PREFACE

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NATURE OF THE KTB CONTROVERSY

One of the liveliest debates among scientists concerns potential causes of catastrophic extinction events, but none have garnered the imagination of scientists and public alike as the Cretaceous–Tertiary boundary (KTB) mass extinction including the demise of the dinosaurs 65 million years ago. Over three decades ago the discovery of anomalous concentrations of iridium in a thin clay layer between Cretaceous limestones and Tertiary claystones led Alvarez and collaborators to propose that a large meteorite crashed into Earth and caused the KTB mass extinction (Alvarez et al., 1980). Because iridium is rare on Earth's surface, relatively common deep in Earth's interior where it can surface via volcanic eruptions, but most abundant in some meteorites, this hypothesis rapidly gained support. With the discovery of the 175 km diameter Chicxulub impact crater on Yucatán in 1991 (Hildebrand et al., 1991), followed by discoveries of impact glass spherule ejecta throughout the Caribbean, Central America, and North America in stratigraphic proximity of the KTB mass extinction (Izett et al., l99l; Swisher et al., l992; Smit et al., 1992) there seemed little doubt that the smoking gun had been found in the Chicxulub impact crater and that the impact-kill hypothesis was all but proven.

For many scientists, the impact-kill hypothesis became a Eureka moment—a beautiful theory that could be expanded with many corollaries to account for virtually all observations. It was reconfirmed by 41 scientists in a recent Science article (Schulte et al., 2010) and expressed well by Birger Schmitz (2011) in his review of Ted Nield's new book *Incoming—Or why we should stop worrying and learn to love the meteorite*. Nield (2011) writes a riveting account on meteorites that begins with fascinating historical facts, heresy, and beliefs through the ages before leading into the scientific geological account of the meteorite theory and an objective treatment of the controversy based on evidence inconsistent with this theory. There is nothing worse than destroying a beautiful theory with facts. Schmitz takes issue with Nield's suggestion that doubters like Gerta Keller and her small team may have a point—the impact harmed nature, but the mass extinction had more varied causes. Schmitz considers this a compromise that belongs in politics, not in science. He goes on to state that he started his career in the 1980s as a non-believer of the impact theory, but has now seen the KTB clay layer in over 50 localities "where the iridium enriched layer always occurs exactly at the level at which the microscopic foraminifera typical of Cretaceous oceans disappear almost completely . . . The precise coincidence of these two events is so compelling that it is difficult to understand how anyone can doubt the direct relationship between them" (Schmitz, 2011).

Similar sentiments, expressed by numerous scientists over the past 30 years, have become the core belief of the impact hypothesis. However, they are missing the point; there never was any disagreement that the mass extinction and iridium anomaly coincide in the KTB clay layer. Their misconception lies in attributing the iridium anomaly to the Chicxulub impact (despite the absence of evidence) simply because no other large impact is known that could account for the Ir anomaly and because more than one large impact over a relatively short time interval is considered unusual. But maybe this is not so unusual. In his review of *Incoming* Schmitz, referring to his own work on the Ordovician discussed in the book, states that "One or two of the meteorites may have been almost as large as the body that took out the dinosaurs." Moreover, he claims that the effects of these large impacts were highly beneficial to life as they coincided with the great Ordovician biodiversity event. With that precedent, why should a similar-sized meteorite at the KTB, or for that matter the pre-KTB Chicxulub impact have been the sole cause for the KTB mass extinction?

Many scientists truly believe that the Chicxulub impact is the sole cause for the KTB mass extinction. But belief is not scientific evidence. Belief biases scientific investigations and clouds judgment, as it leaves no room for new evidence that contradicts belief. The very nature and purpose of scientific research is the search for truth, unravel facts, and accumulate evidence that eventually shows us the true nature of events. Thus science is not static, belief is. In the three decades since the impact theory was proposed, much evidence has been discovered that defies this simple cause-effect scenario and reveals that the Chicxulub impact predates the mass extinction. No iridium enrichment has ever been documented from the Chicxulub impact ejecta layers and no Chicxulub impact spherules have ever been found in the KTB clay, but always in older sediments or reworked into younger sediments (Kramar et al., 2001; Stueben et al., 2005; Miller et al., 2010; Gertsch et al., this volume). The KTB iridium anomaly, if of impact origin, must therefore have originated from another large meteorite impact as suggested for nearly two decades by our team (Keller et al., 2003).

The only indisputable Chicxulub impact evidence is melt rock glass spherules commonly found below the mass extinction horizon from Texas through northeastern Mexico. What these sections have in common are high rates of sediment deposition and a relatively complete record of the mass extinction. But in the northwest Atlantic (New Jersey, Blake Nose off Florida) and through the Caribbean and Central America (Belize, Guatemala, southern Mexico), the record is very incomplete with at least 500 ky missing (hiatus) across the KTB mass extinction due to Gulf Stream erosion. Throughout this region, impact glass spherules are reworked into early Danian sediments above the hiatus and mass extinction horizon. Nevertheless, this juxtaposition of impact-spherule-rich Danian sediments with upper Cretaceous sediments is frequently claimed as proof that the Chicxulub impact is precisely KTB in age and caused the mass extinction (e.g., Olsson et

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al., 1997; Norris et al., 1999; Arenillas et al., 2006; MacLeod et al., 2007). The strong belief in the cause-effect scenario, has led many workers to cast a blind eye to obvious evidence to the contrary. In the words of one reviewer to a paper published in PNAS (Keller et al., 2004): I just can't believe it. How could so many have been so wrong for so long!

The hardest thing in science is to convince other scientists that a very popular hypothesis is wrong. Consensus science wins. The few who dare voice concerns or amass evidence that questions or disproves the hypothesis are derided as misguided, contrarians, and worse. So why do we persist? Is there an ulterior motive? There is only one answer—we want to know the truth. We want to know precisely what caused the mass extinction 65 million years ago. We are driven by curiosity and science to painstakingly sleuth through the sedimentary records of hundreds of localities for any clues, employing a multitude of analytical methods and testing consistency among results from many disciplines (e.g., paleontology, sedimentology, mineralogy, and geochemistry) and cross-correlating numerous sequences to search for consistent patterns.

Over the past two decades more than 65 localities with Chicxulub impact spherule ejecta have been investigated from North and Central America, the northwest Atlantic and Caribbean, and over 100 other localities worldwide. This accumulated scientific evidence is the source of the contentious arguments regarding the age of the Chicxulub impact on Yucatán and whether this impact did or did not cause the KTB mass extinction. This book on the Brazos sections confirms many of those results and adds critical new information on the time sequence of events from the Chicxulub impact to the 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—65 m.y. ago.

WHY BRAZOS?

No mountain of evidence is ever enough to convince those who believe that all is already known and proven. By 2004 we had already demonstrated the pre-KTB age of the Chicxulub impact in northeastern Mexico and the Yucatán impact crater well Yaxcopoil-1 and we were searching for triplicate confirmation of these results. We chose the Brazos River area of Falls County, Texas, as the ideal testing ground for several reasons. The location is 1300 km from the Chicxulub impact crater on Yucatán and in the shallow Western Interior Seaway that 65 m.y. ago spanned northwest through much of North America and may have sheltered sediment accumulation from erosion by strong currents. There is no tectonic disturbance. Sediments remain in much the same way as they were laid down 65 m.y. ago. Sediment deposition occurred in a very shallow environment near the shore with high rates of sediment accumulation amplified by riverine influx from land. The high sediment influx resulted in one of the world's most expanded and complete KTB records with extremely well-preserved fossils and the added bonus of a sandstone complex with Chicxulub impact spherules at the base that link it directly to the impact crater on Yucatán. All these attributes made the Brazos area the ideal location to test the challenging results from northeastern Mexico and Yucatán crater that revealed the Chicxulub impact predates the KTB mass extinction.

In 2005 we set out to test these results based on new drilling and outcrops along the Brazos River and its tributaries the Cottonmouth and Darting Minnow Creeks. The project was supported by the National Science Foundation through the Continental Dynamics Program (Dr. Leonard Johnson), and the Sedimentary Geology and Paleobiology Program (Dr. Richard Lane). Drilling 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 with impact spherules. In addition, a dozen new and old outcrops exposing the KTB were analyzed to obtain a broad regional distribution. Analyses were done by an interdisciplinary team of scientists, including paleontology, sedimentology, sequence stratigraphy, mineralogy, geochemistry, isotope geochemistry, trace element, and platinum group element geochemistry. The results of these studies are presented in this volume in a series of twelve articles and Appendix with data tables and supplementary material.

Results from the Brazos sections exceeded our wildest imaginations. For the very first time and unique to the high rates of sediment accumulation in the shallow protected environment of the Brazos River area, there is a clear separation (~ 1 m) between the KTB mass extinction and the sandstone complex with Chicxulub impact spherules at the base proving that these two events are widely separated in time (Keller et al., this volume). But there is much more. The sandstone complex that is commonly interpreted as impact-generated tsunami deposit, in fact infills submarine channels cut by a sea level fall and subsequently filled by eroded sediments during the rising sea level (Adatte et al., this volume). This deposition occurred over a long time period and was repeatedly interrupted by erosion, followed by recolonization of the sea floor by invertebrates—similar features were previously reported from numerous KTB sequences throughout northeastern Mexico.

At Brazos, there are up to three upward fining impact spherule layers present above the unconformity at the base of the sandstone complex. Lithified clasts overlie the unconformity. Some clasts contain impact spherules in the matrix and in desiccation cracks infilled with spherules (Adatte et al., this volume; Keller et al., this volume). These spherule-rich clasts are irrefutable evidence of a still older primary impact spherule ejecta layer that was lithified, eroded, and redeposited at the time of the sea-level fall. Evidence of this older primary impact ejecta layer was discovered in a yellow clay altered impact spherule layer 45–60 cm below the unconformity. No species extinctions or species abundance changes occurred at the time of the Chicxulub impact, which confirms previous observations in northeastern Mexico (Abramovich et al., this volume; Keller, this volume). Thus, the Brazos sections not only confirmed the pre-KTB age of the Chicxulub impact, but also revealed a multi-event sequence that demonstrates that the Chicxulub impact crashed into Yucatán tens of thousands of years prior to the latest Maastrichtian sea level fall that resulted in widespread erosion of impact spherules and other sediments and their redeposition in submarine channels forming the prominent sandstone complex in the Brazos area and in northeastern Mexico.

The Brazos sections clearly demonstrate that the KTB mass extinction is unrelated to the Chicxulub impact or deposition of the sandstone complex (Hart et al., this volume; Keller, this volume; Tantawy, this volume). The ~ 1 m claystone separation between the top of the sandstone complex and mass extinction reveals that after the last Maastrichtian sea level fall tens of thousands of years passed accompanied by a sea-level rise that continued across the KTB mass extinction. In this interval the mass extinction is clearly marked by the $\delta^{13}C$ shift and the evolution of the first Danian species, but no iridium enrichment. In all Brazos sections, multiple minor iridium enrichments are observed at condensed intervals and redox boundaries (Gertsch et al., this volume; Munsel et al., this volume). None can be attributed to an impact event. Similarly, no major changes are seen in trace element distributions at the the time of the Chicxulub impact or across the KTB (Gertsch et al., this volume; Ulrich et al., this volume). These and other results are documented in this volume. They complement previous studies in northeastern Mexico, but also provide a new dimension to the KTB debate based on their more complete high sedimentation records.

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