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The Chicxulub impact event and its environmental consequences at the Cretaceous–Tertiary boundary

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Abstract

An impact-mass extinction hypothesis for the Cretaceous–Tertiary (K/T) boundary transition has been confirmed with multiple lines of evidence, beginning with the discovery of impact-derived Ir in K/T boundary sediments and culminating in the discovery of the Chicxulub impact crater. Likewise, a link between the Chicxulub impact crater and K/T boundary sediments has been confirmed with multiple lines of evidence, including stratigraphic, petrological, geochemical, and isotopic data. The environmental effects of the Chicxulub impact event were global in their extent, largely because of the interaction of ejected impact debris with the atmosphere. The environmental consequences of the Chicxulub impact event and their association with the K/T boundary mass extinction event indicate that impact cratering processes can affect both the geologic and biologic evolution of our planet.

Keywords: Extinction; Cretaceous; Tertiary; Chicxulub; Impacts; Palaeoecology

1. Introduction

The marine fossil record indicates that mass extinctions and subsequent radiations are part of the evolutionary fabric that has generated greater biological diversity today than in the past (Raup and Sepkoski, 1982). Thus far during the Phanerozoic, five mass extinction events and about two dozen smaller extinction events have occurred, each followed by an evolutionary radiation (Sepkoski, 1986). The mass extinction events were global events that required one or more energetic mechanisms capable of dramatically altering the physical, chemical, and biological environments in which a multitude of species lived. One of the most energetic processes to affect planetary surfaces is impact cratering, which can produce multi-megaton blasts and, thus, environmental havoc.

Substantive suggestions of an impact-mass extinction hypothesis grew as our understanding of impact cratering grew, beginning with the discovery of Barringer Meteorite Crater (also known as Meteor Crater) and continuing with Apollo-era studies of the Moon. (See Kring, 1993; D'Hondt, 1998, for details about the historical development of the impact-mass extinction hypothesis; also see Marvin, 1990, 1999, for an assessment of how impact cratering affects the geological tenet of uniformitarianism.) The number of impact craters on the Moon implies >4 million impact craters with diameters from 1 to >1000 km have been produced on Earth, suggesting a link between the largest of those

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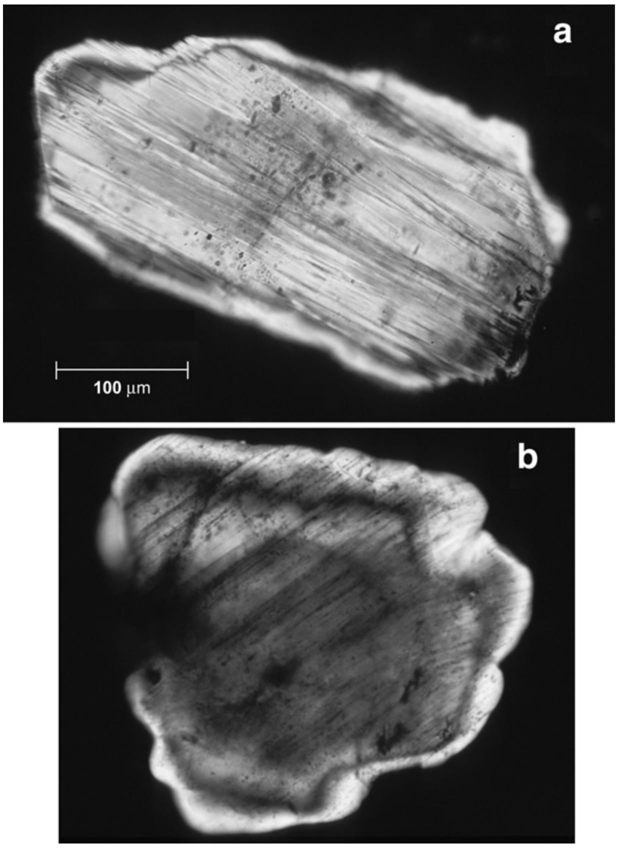

Fig. 1. Shock-metamorphosed quartz from (a) K/T boundary sediments in Haiti (0.45 mm long) and (b) the Chicxulub impact crater (0.32 mm long). The latter is from one of the two discovery samples from the Yucatán-6 borehole. Two sets of planar deformation elements are visible in each grain in the orientations shown. The only geologic process capable of generating this type of shock-metamorphic feature is impact cratering, although similar features can be reproduced in laboratory shock experiments and at nuclear test explosions. The grains are mounted on a spindle stage and viewed with crossed nicols; because the grains are not in thin-section (and, thus, not polished to a constant thickness), birefringence varies from the thicker cores to thinner rims.

events and the demise of a variety of species might be tenable.

The impact-mass extinction hypothesis is an attractive model for dramatic evolutionary change because it is a testable hypothesis. The hypothesis was first substantiated by L. Alvarez et al. (1980) who discovered Ir concentrated in sediment deposited at the Cretaceous–Tertiary (K/T) boundary, coincident with one of the Phanerozoic's largest mass extinction events. Iridium is important because it is normally rare in the Earth's crust (having been sequestered in the Earth's core and mantle during planetary differentiation), except when delivered by impacting asteroids and comets. Based on the abundance of Ir in K/T boundary sediments, L. Alvarez et al. (1980) suggested that an asteroid 10±4 km in diameter hit the Earth, injecting dust into the stratosphere that inhibited photosynthesis for several years, causing the collapse of food chains. Their discovery of Ir was immediately confirmed by multiple other laboratories (Smit and Hertogen, 1980; Ganapathy, 1980; Kyte and Wasson, 1980) and at dozens of locations worldwide (e.g., Alvarez et al., 1982), although this evidence was not universally accepted as evidence of an impact (see Kring, 1993, for a review). The subsequent discovery of shocked quartz (Fig. 1) in K/T boundary sediments by Bohor et al. (1984), however, made any other conclusion difficult to fathom because the only geologic process that can produce shocked quartz is impact cratering (e.g., French, 1990).

2. Discovery of the Chicxulub crater

Several potential impact sites were proposed: the Hawaiian hot spot (Smith and Smoluchowski, 1981), northern Pacific–Bering Sea (Emiliani et al., 1981), Kara impact crater (Hsü et al., 1981), Deccan Traps (Alvarez et al., 1982), British Tertiary igneous province (Cisowski and Housden, 1982), Tagus Abyssal Plain (Alvarez et al., 1982), Manson impact crater (French, 1984; Kunk et al., 1989; Izett, 1990; Shoemaker and Steiner, 1992), Nastapoka arc structure of Hudson Bay (Bohor and Izett, 1986), Colombian Basin (Hildebrand and Boynton, 1990), and Isle of Pines, Cuba (Bohor and Seitz, 1990). For any of these sites to be credible, evidence of shock metamorphism, which is the diagnostic criteria for identifying an impact site (e.g., Grieve et al., 1995), needed to be found. No evidence of an impact origin was found at most of the sites. Those locations that were already demonstrably impact sites (Kara and Manson) were untenable K/T boundary impact sites because they represented craters that were too small to be the source of the globally-distributed debris at the K/T boundary; subsequent radiometric age determinations also demonstrated they were produced prior to the K/T boundary (Koeberl et al., 1990; Trieloff and Jessberger, 1992; Izett et al., 1993).

It was soon realized that the impact ejecta at the K/T boundary contains clues regarding the site of the impact. Bohor and Izett (1986) and Izett (1987) demonstrated that the largest sizes and greatest abundances of shocked quartz occur in the Western Interior of North America, suggesting the impact occurred on or near that continent. This mineralogic evidence is consistent with stratigraphic evidence described by Orth et al. (1987), including reworked boundary deposits along the northern paleocoast of the Gulf of Mexico described by Smit and Romein (1985) and Bourgeois et al. (1988), that suggested the impact may have occurred somewhere near the southern margin of the continent. A thick sequence of impact debris (impact melt spherules and shocked minerals) was then discovered in Haiti by Hildebrand et al. (1990), pointing to an impact site in the Gulf of Mexico or proto-Caribbean region.

This drew attention to a set of nearly-circular geophysical anomalies on the Yucatán Peninsula that were uncovered during oil surveys in the late 1940's (Cornejo Toledo and Hernandez Osuna, 1950). Three exploratory wells (Yucatán-6, Chicxulub-1, and Sacapuc-1) drilled into the structure by Petroleos Mexicanos (PEMEX) penetrated an aphanitic melt rock that was originally interpreted to be an extrusive (volcanic) andesite (Guzmán and Mina, 1952; López-Ramos, 1975) of late Cretaceous age based on stratigraphic context. Kring et al. (1991), however, discovered shocked quartz and altered impact melt in the Yucatán-6 borehole, demonstrating an impact origin for the Chicxulub structure (Fig. 1). (The name Chicxulub was selected for the impact crater because a small town, Chicxulub Puerto, is located above the center of the structure.) Two lithologies were described in the borehole: a polymict breccia that was stratigraphically above a unit of melt, a sequence also seen in other boreholes (Fig. 2). Definitive shocked quartz and altered impact melt were found in the polymict breccia. These shocked quartz grains indicated the Chicxulub structure was a good candidate source for the shocked quartz found in K/T boundary sediments. Possible shocked quartz was also described in the melt unit, which was interpreted to have an impact origin too. That data, when combined with a re-analysis of geophysical and stratigraphic data by Penfield and Camargo (1991) and Hildebrand et al. (1991), suggested the crater was ~180 km in diameter and, thus, the product of an impact event large enough to be responsible for the Ir and shocked quartz found globally at the K/T boundary.

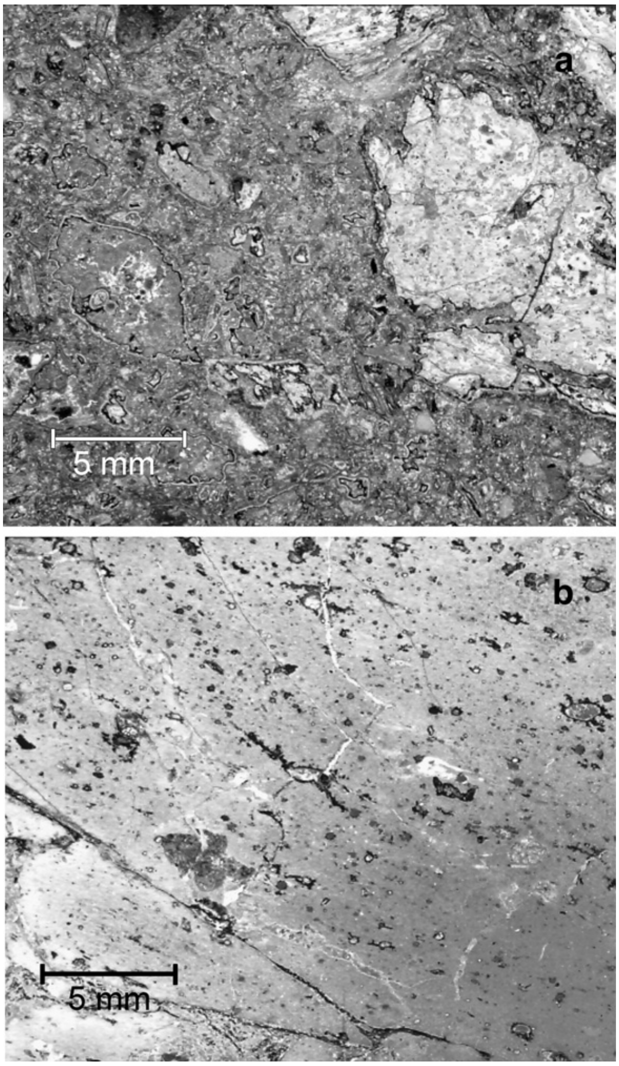

Fig. 2. Examples of impact lithologies in the Chicxulub crater, which are part of the Yaxcopoil-1 core that was recovered by the Chicxulub Scientific Drilling Project. Melt-bearing polymict breccias or suevites (a) are composed of impact melt fragments (often altered because of post-impact hydrothermal activity and diagenesis) and clasts from target lithologies in a clastic matrix. The matrix is composed of additional solidified melt fragments, phyllosilicates (possibly altered glass), and carbonate. Shock-metamorphosed quartz and other phases are found in these breccias. Underlying impact melt (b) is composed of a microcrystalline pyroxene and feldspar assemblage that entrained a few xenoliths and xenocrysts, many of which are also shock-metamorphosed.

3. Confirming an impact origin for the Chicxulub structure

Several studies rapidly confirmed an impact origin for the Chicxulub structure. It was shown that the composition of the impact melt rock in the Yucatán-6 borehole could not have been produced by volcanic processes, but was instead produced by bulk melting of the Earth's crust by an impact event (Kring and Boynton, 1992). Reaction textures between surviving clasts of target rock incorporated into the melt were similar to those seen at the Manicouagan and Mistastin impact craters (Kring and Boynton, 1992). Some of those surviving clasts were composed of shocked quartz (Hildebrand et al., 1992) and shocked feldspar (Kring and Boynton, 1992). Shocked quartz was also confirmed in the breccia that was above the melt (Sharpton et al., 1992, 1996; Claeys et al., 2003). Traces of an impacting asteroid or comet may have been detected, although results have been contradictory. Chemical analyses of impact melt samples with extraterrestrial Ir and/or Os were reported (Sharpton et al., 1992; Koeberl et al., 1994; Gelinas et al., 2004), followed by a report of

Ir metal grains (Schuraytz et al., 1996), although no significant Ir was reported in other samples (Hildebrand et al., 1993; Claeys et al., 1995). It is currently unclear whether there are analytical discrepancies, whether the different results imply projectile components are heterogeneously distributed in the impact melt, or both.

4. Linking the crater to the K/T boundary

Additional studies confirmed a link between Chicxulub and debris at the K/T boundary. The impact site, which contains both Ca-carbonate and Ca-sulfate deposits, was a good source for the unusually calcic impact melt spherules deposited in K/T boundary deposits in Haiti (Sigurdsson et al., 1991a,b; Kring and Boynton, 1991; Maurrasse and Sen, 1991; Izett, 1991). Chemical similarities between the Chicxulub melt rock and glassy silica-rich impact melt spherules deposited in Haiti suggested the Chicxulub impact event occurred precisely at the K/T boundary (Kring and Boynton, 1992). Within months this was confirmed with radiometric techniques that indicated the ages of the two melt populations were the same to within the uncertainties of the technique, 64.98 ± 0.05 Ma and 65.01 ± 0.08 Ma, respectively (Swisher et al., 1992). Independent analyses of the melt in the Chicxulub crater and K/T boundary melt spherules generated similar ages, 65.2 ± 0.4 Ma (Sharpton et al., 1992) and 64.5 ± 0.1 Ma (Izett et al., 1991), respectively, the latter of which was further resolved to be 64.42 ± 0.06 Ma (Dalrymple et al., 1993). Strontium and oxygen isotopic compositions of the Haitian K/T impact melt spherules are consistent with a mixture between Chicxulub melt rock and a marine carbonate of K/T boundary age (Blum and Chamberlain, 1992; Blum et al., 1993). A link between Chicxulub and K/T events was also indicated by the thickness of the K/T boundary ejecta in the North American region (e.g., Hildebrand et al., 1990), which decreases with distance exactly as one would expect if it had been ejected from the Chicxulub structure (Hildebrand and Stansberry, 1992; Vickery et al., 1992; Kring, 1995). This trend is not consistent with other proposed impact sites. The fluence of shocked quartz is also larger in K/T boundary deposits closer to the Chicxulub site than those farther from the Chicxulub site (Kring et al., 1994). Finally, unshocked zircons deposited in K/T boundary sediments have the same primary source ages as zircons in the Chicxulub target rocks and severely shock-metamorphosed zircons within those same deposits have ages that have been reset to 65 Ma, the age of the impact event (Krogh et al., 1993; Kamo and Krogh, 1995).

5. Objections to impact-mass extinction hypothesis

There is broad consensus that the Chicxulub structure is an impact crater and that it is linked to the K/T boundary mass extinction event. Objections, however, exist among a small number of investigators. Some of the objections have passed (and, thus, will not be considered further here), but a few remain. Some investigators maintain the floral and faunal turnover in the latest Cretaceous and earliest Tertiary was gradual and/or that any impact-driven extinction event at the K/T boundary was relatively minor; e.g., Keller (1996) writes “The current database thus indicates that long-term environmental changes as a result of climate cooling followed by short-term warming, sea-level fluctuations, ocean anoxia, and volcanism that characterized the latest Maastrichtian to earliest Paleogene were primarily responsible for the observed long-term trends in foraminiferal turnovers. Superimposed upon these long-term faunal trends is short-term catastrophic event (impact or volcanism) at the K/T boundary, with its attendant biotic effects which were largely limited to low latitudes (no mass extinction in high latitudes).” This argument is based largely on an assessment of the distribution of foraminifera species in the latest Cretaceous and earliest Tertiary that is interpreted to show several stages of extinction over a broad interval of time (e.g., Keller, 1988; Keller and Barrera, 1990), which contradicts other interpretations of foraminifera (e.g., Smit, 1982; Molina et al., 1998; Arenillas et al., 2000a,b) and nannofossil (Pospichal, 1994) biostratigraphy in the same sediments. A blind test of strata at the K/T boundary global stratotype (El Kef, Tunisia) was organized to resolve the controversy, but those results were also contested (Lipps, 1997, pp. 65–66; Ginsburg, 1997, pp. 101–103, and references therein).

It has also been argued that the Chicxulub impact event occurred prior to the K/T boundary (e.g., Stinnesbeck and Keller, 1996; Keller, 2001; Keller et al., 2004a,b) and that some other cause must be responsible for any extinctions at the K/T boundary, perhaps an even larger impact event (Keller, 2004) that produced an undetected impact crater. This poses a stratigraphic problem. To be valid, the argument means the impact that generated the Chicxulub crater did not distribute material globally to form an identifiable stratum at locations like El Kef (even though multiple model calculations indicate it would) and that a second impact event is responsible for the shocked quartz and Ir anomalies found globally at the boundary. The absence of two ejecta horizons is not explained, nor is the absence of a second crater explained. Furthermore, the argument does not explain the similarities of zircon ages and impact melt spherule compositions at the K/T boundary with materials found at the Chicxulub impact site.

Before discussing this and other objections further, it is perhaps useful to first review the stratigraphic nature of impact ejecta deposits from large impact craters. The Ir-rich horizon with which most investigators are familiar was distributed globally (e.g., Alvarez et al., 1982). It represents the remnants of a vapor-rich plume of high-energy ejecta from the impact site (e.g., Alvarez et al., 1980; Vickery and Melosh, 1990; Alvarez, 1996). Most of the ejected mass, however, was not so widely distributed. Excavated rocky and impact-melted material was deposited in large quantities that decrease with distance from the crater. Consequently, in the vicinity of a crater one will find a unit of rocky and/or molten debris, overlaid by a unit of material from the vapor-rich plume, while at distant localities one will only find the latter unit. (See Smit, 1999; Kring and Durda, 2002 for more details about stratigraphy of the units and the distribution of impact components within them.) At intermediate distances, where debris simply settled through the atmosphere and a water column, one finds a basal unit of rock and partially- to wholly-altered spherules overlaid by an Ir-rich cap. Close to the crater, however, the material in these units could be affected by impact-generated tsunamis, seismic-induced sediment slumping, and other energetic processes that occurred when >25 trillion metric tons of rock and impact-melted material were excavated and redeposited, producing complex sequences along the northern margin of the Gulf of Mexico (Smit and Romein, 1985), along the western and southern margins of the Gulf of Mexico (Smit et al., 1992a, 1996; Arz et al., 2001a,b; Soria et al., 2001; Alegret et al., 2002; Grajales-Nishimura et al., 2003; Lawton et al., 2005), in the Gulf of Mexico basin (Alvarez et al., 1992), the seaway between North and South America (now preserved in Haiti; Maurrasse and Sen, 1991; Kring et al., 1994) and the nascent Yucatán Basin (now preserved in Cuba; Tada et al., 2003; Alegret et al., 2005).

Examples of complex K/T boundary deposits relatively close to the Chicxulub crater are sometimes used to argue that the Chicxulub impact event preceded the K/T boundary by several hundred thousand years (e.g., Keller et al., 1993; Stinnesbeck et al., 1993; López-Oliva and Keller, 1996; Stinnesbeck and Keller, 1996; Adatte et al., 1996). The coarsest portion of these deposits is usually composed of glassy to altered spherules, which most investigators interpret to be impact melt spherules (Fig. 3). Finer-grained material usually overlay the spherules and often have multiple cross-bedding features that indicate changing current directions (Fig. 4), consistent with an impact-induced and basin-wide seiche during the sedimentation of finer-grained debris. This may include reworked sediments affected by the impact. At the top of the sequences, one finds Ir-rich sediment that would have settled more slowly through the atmosphere before settling through any water column. Shocked-quartz has also been described in the units. Despite the spherules, anomalously-high Ir, and shocked quartz, some argue “the deposits contain no unequivocal evidence of impact origin” (Keller et al., 1993). Rather than viewing this as a complex unit produced by an energetic impact event, they are instead interpreted by some investigators to be “deposited by normal sedimentary processes over an extended time period spanning thousands of years” (Stinnesbeck and Keller, 1996), with

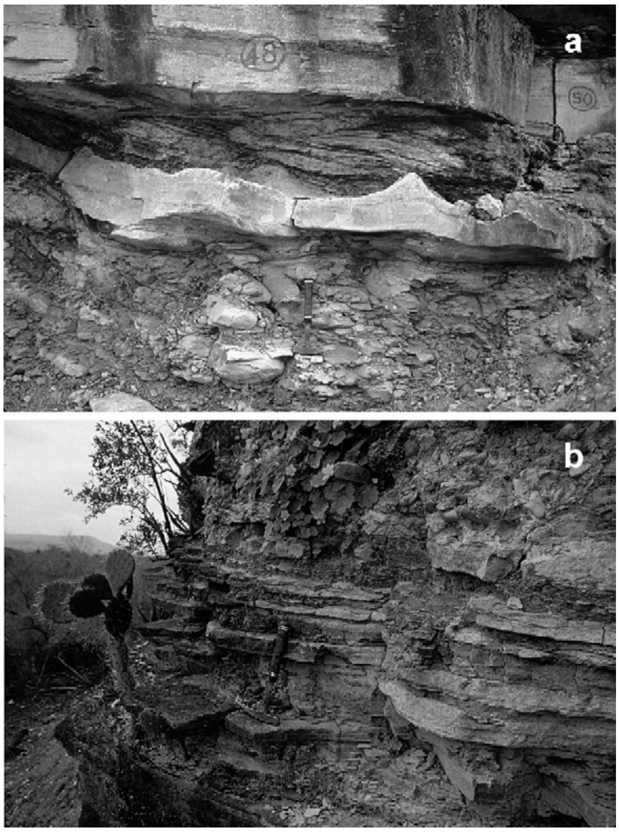

Fig. 3. An example of a complex impact-related sequence at Arroyo el Mimbral, Tamaulipas, Mexico, deposited relatively close to the Chicxulub impact crater. The lower portion of the sequence (a) is composed of altered spherules with an interbedded sandy limestone, and overlain by a laminated sandstone. The spherules are interpreted to be impact melt spherules from the Chicxulub impact crater. The scale is indicated by the hammer. The upper portion of the sequence (b) is composed of interlayered sandstones, siltstones, and shales. The top of this sequence (where hammer is resting) contains anomalously high concentrations of Ir. See Smit et al. (1992a,b) and Stinnesbeck et al. (1993) for details.

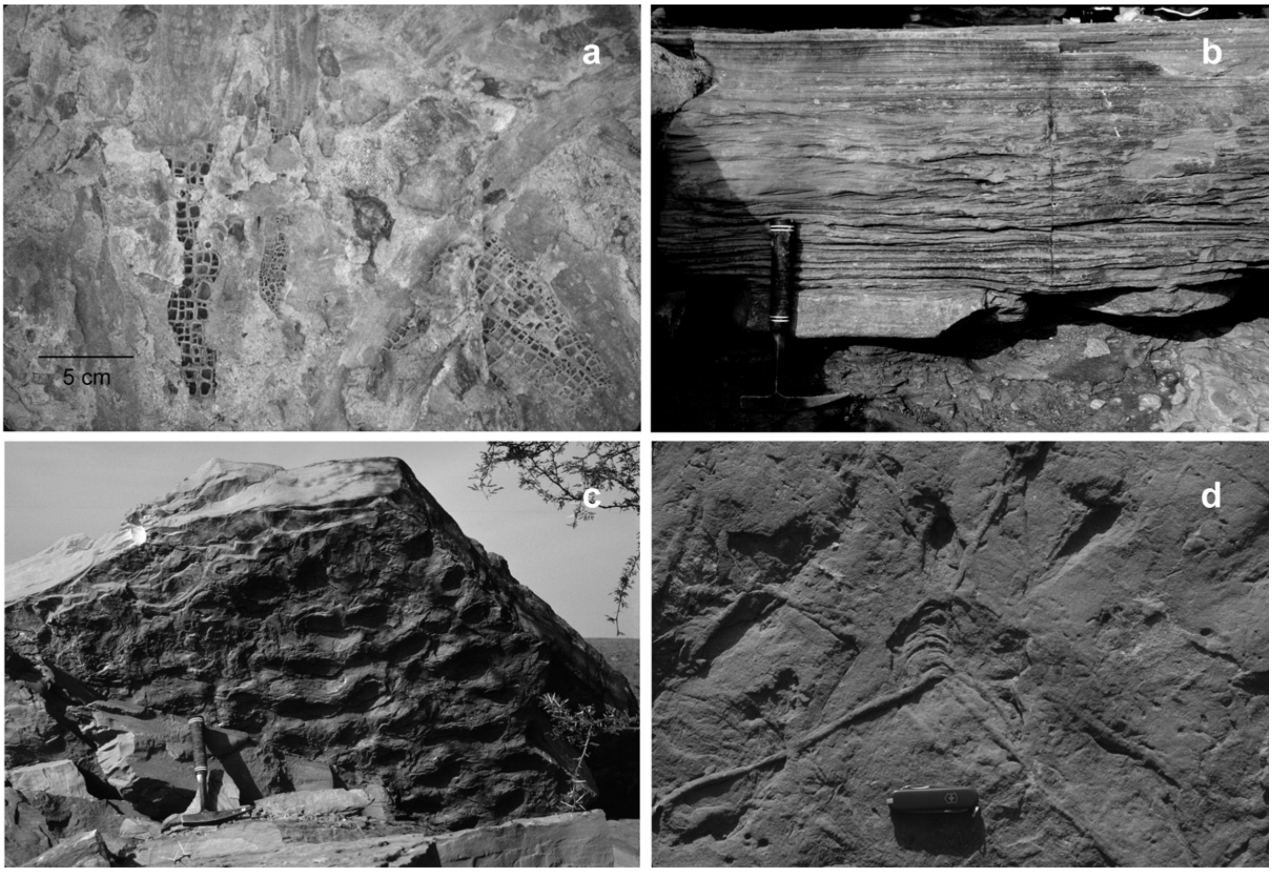

Fig. 4. Features within the complex K/T boundary deposits in the vicinity of the Chicxulub impact crater. At the base of the laminated sandstone unit at Arroyo el Mimbral (Fig. 3a), there is abundant continental plant debris (a), which is interpreted to have been carried sea ward by either tsunami backwash or channelized flow of slumping material. Climbing ripples in cross-section (b) indicate alternating current directions occur in the upper portion of a similar sequence at Arroyo la Lajilla, Tamaulipas, Mexico. Hammer for scale. Ripple marks (c) can be seen along bedding planes within this upper unit at El Peñon, Nuevo Leon, Mexico. Bioturbation within the sequences (d) was either generated by organisms that survived the impact event and/or burrowed down from the top of the sequences. Alternatively, they indicate the sequences represent normal sedimentary processes, despite the presence of spherules, shocked quartz, and anomalously high Ir. See Stinnesbeck et al. (1993) and Smit et al. (1996) for details. The scale bar in (a) is approximate. A 33 cm long hammer is shown for scale in (b) and (c). A 6 cm long pen knife is shown for scale in (d).

the spherule-rich material at the base of the sequences occurring 200,000 to 300,000 years before the K/T boundary (Keller, 2001).

The evidence for this alternative interpretation comes in two forms. Upper Cretaceous foraminifera are reported within the complex sequence, which are interpreted to be an indigenous product of normal marine life and sedimentation (e.g., López-Oliva and Keller, 1996; Stinnesbeck and Keller, 1996; Adatte et al., 1996); other investigators interpret them to be the product of reworking of excavated Upper Cretaceous sediments by the impact event, the highly energetic deposit of ejecta onto latest Cretaceous surfaces, impact-generated turbidity currents, or the erosion and backwash of impact-generated tsunamis (e.g., Smit et al., 1996; Arz et al., 2001a,b). The second form of evidence is bioturbation within the sequence (Fig. 4), which is interpreted to represent multiple episodes of colonization during multiple episodes of sediment deposition (Stinnesbeck and Keller, 1996); other investigators interpret them to represent bioturbation from the top of the sequence (Smit et al., 1996).

Although the K/T boundary sequences around the Gulf of Mexico basin are consistent with the effects of the Chicxulub impact event, a possible discordance between the ages of the Chicxulub impact event and K/T boundary was raised again following the recovery of a recent core from the interior of the Chicxulub crater. The Chicxulub Scientific Drilling Project produced the Yaxcopoil-1 core from a depth of ~400 m (in Tertiary cover) to 1511 m (in blocks of target rock beneath an impact-melt bearing sequence) between the peak ring and final rim of the crater (Dressler et al., 2003). At a depth of ~794 m the sediment became laminated and then, at a depth of 794.60 m, a macroscopically unambiguous melt-bearing breccia (suevite) was encountered. A sequence of ~100 m of melt-bearing impactites then followed (Fig. 2) until a depth of ~895 m was reached, where blocks of target rocks crosscut by cataclastic and melt veins were encountered. (See the June and July 2004 issues of *Meteoritics and Planetary Science* for the project's initial reports regarding petrological, geochemical, and geophysical assessments of the impactites.)

With regard to the timing of the Chicxulub impact event and its link to the K/T boundary, special attention has been drawn to the upper ~50 cm of the impactite sequence (from depth of ~794.10 to ~794.60 m). This is a fine-grained, laminated unit that overlies a coarser 13-m thick suevite, which, in turn, overlies a even coarser 15-m thick suevite (e.g., Dressler et al., 2003). Rather than considering the upper 50 cm as the upper portion of a normally-graded impact-related sequence or a reworked sequence, Keller et al. (2004a,b) have argued that the fine-grained sediments are unrelated to the Chicxulub impact event and that the 50 cm, thus, represents 300,000 years of post-impact sedimentation in the Chicxulub basin that separates the Chicxulub impact event with the K/T boundary. They report that the 50 cm contains Upper Cretaceous planktic foraminifera and carbon-isotope compositions of Upper Cretaceous rocks, which they interpret to mean was deposited after the Chicxulub impact event and before the K/T boundary. In this scenario, one might expect an Ir anomaly at the top of the 50 cm; one was not found and it was argued that it is missing because of a hiatus (Keller et al., 2004a). Their own data, however, is consistent with an impact-related origin for the ~50 cm.

First, Upper Cretaceous foraminifera may occur in the sediments because Upper Cretaceous rocks were part of the target sequence and are at the top of slumped blocks in the crater adjacent to the drill site. It has been argued that there is a diverse assemblage of foraminifera characteristic of a specific Upper Cretaceous biozone in these sediments, implying the foraminifera are not reworked specimens (Keller et al., 2004a,b), but this was not confirmed by other investigators. The few planktic foraminifera reported by others are consistent with impact-reworked lithologies (Arz et al., 2004; Smit et al., 2004); it was also suggested (Smit et al., 2004; Arz et al., 2004) that dolomite crystals of different sizes were misidentified as foraminifera in the report by Keller et al. (2004a).

Second, an Upper Cretaceous carbon isotope signature occurs in the sediments because they are dominated by reworked Upper Cretaceous sediments from the target sequence.

Third, while there is no Ir anomaly at the top of the 50 cm sequence, the Ir concentrations in the 50 cm sequence are 10 times higher than background samples in Gubbio K/T boundary samples. Furthermore, if one calculates the fluence of Ir in the entire 50 cm of sediments, one finds it is similar (14 ng/cm^2 vs. 23 ng/cm^2) to the Ir fluence at Gubbio (Alvarez et al., 1990). Thus, one could argue that the 50 cm of sediments are stratigraphically correlated with the K/T boundary at Gubbio.

Although the upper 50 cm of the sequence is dominantly of an impact origin (it even contains shocked quartz; Smit et al., 2004), it is not a simple air fall deposit. The lowermost ~40 cm is laminated and crossbedded and the upper ~10 cm is bioturbated. Components in the lower interval were transported laterally and the upper interval may have represented a hardground (Smit et al., 2004; Arz et al., 2004). It is not generally realized that the Yaxcopoil-1 core sampled the modification zone of the crater and thus represent material in the rising wall of the crater, ≳300 m above the basin floor (Kring, 2005). Consequently, the site may not have been immediately submerged by a marine incursion, but rather part of an evaporative closed basin with fluctuating water levels. This is consistent with the type of secondary mineralization in the melt-bearing impactites (Zurcher and Kring, 2004). It is also consistent with a lack of basal foraminifera biostratigraphic zones of the Tertiary, which implies the site represented by Yaxcopoil-1 was not submerged by foraminifera-bearing waters until 300,000 (Keller et al., 2004b) to 2 million (Smit et al., 2004) years after the impact event and K/T boundary. Others, however, propose a marine water invasion immediately following the impact event at the K/T boundary (Goto et al., 2004; Arz et al., 2004).

Interestingly, the criticisms of an impact-mass extinction hypothesis have evolved, producing objections in several different forms: iridium anomalies are artifacts of "temporally incomplete (or extremely condensed)" sections (MacLeod and Keller, 1991) rather than caused by an impact event; if an impact did occur at the K/T boundary, however, then it only caused a small low latitude extinction effect, while other geologic processes were responsible for globally-distributed extinctions that occurred over several hundred thousand years (Keller, 1996); the extinctions that most investigators attribute to the K/T boundary really began 500,000 years before the boundary and any event at the K/T boundary affected less than 10% of the total foraminiferal population (Keller, 2001); the Chicxulub impact event is unrelated to any K/T boundary impact event, occurring ~300,000 years before the K/T boundary and is, thus, not responsible for the K/T boundary mass extinction event (Keller et al., 2004a). As discussed above, these arguments rely on contested interpretations of foraminifera biostratigraphy and interpretations of deposits with impact ejecta in them, which are generally flawed and untenable because they cannot be reconciled with multiple observations.

The form of the objections has recently shifted, however. Rather than objecting to an impact-mass extinction hypothesis, or a specific link between the Chicxulub impact event and K/T boundary mass extinctions, it was recently suggested that multiple impact events (Keller et al., 2003, 2004) or a comet shower (Keller et al., 2004b) affected the end of the Cretaceous. Furthermore, they argue that because the Chicxulub impact event occurred 300,000 years before the K/T boundary, a much larger impact event, producing a crater ~250 km in diameter, occurred at the K/T boundary (Keller, 2004). The concept of multiple impacts is not new (e.g., Kring, 1993). The Manson crater, for example, was once thought to have occurred at or near the K/T boundary and, thus, a contributor to the effects of Chicxulub. However, a better radiometric age determination indicates Manson formed 73.8±0.3 Ma, not ~65 Ma (Izett et al., 1993). Neither is there any stratigraphic evidence of multiple impacts. The two-layer couplet observed near the Chicxulub impact site is consistent with relatively high- and low-energy ejecta from a single impact crater (Smit and Romein, 1985; Orth et al., 1987; Kring and Durda, 2002, and references therein). Furthermore, the thickness of the lower unit increases as one approaches Chicxulub, and the size and fluence of shocked quartz in the upper unit increases as one approaches Chicxulub, suggesting a single source for the units. Reworking of impact ejecta and adjacent sediments near the impact site should not be confused as evidence for multiple impacts.

The hypothesis of multiple impact events has also been tested using trace element and isotopic methods. An analysis of Ir abundances over a 10 Ma section of latest Cretaceous and earliest Tertiary limestones that bracket the K/T boundary did not detect Ir from more than one impact event (Alvarez et al., 1990). Likewise, an analysis of helium isotope abundances in latest Cretaceous and earliest Tertiary limestones from Italy was unable to detect an enhanced accretion rate of extraterrestrial material and concluded the K/T impact was not a member of a comet shower, but rather caused by an isolated comet or asteroid (Mukhopadhyay et al., 2001a,b). These methods do not preclude small impact events, but those are likely to have had limited effects. It is still an interesting question, however, what type of impact event is needed to cross the threshold for extinctions (e.g., Kring, 2002).

6. Environmental effects of the Chicxulub impact

The discovery of the Chicxulub crater dramatically enhanced the community's ability to assess the environmental effects of an impact at the K/T boundary, because both the geographic location of an impact site and the target rocks involved in an impact can affect the environmental outcome. For example, anhydrite in the Chicxulub target sequence implies that sulfate aerosols were deposited in the stratosphere, affecting the radiative budget of the atmosphere (heating the stratosphere while cooling the Earth's surface) before settling to the troposphere where they were washed out as acid rain (e.g., Brett, 1992). Identifying the impact site and size of the crater was also important, because the amount of debris ejected also affects the environmental outcome. Any global, extinction-driving effects of an impact are largely caused by the interaction of this impact debris with the atmosphere.

6.1. Acid rain

Model calculations suggest the atmosphere can be shock-heated by an impact event, producing nitric acid rain (Lewis et al., 1982; Prinn and Fegley, 1987; Zahnle, 1990). The atmosphere is heated when an asteroid or comet pierces the atmosphere, the vapor-rich plume expands from an impact site, and ejected debris rains through the atmosphere. In large Chicxulub-size impact events, the latter is the most important, producing $\sim 1\times10^{14}$ mol of NO_x in the atmosphere and, thus, $\sim 1\times10^{15}$ moles of nitric acid rain (Zahnle, 1990). An additional $\sim 3\times10^{15}$ mol of nitric acid may have been produced by impact-generated wildfires (Crutzen, 1987; more details about the fires below). The rain may have fallen over a period of a few months to a few years.

Because the Chicxulub impact occurred in a region with anhydrite, sulfur vapor was also injected into the stratosphere, producing sulphate aerosols and eventually sulfuric acid rain (Brett, 1992; Sigurdsson et al., 1992; Kring, 1993; Pope et al., 1994; Ivanov et al., 1996; Pope et al., 1997; Pierazzo et al., 1998; Yang and Ahrens, 1998; Gupta et al., 2001; Pierazzo et al., 2003). Estimates of the amount of S liberated vary, ranging from 5.5×10^{15} to 4.3×10^{18} g, although values seem to be converging on 7.5×10^{16} to 6.0×10^{17} g S, which would have produced 7.7×10^{14} to 6.1×10^{15} mol of sulfuric acid rain. Additional S would have been liberated from the projectile (Kring et al., 1996). Although the projectile is the principal source of S in most impact events, it is a small contribution in the Chicxulub event because the target was so rich with anhydrite (Kring et al., 1996; Kring, 2003). The combination of sulfuric acid rain and nitric acid rain was not sufficient to acidify ocean basins (D'Hondt et al., 1994), but it would have compounded the effects on shallow and/or poorly-buffered estuaries and continental catchments and waterways (Bailey et al., 2005). An impact-generated buffer has also been proposed to mitigate some of the effects of any acid rain (Maruoka and Koeberl, 2003).

The model-derived estimates for the amount of acid rain are consistent with chemical leaching that is inferred from the compositions of K/T boundary deposits (Retallack, 1996). They are consistent with etching of K/T spinel crystals (Preisinger et al., 2002) and low C/S ratios in terrestrial K/T boundary sediments (Maruoka et al., 2002). They are also consistent with $^{87}Sr/^{86}Sr$ values in marine sediments across the boundary that imply enhance continental weathering (Vonhoff and Smit, 1997), although it is not clear whether the enhanced erosion and chemical weathering were caused by acid rain leaching of land surfaces or the denudation of flora from the land, the latter of which could have been caused by acid rain and many other impact-generated effects.

6.2. Wildfires

Evidence of impact-generated fires was recovered from K/T boundary sequences in the form of fusinite (Tschudy et al., 1984), soot (Wolbach et al., 1985, 1988, 1990), pyrolitic polycyclic aromatic hydrocarbons (Venkatesan and Dahl, 1989), carbonized plant debris (Smit et al., 1992a), and charcoal (Kruge et al., 1994). That the impact would generate atmospheric heating was recognized (e.g., Schultz and Gault, 1982) soon after Ir was found at the K/T boundary and incorporated into models of nitric acid rain described above.

The distribution of those fires is still poorly understood. Although soot is found globally, it is an airborne particulate and, thus, not a good indicator of where fires were ignited. Model calculations have suggested a range of possibilities. The global distribution of Ir indicates ejecta was distributed globally, which may have caused widespread atmospheric heating so severe that ground temperatures may have risen several hundred degrees, causing the spontaneous ignition of fires (Melosh et al., 1990). Energy deposition was generally considered to be evenly distributed around the world (Zahnle, 1990). The discovery of the Chicxulub impact location allowed the ignition of fires to be further explored, which suggested that while heating may have occurred globally, threshold temperatures for generating fires may have had a restricted geographic distribution (Kring and Durda, 2002). For example, fires may have been generated in southern North America, but the northern part of the continent may have been spared unless fires spread from the south. Several additional parameters (e.g., trajectory of the impacting object, mass of ejecta and its speed distribution, and ignition thresholds for different types of vegetation; e.g., Durda and Kring, 2004) affecting the distribution of fires remain to be further explored. If the ejected mass or speed distribution was sufficiently low then fires may have even been limited to the vicinity of the impact event, produced not by impact ejecta but by the direct radiation of the impact fireball (Shuvalov, 2002), which had a plasma core with temperatures in excess of 10,000 °C.

The amount of soot recovered from K/T boundary sediments (Wolbach et al., 1985, 1988, 1990) imply that the fires released $\sim 10^4$ GT of CO_2, $\sim 10^2$ GT CH_4, and $\sim 10^3$ GT CO (Crutzen, 1987; Kring, 2003), which is equal to or larger than the amount of CO_2 produced from vaporized target sediments (Kring and Durda, 2001). This may have had a severe effect on the global carbon cycle.

6.3. Dust and aerosols in the atmosphere

Model calculations suggest that dust and sulphate aerosols from the impact event, and soot from post-impact wildfires, caused surface temperatures to fall and prevented sunlight from reaching the surface where it was needed for photosynthesis (Alvarez et al., 1980; Toon et al., 1982; Pollack et al., 1983; Covey et al., 1990, 1994; cf., Pope, 2002). These model calculations are consistent with the fossil record, which indicates the base of the marine food chain, composed of photosynthetic plankton, collapsed. Photosynthetic plankton cannot be extinguished by slight increases or decreases in average temperatures, or the presence or absence of organisms higher up the food chain. They are only affected by the availability of their energy source, light. Consequently, the loss of photosynthetic plankton following the Chicxulub impact event is evidence that sunlight was significantly blocked, whether it was by dust, soot, aerosols, or some other agent.

The timescale for particles settling through the atmosphere range from a few hours to approximately a year, which may have been further augmented by the time needed to settle through freshwater or marine water columns (e.g., Kring and Durda, 2002). The time needed for the bulk of the dust to settle out of the atmosphere is ambiguous, however, because the size distribution of the dust is unclear. Some sites seem to be dominated by spherules ~250 μm in diameter (e.g., Montanari, 1991;

Smit et al., 1992b; Smit, 1999), which would have settled out of the atmosphere within hours to days. However, if there is a substantial amount of submicron material, then it may remain suspended in the atmosphere for many months (Toon et al., 1982; Covey et al., 1990). Soot, if it was able to rise into the stratosphere, would have taken similarly long times to settle. Soot that only rose into the troposphere, however, would have been flushed out of the atmosphere promptly by rain.

The dust, aerosols, and soot caused surface cooling after the brief period of atmospheric heating that immediately followed the impact. The magnitude of that cooling is unclear, however, because the opacity generated by the three components is uncertain and their lifetime in the atmosphere is also uncertain (Toon et al., 1997). Nonetheless, significant decreases in temperature of several degrees to a few tens of degrees have been proposed for at least short periods of time in some areas of the Earth (Covey et al., 1994; Toon et al., 1997; Pope et al., 1997; Gupta et al., 2001; Pierazzo et al., 2003). Following the impact, enhanced abundances of Boreal dinoflagellate cysts and benthic foraminifera have been observed in samples at El Kef (Brinkhuis et al., 1998), which usually represents much warmer Tethian waters (~27° N paleolatitude). The enrichment of the Boreal species has been interpreted to reflect cooler temperatures for a period of ~2 ka after the Chicxulub impact event at the K/T boundary (Galeotti et al., 2004).

6.4. Ozone destruction

Ozone-destroying Cl and Br can be produced from the vaporized projectile, vaporized target lithologies, and biomass burning (Kring et al., 1995; Kring, 1999; Birks et al., 2007). Over 5 orders of magnitude more Cl than is needed to destroy today's ozone layer was injected into the stratosphere, compounded by the addition of Br and other reactants. The changes in nitrogen chemistry generated by the atmospheric heating described above also had the capacity to destroy ozone (Toon et al., 1997). The affect on the ozone layer may have lasted for several years, although it is uncertain how much of an effect it had on surface conditions. Initially, dust, soot, and NO_2 may have absorbed any ultraviolet radiation and sulphate aerosols may have scattered the radiation (Kring, 1999). The settling time of dust was probably rapid relative to the time span of ozone loss, but it may have taken a few years for the aerosols to precipitate (Kring et al., 1996; Pope et al., 1997; Pierazzo et al., 2003).

6.5. Greenhouse gases

Water and CO_2 were produced from Chicxulub's target lithologies and the projectile, which could have potentially caused greenhouse warming after the dust, aerosols, and soot settled to the ground (e.g., O'Keefe and Ahrens, 1989; Hildebrand et al., 1991; Takata and Ahrens, 1994; Pope et al., 1994; Pierazzo et al., 1998). Significant CO_2, CH_4, and H_2O were added to the atmosphere. Some of these components came directly from target materials. These include carbonates, which when vaporized liberate CO_2. They also include hydrocarbons, the remainder of which has subsequently migrated into cataclastic dikes beneath the crater (Kenkmann et al., 2004; Kring et al., 2004) and impact breccias deposited along the Campeche Bank (Grajales-Nishimura et al., 2000, 2003). Water was liberated from the saturated sedimentary sequence and overlying sea (the lesser of the two sources; Pierazzo et al., 1998).

The residence times of gases like CO_2 are greater than those of dust and sulphate aerosols, so greenhouse warming may have occurred after a period of cooling. Estimates of the magnitude of the heating varies considerably, from an increase of global mean average temperature of 1 to 1.5 °C based on estimates of CO_2 added to the atmosphere by the impact (Pierazzo et al., 1998) to ~7.5 °C based on measures of fossil leaf stomata (Beerling et al., 2002).

6.6. Local and regional effects

The local and regional effects of the impact were enormous. Tsunamis radiated across the Gulf of Mexico, crashing onto nearby coastlines, and also radiated farther across the proto-Caribbean and Atlantic basins. Tsunamis were 100 to 300 m high when they crashed onto the gulf coast (Bourgeois et al., 1988; Matsui et al., 2002) and ripped up sea floor sediments down to depths of 500 m (Smit, 1999). As noted above, the Gulf of Mexico region was also affected by the high-energy deposition of impact ejecta, density currents, and seismically-induced slumping of coastal sediments (e.g., Smit et al., 1992a; Alvarez et al., 1992; Smit et al., 1996; Bohor, 1996; Smit, 1999; Soria et al., 2001; Arz et al., 2001a,b; Alegret et al., 2002; Lawton et al., 2005) following magnitude 10 earthquakes (Kring, 1993). The tsunamis may have penetrated more than 300 km inland (Matsui et al., 2002), before backwash of the tsunamis carried continental debris basin-ward, depositing the material in channelized- to relatively deep-marine sequences. The sediment sequences at the K/T boundary indicate waves arrived onshore after the coarsest impact ejecta (e.g., impact melt spherules) was deposited, which a model calculation suggests may have been 5 to 10 h after the impact event (Matsui et al., 2002). Multiple waves affected coastal regions over a period of a day (perhaps longer), before the finest, Ir-bearing, airborne component was deposited.

The landscape (both continental and marine) was buried beneath impact ejecta that was several hundred meters thick near the impact site and decreased with radial distance. Peak thicknesses along the crater rim may have been 600 to 800 m (Kring, 1995). Along the Campeche bank, 350 to 600 km from Chicxulub, impact deposits of ∼50 to ∼300 m have been logged in boreholes (e.g., Grajales-Nishimura et al., 2000).

Impact events also produce shock waves and air blasts that radiate across the landscape (Kring, 1997; Toon et al., 1997). Winds far in excess of 1000 km/h are possible near the impact site, although they decrease with distance from the impact site. The pressure pulse and winds can scour soils and shred vegetation and any animals living in nearby ecosystems, in addition to many other effects (Kring, 1997). An initial estimate of the area damaged by an air blast was a radius 1500 km (Emiliani et al., 1981). There are several factors that can effect this estimate, so the uncertainty might be better reflected in a range of radii from ∼900 to ∼1800 km (Toon et al., 1997). The pressure pulse and air blast would have swept across the Gulf of Mexico and bordering landmasses (what are now the southern Yucatán, gulf coast of Mexico, and the gulf coast of the United States). The travel times are quite short, so this effect would have occurred in advance of any falling debris or tsunamis. Consequently, damaged forests already existed along coastlines by the time tsunamis hit them. A backwash of air (Kring, 1997) may have also carried some of the debris seaward before impact ejecta landed in the water and tsunamis hit.

Significant heat would have been another important regional effect. As outlined above in the discussion of impact-generated wildfires, core temperatures in the plume rising from the crater were in excess of 10,000 C (e.g., Pierazzo et al., 1998; Shuvalov, 2002). Temperatures may have been high enough to generate fires within distances of 1500 to 4000 km (Shuvalov, 2002). Such high temperatures would have also have been devastating for animals living within that range. This thermal pulse would have been relatively short-lived (5 to 10 min; Shuvalov, 2002), so some organisms may have escaped this particular effect if sheltered. Additional heating created when impact ejecta fell through the atmosphere continued for 3 to 4 days (Kring and Durda, 2002). If fires were ignited, organisms may have needed to survive a more extended period of high temperatures.

7. Post-impact recovery

The regional and global effects of the Chicxulub impact event altered the physical state of the environment for periods of at least several years if not >1000 years. In regions where fires occurred, the landscape may have been largely cleared of vegetation. Ferns appear to have been the pioneering recovery plant in some parts of North America, Japan, and New Zealand, because fern spores are very abundant relative to gymnosperm and angiosperm pollen (Tschudy et al., 1984; Saito et al., 1986; Vajda et al., 2001). Where ferns did not occur prior to the impact event, algae and moss were alternative pioneering types of vegetation (Sweet and Braman, 1992; Brinkhuis and Schioler, 1996). Conditions may have been relatively anoxic following the impact event and seemed to have favored methanogens, at least in North America (Gardner and Gilmour, 2002).

The relative proportions of pollen and spore indicate the gymnosperm forest canopy and most of the angiosperm understory was destroyed. These “survival” ecosystems were soon replaced with “opportunistic” ecosystems. In northern North America, these were composed of a different type of fern and several types of flowering plants, producing an herbaceous groundcover. Eventually the forest canopies returned.

Deciduous trees appear to have survived the consequences of the impact event better than evergreen trees in North America, possibly because of their dormant capacity and their ability for wind-pollination, which could proceed without the need of specific pollinating animals that may have been exterminated by the impact. Interestingly, insects seem to disappear (and possibly many species go extinct) after the impact, based on a dramatic drop in the frequency of insect-damaged leaves in the fossil record of North Dakota (Labandeira et al., 2002). It is not clear if the insects died directly from the effects of the impact event or if they were extinguished because their plant hosts were killed.

Ecosystem collapse seems to have been uneven. Gymnosperm, for example, may not have been as dramatically affected in the northern part of the continent, suggesting part of the canopy may have survived at those distant locations (Sweet and Braman, 1992). If so, then the recovery may have also proceeded at different rates.

Important biochemical cycles were perturbed if not completely interrupted. Perhaps the most severely affected biochemical system was the carbon cycle. In modern ecosystems, for example, forests contain 80% of all above ground carbon (Dixon et al., 1994). Consequently, if those forests were severely damaged by fire, acid rain, or other processes, significant perturbations of the carbon cycle are expected. Based on analyses at a mid-continent site within the western interior of North America, it has been estimated that the carbon cycle may have required 130 ± 50 ka to recover (Arens and Johren, 2000).

In the marine realm, a pre-impact near-shore foraminifera taxa maintained its presence in that environmental niche, but also colonized open-ocean environments (D'Hondt et al., 1996). The recovery was not the same in all geographic locations. For example, the expansion of some molluscs seems to have been much more rapid in the vicinity of the impact event than in other portions of the world (Jablonski, 1998). In addition, the expansion in the Gulf of Mexico region seems to have favored a greater proportion of invading taxa than the recovery in other areas of the world (Jablonski, 1998). These types of disruptions also affected the carbon cycle, which may have taken longer to recover in the marine realm than on land. For example, the flux of organics to the deep ocean may have required ~ 3 Ma to recover (D'Hondt et al., 1998).

8. Conclusions

Impact debris has been widely documented in K/T boundary sediments, confirming an impact event produced the mass extinctions that have historically characterized that boundary. Stratigraphic, petrologic, geochemical, and isotopic data indicate the source of that debris is the Chicxulub impact crater on the Yucatán Peninsula, Mexico. Cretaceous–Tertiary boundary impact ejecta deposits are thicker as one approaches the Chicxulub site; K/T boundary impact melt spherules have compositions that are similar in composition to target rocks at the Chicxulub site; K/T boundary shocked minerals are similar to those found at the Chicxulub site; K/T boundary zircons are similar in age to those found at the Chicxulub site; etc.

Not surprisingly, the K/T boundary sequences in the vicinity of the Chicxulub crater are complex, reflecting the high-energy conditions created by the impact event, and should not be confused for "normal" sedimentological processes occurring over periods of 300,000 to 500,000 years.

An impact-mass extinction hypothesis for the K/T boundary is further supported by the magnitude of environmental effects that an impact the size of Chicxulub could wreak. Regional effects include seismic effects, shock-wave and air blast, high-temperatures and fires, burial, tsunamis, and erosion. Global effects include atmospheric heating, changes in nitrogen chemistry that lead to nitric acid rain, deposition of sulphate aerosols which cool the surface before falling as sulfuric acid rain, wildfires, soot and dust preventing sunlight from reaching the surface, destruction of the stratospheric ozone layer, enhanced erosion, and greenhouse warming. Impact-generated atmospheric heating is followed directly by short-term cooling and eventually a period of warming, as indicated here and above.

There is still much to learn. The Chicxulub impact crater provides an excellent opportunity to study the geological processes associated with the formation of large (> 100 km diameter) craters and the detailed relationship between a crater, the lithologies that are excavated, and their deposition in proximal to distal ejecta deposits. In the past, our studies of such large craters were limited to those on other planetary surfaces by, largely, remote sensing techniques or theoretical modeling. More drilling into the crater and buried ejecta horizons, plus many more analyses of outcrops are needed.

Additional details of the impact's environmental effects need to be explored too. Some of the parameters used in theoretical calculations can be improved. More importantly, however, the models need to be tested with the geologic record. The Chicxulub impact event provides an exquisite opportunity to study impact-generated environmental effects, because there are so many well-preserved K/T boundary sequences that represent a large range of ecosystems around the world. Integrating theoretical models of impact-generated affects and physical and chemical signatures of them in the geologic record will help build a robust assessment of the environmental consequences of impact events.

Our understanding of the environmental effects is sufficiently mature, however, that the community is poised to develop and test hypotheses of how flora and fauna reacted (or failed to react), leading to outcomes of extinction or survivorship. This will be a complicated task. In some cases, the outcome may rely on survivor capabilities of specific organisms. This will require an understanding of the physiology of organisms and how they will react to specific perturbations and suites of perturbations. In most cases, however, the outcome is likely going to depend on the impact's effect on the fabrics of ecosystems. This will require an analysis of how environmental perturbations affect integrated biologic and biogeochemical systems. Each type of ecosystem may have been affected differently by the environmental effects of the impact. In addition, there appears to be regional heterogeneities in the magnitude of environmental effects, so even similar types of ecosystems, if located in different parts of the world, may have been affected by the impact in different ways. The recovery of ecosystems may have been similarly complex and requires a similar analytical focus.

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