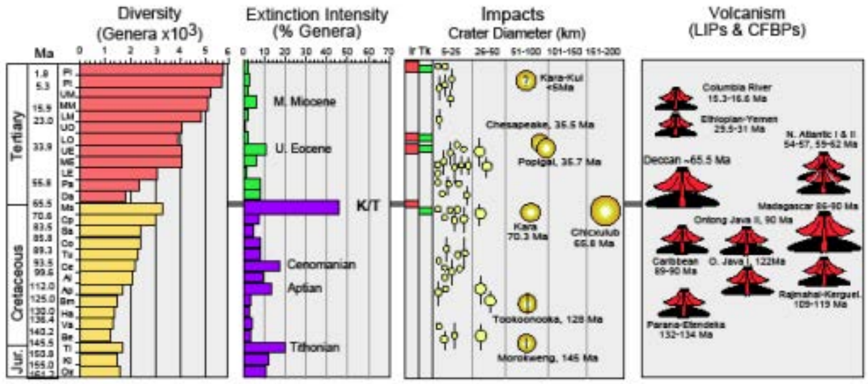
Geoscientist Online 5 May 2010

Editor's note: To see the shortened captions to these figures, please view this page in Internet Explorer. The captions will appear as you roll your cursor over the images.

Most mass extinctions that have afflicted life on Earth during the past 500 million years have occurred during times of major volcanic eruption (Fig. 1) and all were accompanied by major changes in climate, sea level and oxygenation levels in the ocean.



Among the five major mass extinctions, only the end-Cretaceous (KT) displays a close coincidence of four factors - an iridium anomaly (commonly assumed to represent an impact), an impact crater (Chicxulub), a large igneous province (the Deccan Traps) and major climate and sea level changes (Fig. 2). The KT mass extinction also differs in that it follows the longest period (145-65.5Ma) of low background extinction (Fig. 2). Throughout the Cretaceous, generic diversity had increased, accelerating during the Campanian and peaking during the late Maastrichtian, prior to the mass extinction (Fig. 2).



Volcanologists and palaeontologists have long sought to explain extinctions by SO_2/acid rain poisoning by continental flood basalt provinces (CFBPs) and large igneous provinces (LIPs), and eutrophication - exacerbated by climate change. Large impacts would create similar effects, and although hybrid hypotheses have tried to link all three together, the Deccan eruptions are not linked to the Chicxulub impact. Moreover, in 2003 Ivanov and Melosh concluded that large impacts could not initiate LIP eruptions.

Since 1980, a meteorite impact as the cause for the KT mass extinction has become the most popular idea - but neither the impact nor volcanism hypothesis has ever been entirely convincing on its own. Critical aspects of the record (selective nature, variable rates, gradual or stepwise extinctions, timing) could not be perfectly reconciled with either.

A most vexing problem has been correlating the KT mass extinction with either potential cause. Mass extinction, impact and volcanism markers are never observed in the same sequences for any of a number of reasons - an incomplete record, non-preservation of one or other signal, or because the events were not coeval. Frequently, correspondence between impact and mass extinction must be inferred from correlations lacking necessary resolution; or by radiometric dating with large (1%) error bars; or merely on an assumption that the mass extinction must have been caused by an impact, and that this impact must have been Chicxulub.

Impact controversy

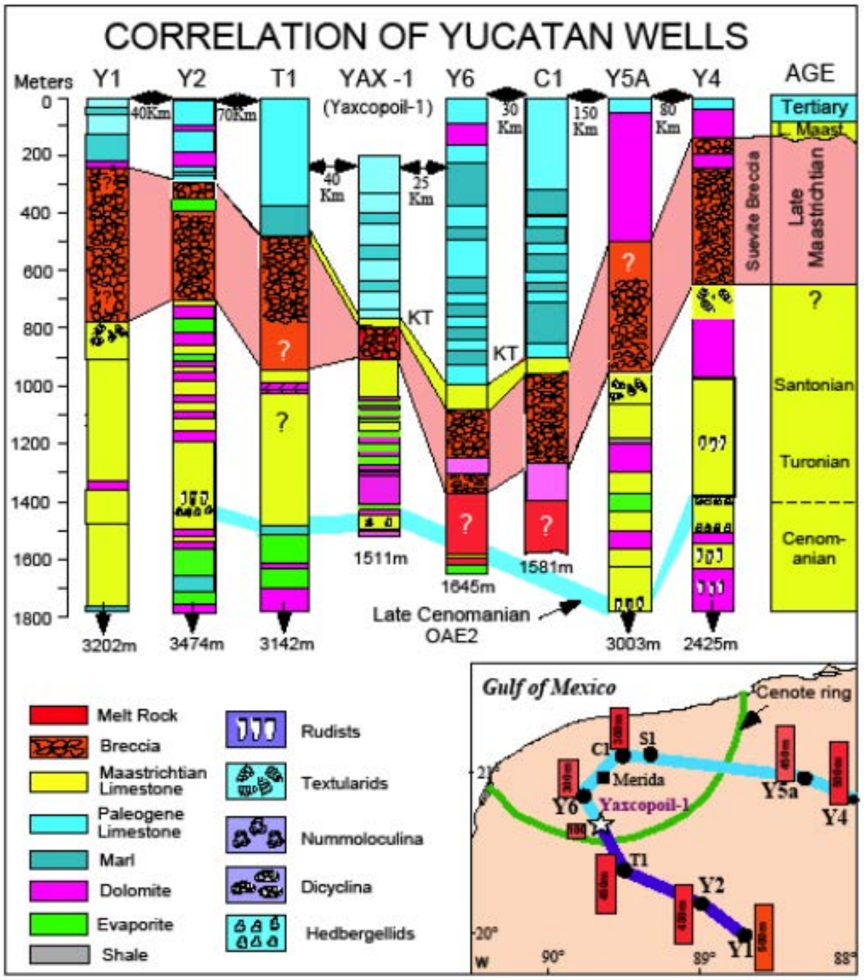
Within a short time of the discovery of the famous iridium anomaly at the KT boundary at Gubbio, Italy, the controversy resolved itself into two contrasting schools. One held that the KT events reflected the catastrophic effects of a large (10km) bolide colliding with the Earth. The other held that the KT extinction was the culmination of long-term changes in the Earth's biota, accelerated by a bolide impact.

In a 1994 field guide to the crucial localities in Mexico I 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. 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 dogma. Yet ugly little facts kept surfacing, and now taken together those ugly little facts call for a (long overdue) re-evaluation of the KT impact-kill hypothesis, and a re-examination of Deccan volcanism as a potential cause.

A quick guide to some of the most persistent arguments of the Chicxulub-

- Whether a sandstone complex between the spherule layer and the KT boundary represents tsunami deposition, or submarine channel infill by current transport, gravity flows and slumps associated with slope conditions and a sea-level fall.
- Whether the stratigraphically oldest spherule layer discovered in upper Maastrichtian sediments in NE Mexico and Texas is due to slumps, or represents the time of the impact (about 300ky prior to the mass extinction).
- Whether the impact breccia in Chicxulub crater core Yaxcopoil-1 marks the KT boundary, and therefore sediments up to the KT should be interpreted as backwash and crater infill, 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 Chicxulub impact breccia.
- Whether the Chicxulub impact caused the KT extinction, or caused neither the extinction nor any significant environmental effects.
- Whether the KT boundary should be re-defined solely on the mass extinction and the

presence of any impact evidence (Ir anomaly, impact spherule ejecta, impact breccia) 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 the coincident Ir anomaly.



Impact-kill

The impact hypothesis evolved quickly into a virtually unassailable “truth” scepticism about which could be scornfully dismissed. “Everybody knows that an impact caused the mass extinction.” “Palaeontologists can’t accept that the mass extinction was instantaneous.” “Palaeontologists are ... bad scientists ...like stamp collectors.” “How could so many scientists be so wrong for so long?”.

It all began with the discovery of a sharp peak of anomalous iridium concentration in a thin clay layer at the KT boundary near Gubbio, Italy, in 1979. Iridium occurs in concentrations in some meteorites and deep within the Earth where it is brought to the surface by volcanic eruptions. A volcanic Ir source, it was thought, could not have resulted in a sharply peaked concentration, whereas a meteorite crashing into Earth could leave this tell-tale anomaly in a single instant.

Today, this assumption is questioned, and new data suggest (see below) that the Deccan eruptions did in fact occur rapidly enough to deposit peak Ir anomalies. But back then, the coincidence of the anomaly and mass extinction of planktic foraminifera looked convincing. Although an impact theory had been proposed before, now for the first time actual supporting evidence existed, making it testable.

Although the idea attracted scientists from diverse fields, sadly this rarely resulted in integrated interdisciplinary studies. Increasingly, new findings were judged by how well they supported the hypothesis, rather than how well they tested it. An unhealthy “us vs. them” culture developed, and any who dared question the hypothesis were derided, dismissed or ignored.

Yet controversy persisted 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 a new set of investigative tools and methods. Where formerly samples were taken at metre intervals, now it was by the centimetre - or even a few millimetres. The new toolkit was soon being applied elsewhere and led to advances and breakthroughs for all mass extinction events and major catastrophes. This unintended consequence has been a lasting achievement of the impact hypothesis.

The Smoking Gun?

But where was the crater? After a 10-year search a circular magnetic and gravity anomaly on the north western margin of the Yucatan peninsula, Mexico was hailed as the “smoking gun” (Fig. 3). This had been first identified a decade earlier, but had evaded wider notice. Its diameter was first announced as 180-200km, then expanded to 300km and subsequently reduced to 150-170 km. It was linked to the KT boundary on evidence of shocked quartz and an Ir anomaly within the impact breccia (the latter 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 KT boundary, although the recognized error margin for $^{40}Ar/^{39}Ar$ ages today is 1%, or 600ky. But then, the case seemed sealed.

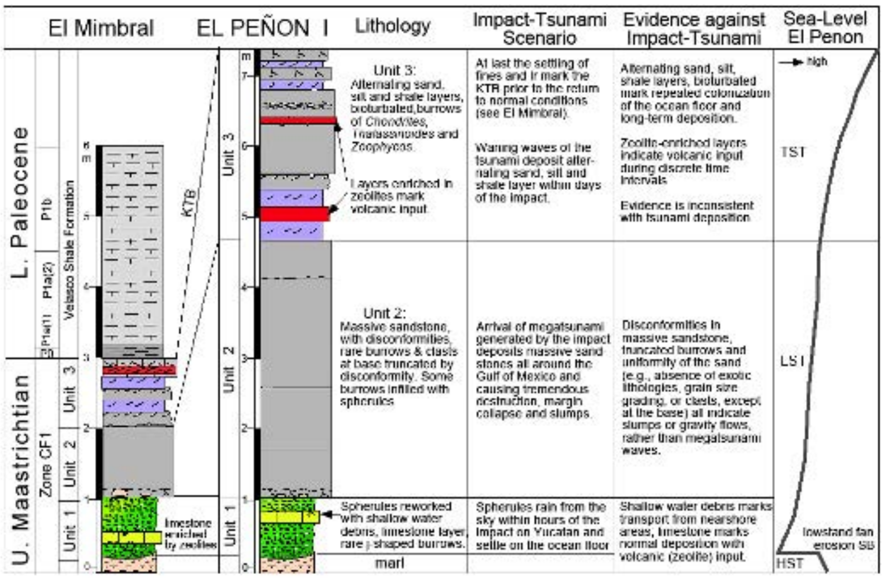
But one critical element was still missing – the age of the sediments overlying the impact breccia in wells taken by Mexico’s oil company PEMEX from the Chicxulub crater. Without this, all that could be said with confidence was that the breccia had been deposited sometime within the rather large error margin of $^{40}Ar/^{39}Ar$ ages spanning the KTB - insufficient to claim cause-and-effect. But in the exuberance of the time, this critical detail was considered inconsequential.

Only in the first announcement was it acknowledged that determining the precise age of Chicxulub was impossible from available data. Indeed, Lopez Ramos had previously determined a late Maastrichtian age for the limestone above the impact breccia in Chicxulub wells C1 and Y6 (Fig. 4). This was a problem. Alan Hildebrand sent a single sample from well Y6 N12 about 70m above the impact breccia to me, and I shared it with W Sliter for age determination. We both reported a late Paleocene (zone P3) age. This was erroneously taken to imply a KT age for the impact breccia, and that the earlier age-assignment was invalid. But Lopez Ramos’ report could not be verified because no samples were available. Likewise, Hildebrand had no samples for the 70m between the impact breccia and sample Y6 N12.

It was rumoured that the PEMEX core store had burned down and all cores destroyed, except for the few analysed by the small group that announced the ‘smoking gun studies’. When Chicxulub cores re-appeared, a biostratigraphic study of all existing PEMEX wells from the Chicxulub area revealed that at least 18m of undisturbed late Maastrichtian limestones overlay the impact breccia in wells Y6 and C1 (Fig. 4). The authors cautioned that it was impossible to substantiate Chicxulub as KT impact crater.

The warning went unheeded. Substantiating the KT age of Chicxulub now rested on the stratigraphic position of the impact spherule layer in Haiti; though this proved difficult because impact spherules (and two PGE anomalies) are present in early Danian zone P1a sediments in Haiti. Similarly in southern Mexico, Belize and Guatemala, spherule-rich layers were reported from early Danian sediments overlying the KT unconformity. 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.

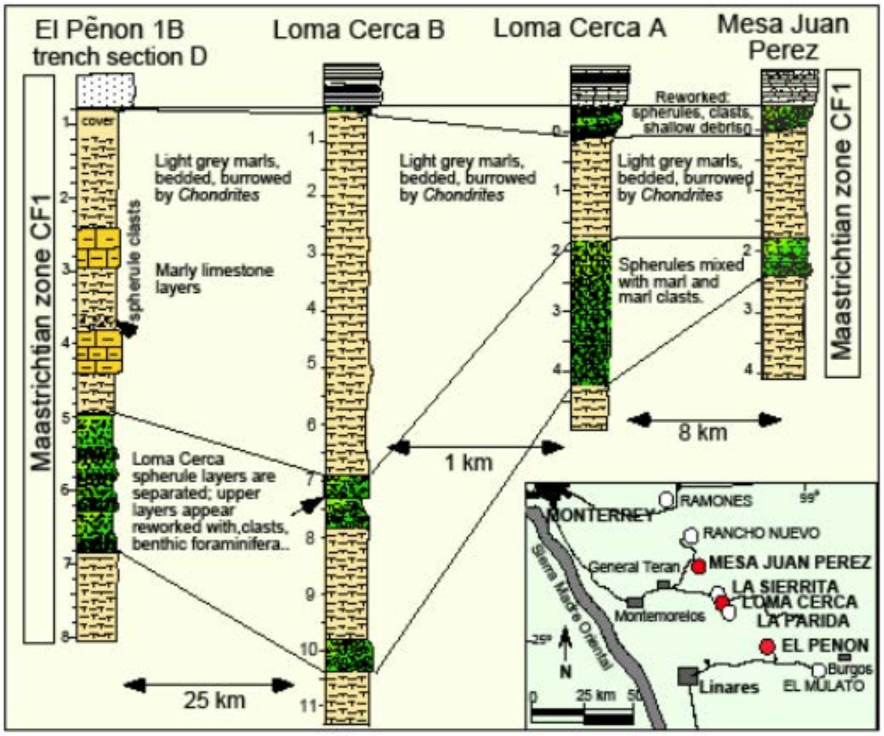
Consequently, the KT boundary was now placed at the impact spherule layer – based on a blithe assumption that the Chicxulub impact had caused the mass extinction, and that the sandstone complex was the result of an impact-generated mega-tsunami event. Although widely accepted, this theory fuelled its own controversy.



Impact-tsunami deposits?

Inconclusive age control of the Chicxulub crater 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, there were problems from the very beginning. Impact glass spherules in NE Mexico first turned up in El Mimbral and subsequently at El Peñon. At both localities a 1m-thick glauconite 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). Above the sandstone complex, an Ir anomaly was detected at El Mimbral, coincident with the mass extinction of planktic foraminifera. If the Chicxulub impact caused the mass extinction and Ir anomaly, then the spherules should be stratigraphically nearby. Why the separation?

Assuming that spherules, Ir anomaly and mass extinction all originated in the same event, then the sandstone complex could be interpreted as impact-generated tsunami deposit. In this scenario, spherules rained from the sky minutes to hours after 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.

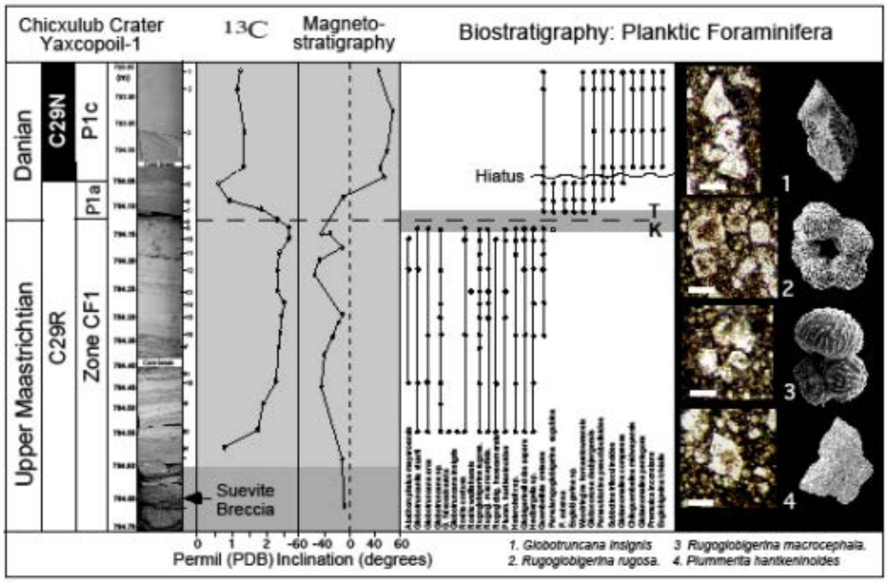


Alas, too many facts contradicted the tsunami-deposition hypothesis for the sandstone complex in NE Mexico, including multiple spherule layers, separated by a 20-25 cm thick sandy limestone (unit 1) containing j-shaped burrows infilled with spherules. Spherule deposition (unit 1) thus occurred twice, separated by a long period of limestone sedimentation. In unit 3 two ash layers and several bioturbated horizons within the alternating sand-shale layers, all indicated that deposition took place over an extended period (Fig. 6).

These spherule layers could not have rained from the impact cloud, a fact also evident from abundant reworked shallow-water debris transported from nearshore areas at El Mimbral. Instead, they indicate deposition over an extended interval, probably related to the latest Maastrichtian regression, which scoured submarine channels (Fig. 6). During subsequent low sea levels, spherule debris eroded from nearshore areas was transported seaward and deposited in the channels (unit 1). Gravity slumps led to massive unsorted sand influx (unit 2). With the rising sea level (TST) the coarse and fine layers of unit 3 mark periods of rapid sediment influx alternating with normal sedimentation and colonisation of the ocean floor (burrows in fine grained layers, Fig. 6).The iridium anomaly and KT mass extinction at El Mimbral in the clay layer above the sandstone complex mark a condensed interval followed by the continued rise in sea level. The same lithological, faunal and geochemical characteristics are observed in dozens of outcrops in NE Mexico.

How old is Chicxulub?

The sedimentology and burrowing of the sandstone complex raised initial doubts about the supposed KT age of these deposits. Further doubts followed with the discovery of a 2m-thick impact spherule unit interbedded in late Maastrichtian marls. This was 4-5m below the spherule layers at the base of the sandstone complex at El Peñon, 9m below that at Loma Cerca and 2m below at Mesa Juan Perez (NE Mexico - Figs. 5, 7). These older spherule layers were not reworked from shallow waters (contained no wood, leaves or shallow-water benthic forams as are common in the spherule layers at the base of the sandstone complex). This oldest spherule layer predates the KT boundary by as much as 300,000 years (it occurs near the base of planktic foram zone CF1, which spans the last 300,000 years of the Maastrichtian).



How could an impact leaving a 170km-wide crater not have caused the mass extinction, people asked. But a better question would have been: why should an impact with a 170km-wide crater have caused one of Earth's largest five mass extinctions when other, equally large impacts, (such as the Manicouagan impact (Late Trias - 150km), and the late Eocene Popigai and Chesapeake impacts (c. 100km) have left no measurable environmental effects? Quantitative analysis of planktic forams across the primary Chicxulub impact spherule layer has shown that not a single species became extinct as a result of this impact, either.

In 2001-2002, coring of Yaxcopoil-1 by DOSECC (Drilling, Observations and Sampling of the Earth's Continental Crust) was supposed to resolve the age issue once and for all. Instead, the new crater core also supported a pre-KT age. In a 50cm-thick laminated micritic and partially dolomitised limestone between the top of the impact breccia and a 1cm-thick green clay layer that marks the KTB and mass extinction (Fig. 8), crucial evidence was found.

Above this 50 cm interval the first early Danian species of zone Pla (Parvularugoglobigerina eugubina) are seen - coincident with the characteristic $\delta^{13}C$ shift of the KTB. In the limestone below, planktic forams indicate deposition during zone CF1 (magnetochron 29R). Sedimentology and mineralogy (five thin glauconite layers, bioturbation and absence of high-energy deposition and exotic clasts) further supported the idea that normal, slow deposition occurred over an extended period.

This was incompatible with a tsunami backwash/crater infill interpretation. Moreover, the pre-KT age of the Chicxulub impact breccia supported those early observations of Lopez Ramos and Ward, based on PEMEX cores in the Chicxulub crater area - as well as earlier observations of the pre-KT age of the Chicxulub impact based on the stratigraphically oldest impact spherule layer in NE Mexico (Figs. 4, 7). The critical drilling test that was to prove the Chicxulub impact as KT in age, and hence caused the mass extinction, had failed.

This continuing controversy led people to suggest that impact and tsunami disturbance made any age determination unreliable near the crater. And so, with this in mind, we turned our focus to the KT sequences along the Brazos River in Texas, 1300km from Chicxulub. 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, deposited near the entrance to the shallow Western Interior Seaway, have experienced only minor tectonic disturbance in the last 65 million years. They differ from the outer shelf/upper slope sections of NE Mexico sections mainly by being shallow and having high sedimentation rates. They share critical similarities, including a sandstone complex with reworked spherules at its base. This had long been interpreted as KT impact tsunami or related deposit, and served as type section for the impact tsunami interpretation in NE Mexico. In Texas (as in NE Mexico) this interpretation, which assumed that the sandstone was created by the Chicxulub Impact, required the KTB to occur at its base. Alas, standard KT-defining paleontological and stable isotope criteria contradicted this. Nevertheless, the Brazos sections are the ideal testing ground for both the age of the Chicxulub impact and its biotic and environmental consequences.

In 2005 we set out to test the results from NE Mexico and Yaxcopoil-1 with a new drilling and outcrop study along the Brazos River, with support from the US National Science Foundation. Drilling of Brazos sections spanned from Danian through Maastrichtian, and recovered the KT interval and sandstone complex (Fig. 9). New outcrops exposing the KTB were sampled, to obtain a broad regional distribution. All sections were studied by an international scientific team.

Early Results show that the sandstone complex is separated from the KT boundary by up to 1m of claystones, 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 period, inconsistent with tsunami deposition.

Between 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.

Criticism of these results has focused on the placement of the KT boundary. Some 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. Impact craters seem to beget circular reasoning; the KT boundary definition must include independent criteria.

Volcanism

Before the impact hypothesis was proposed by Alvarez et al. (1980), palaeontologist Dewey McLean (1978) had advocated CO_2 emissions from Deccan volcanism as the most likely main cause for the KT mass extinction. This set him on a direct collision course with the Alvarez team. Most dinosaur experts were highly sceptical of the impact theory, 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 (19 January 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, 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 extended to anyone who disagreed with the impact hypothesis (and especially those who offered Deccan volcanism as an alternative). Special invective was 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. These attacks from a big-hitting Nobel Prize winner scared scientists away. Deccan volcanism became an unremarked (or invisible?) elephant in the room.

Nevertheless, the study of Deccan volcanism continued to be actively pursued by geophysicist Vincent Courtillot and collaborators at the Institut de Physique du Globe (Paris, France). From the start, Courtillot advocated Deccan volcanism not as alternative to an impact, but as contributing factor. Discussions gradually shifted towards volcanism as dominant long-term factor, with impact as the “last straw”, at the KTB.

But demonstrating that Deccan volcanism was the principal cause faced daunting hurdles. For over two decades, the main Deccan eruptions were shown to have occurred over less than 800,000 years (within magnetic polarity C29r, spanning the KTB). Determining where, within this major eruptive phase, the KT mass extinction occurred, remained problematic. Models of the Deccan Traps' biotic and environmental consequences generally underestimated the duration, eruption-rate and gas emissions by orders of magnitude. This led workers to think that volcanism could not have been one of the major causes of the KT mass extinction.

This view is rapidly and radically changing, principally due to three recent studies. Chenet et al. have estimated that 80% of the 3500m-thick Deccan Traps were erupted over a very short time - possibly less than 10,000 years - with most of that time taken up by the quiet periods between eruptions. The entire Deccan lava pile was 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 in the early Danian.

Self *et al*., measuring sulphur and chlorine gas concentrations in glass inclusions, determined that one cubic kilometre of erupted lava would have released between 3.5 to 5.4 teragrams of SO_2, and one teragram of HCL. These 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.

Then Keller et al. revealed in 2008 that the mass extinction coincided with the end of the main phase of Deccan volcanism. These results are based on sedimentological, microfacies and biostratigraphic data of 4-9m-thick inter-basalt-flow sediments in four quarry outcrops in SE India. Here, the so-called Rajahmundry traps mark the end of the main phase of Deccan volcanism, and include the world's longest lava flows, extending 1300km 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 foram assemblages of zone P1a, which mark the subsequent evolutionary recovery following the KT mass extinction.

These results strongly suggest that Deccan volcanism played a critical role in the KT mass extinction, which took place after the last mega-pulse of the main phase of Deccan volcanism. 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 even account for at least some of the Ir anomalies.

Conclusion

After 30 years of intense controversy and often unscholarly invective, KT studies may have finally reached the point where the sum of scientific evidence points overwhelmingly away from a KT impact and towards volcanism and associated climate and environmental changes as the likely cause for the mass extinction.

With the discovery of the Chicxulub structure in 1990 and its claim as the smoking gun, the crater became widely accepted as the trace of the impact that caused the KT mass extinction. Yet, in a perverse twist of fate, Chicxulub's discovery turned out to be a boon to those scientific sceptics who had raised questions about this impact. For the first time, the hypothesis could be tested directly, based on the impact crater itself and 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.

Nevertheless, as controversies go this one will die hard. Just recently, impact proponents have re-asserted their belief that the Chicxulub impact was the sole cause for the KT mass extinction.

Acknowledgements

The material of this study is based upon work supported by the US National Science Foundation through the Continental Dynamics Program and Sedimentary Geology and Paleobiology Program under NSF Grants EAR-0207407 and EAR-0447171.

References

** Prof. Gerta Keller works at the Department of Geosciences, Princeton University, Princeton NJ*