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OCEAN DRILLING PERSPECTIVES ON Meteorite Impacts

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Derrick of the platform Liftboat *Myrtle* at night.
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ABSTRACT. Extraterrestrial impacts that reshape the surfaces of rocky bodies are ubiquitous in the solar system. On early Earth, impact structures may have nurtured the evolution of life. More recently, a large meteorite impact off the Yucatán Peninsula in Mexico at the end of the Cretaceous caused the disappearance of 75% of species known from the fossil record, including non-avian dinosaurs, and cleared the way for the dominance of mammals and the eventual evolution of humans. Understanding the fundamental processes associated with impact events is critical to understanding the history of life on Earth, and the potential for life in our solar system and beyond.

Scientific ocean drilling has generated a large amount of unique data on impact processes. In particular, the Yucatán Chicxulub impact is the single largest and most significant impact event that can be studied by sampling in modern ocean basins, and marine sediment cores have been instrumental in quantifying its environmental, climatological, and biological effects. Drilling in the Chicxulub crater has significantly advanced our understanding of fundamental impact processes, notably the formation of peak rings in large impact craters, but these data have also raised new questions to be addressed with future drilling. Within the Chicxulub crater, the nature and thickness of the melt sheet in the central basin is unknown, and an expanded Paleocene hemipelagic section would provide insights to both the recovery of life and the climatic changes that followed the impact. Globally, new cores collected from today's central Pacific could directly sample the downrange ejecta of this northeast-southwest trending impact.

Extraterrestrial impacts have been controversially suggested as primary drivers for many important paleoclimatic and environmental events throughout Earth history. However, marine sediment archives collected via scientific ocean drilling and geochemical proxies (e.g., osmium isotopes) provide a long-term archive of major impact events in recent Earth history and show that, other than the end-Cretaceous, impacts do not appear to drive significant environmental changes.

INTRODUCTION

Large meteorite impacts have significantly influenced Earth history, possibly driving the early evolution of life (e.g., Kring, 2000, 2003; Nisbet and Sleep, 2001) and the initial compositions of the ocean and the atmosphere (e.g., Kasting 1993). They also have the potential to completely reshape the biosphere (e.g., Alvarez et al., 1980; Smit and Hertogen, 1980). The Cretaceous-Paleogene (K-Pg) mass extinction, almost certainly caused by the impact of a meteorite on the Yucatán carbonate platform of Mexico 66 million years ago, known as the Chicxulub impact, is the most recent major mass extinction of the so-called Big Five (e.g., Raup and Sepkoski, 1982). It ended the dominance of non-avian dinosaurs, marine reptiles, and ammonites, and set the stage for the Cenozoic dominance of mammals that eventually led to the evolution of humans (Schulte et al., 2010; Meredith et al., 2011). The environmental effects of the Chicxulub impact and the resulting mass extinction occurred over a geologically brief time period, with the major climatic changes lasting years to decades (e.g., Brugger et al., 2017). The subsequent recovery of life provides an important analog for the potential recovery of biodiversity following geologically rapid anthropogenic extinction due to climate change, acidification, and eutrophication.

The K-Pg impact hypothesis was controversial when first proposed (Alvarez et al., 1980; Smit and Hertogen, 1980), but careful correlation of impact material from K-Pg boundary sections across the world led to its gradual acceptance (e.g., Schulte et al., 2010). The discovery of the Chicxulub crater (Penfield and Carmargo, 1981; Hildebrand et al., 1991) and its clear genetic relationship with K-Pg boundary ejecta provided compelling evidence for this hypothesis. Scientific ocean drilling has been instrumental in discovering widespread physical, chemical, and biological supporting evidence, and in documenting the global environmental and biotic effects of the impact (e.g., see summary in Schulte et al., 2010). Drilling by International Ocean Discovery Program Expedition 364 into the Chicxulub crater has yielded valuable insights into the mechanisms of large impact crater formation and the recovery of life (Morgan et al., 2016, 2017; Artemieva et al., 2017; Christeson et al., 2018; Lowery et al., 2018; Riller et al., 2018).

Although the K-Pg is the only mass extinction that is widely (though not universally) accepted to have been caused by an extraterrestrial collision, impacts have been suggested at one point or another as drivers for every major Phanerozoic extinction event (e.g., Rampino and Stothers, 1984) and many other major climate events (e.g., Kennett et al., 2009; Schaller et al., 2016). The discovery of an iridium layer at the K-Pg boundary as the key signature of extraterrestrial material (Alvarez et al., 1980) spurred the search for other impact horizons through careful examination of many other geologically significant intervals. So far no other geologic event or transition has met all the criteria to indicate causation by an impact (e.g., the presence of iridium and other platinum group elements in chondritic proportions, tektites, shock-metamorphic effects in rocks and minerals, perturbation of marine osmium isotopes, and, ideally, an impact crater), although many periods would meet at least one of these (e.g., Sato et al., 2013; Schaller et al., 2016; Schaller and Fung, 2018). The search for impact evidence continues.

For the last 50 years, analyses of geological and geophysical data collected by the Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), Integrated Ocean Drilling Program, and International Ocean Discovery Program (IODP) have provided a unique perspective on Earth history. Rock samples collected by IODP and its sister organization, the International Continental scientific Drilling Program (ICDP), have provided insights into impact cratering processes and the effects of events of different magnitudes on the climate and the biosphere, supplying an exceptional record of processes that are ubiquitous across the solar system (and, presumably, beyond). This article focuses on ocean drilling perspectives on meteorite impacts. We examine the contributions of scientific ocean drilling to our understanding of impact events, from detailed records of extinction and chemical and physical perturbation in the marine realm to the mechanisms by which rocks are deformed to create peak rings (a discontinuous ring of hills) in impact craters. The exciting results of drilling in the Chicxulub crater in 2016 raise new questions and suggest promising new challenges and avenues of investigation of deep-sea records of impact events that can only be undertaken by a program such as IODP. (Note that important contributions from onshore drilling by the ICDP into the Chicxulub, Lake Bosumtwi, Chesapeake Bay, and Lake El'gygytgyn impact craters are summarized by, respectively, Urrutia-Fucugauchi et al., 2004; Koeberl et al., 2007; Gohn et al., 2008; and Melles et al., 2012).

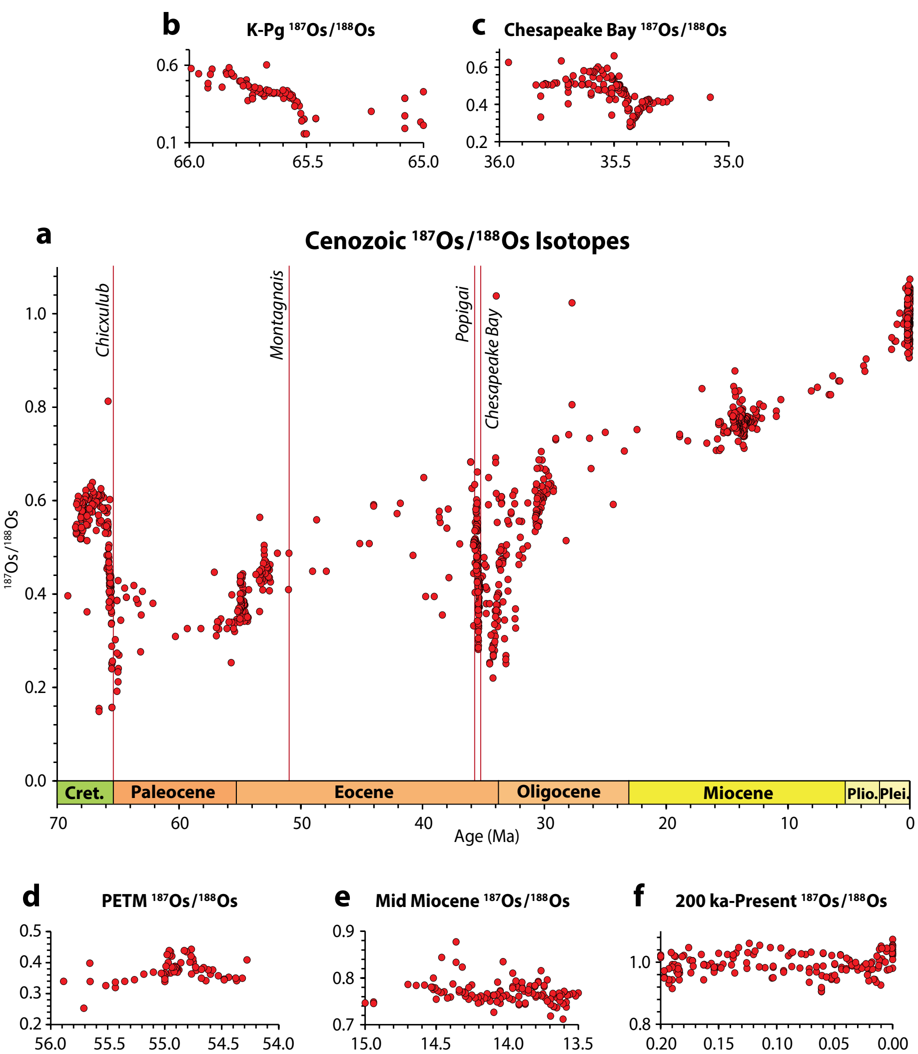


FIGURE 1. Marine osmium isotopes (a) through the Cenozoic (after Peucker-Ehrenbrink and Ravizza, 2012). These data, the majority of which come from DSDP/ODP/IODP cores, record the long-term trend toward more radiogenic (i.e., continental-weathering derived) $^{187}Os/^{188}Os$ ratios in the ocean throughout the Cenozoic. Superimposed on this long-term trend are several major, rapid shifts toward unradiogenic ratios driven by impact of extraterrestrial objects. This effect is evident in intervals associated with impact events, including (b) the Chicxulub impact and (c) the Chesapeake Bay impact. Other intervals of major environmental change lack the diagnostic negative excursion, including (d) the Paleocene-Eocene Thermal Maximum, (e) the Miocene Climate Transition, and (f) the Younger Dryas. Red lines are well-dated large (>35 km crater diameter) impacts (after Grieve, 2001). Note that these data are plotted against the 2012 Geologic Time Scale (Peucker-Ehrenbrink and Ravizza, 2012); more recent dating puts the K-Pg boundary at 66.0 million years ago (Renne et al., 2013).

MARINE RECORD OF IMPACTS

Scientific ocean drilling provides the raw materials that enable scientists to generate high-resolution composite records of geochemical changes in the ocean through time. One of the geochemical proxies used is the isotopic ratio of osmium ($^{187}Os/^{188}Os$) in seawater, as reflected in marine sediments. Osmium (Os) isotopes in ocean water are the result of secular changes in the amount of mantle-derived (depleted in ^{187}Os) and crustal materials (enriched in ^{187}Os) (Pegram et al., 1992). Changes in $^{187}Os/^{188}Os$ of marine sediments over time can be used as proxies for flood basalt volcanism (e.g., Turgeon and Creaser, 2008), weathering flux (Ravizza et al., 2001), ocean basin isolation (e.g., Poirier and Hillaire-Marcel, 2009), and, importantly for our purposes, the detection of impact events (Turekian, 1982; Peucker-Ehrenbrink and Ravizza, 2000, 2012; Paquay et al., 2008).

Chondritic meteors have an Os isotopic ratio similar to that of Earth's mantle, and extraterrestrial impacts result in a strong, rapid excursion to unradiogenic (i.e., closer to 0) marine $^{187}Os/^{188}Os$ ratios (Luck and Turekian, 1983; Koeberl, 1998; Reimold et al., 2014; Figure 1). The only two such excursions in the Cenozoic are Chicxulub (Figure 1b) and the late Eocene (~35 million years ago; Poag et al., 1994; Bottomley et al., 1997) dual impacts at Chesapeake Bay on the North American Atlantic coastal plain and Popigai in Siberia (Figure 1c; Robinson et al., 2009; Peucker-Ehrenbrink and Ravizza, 2012). Such Os isotope excursions would only be expected from chondritic impactors, but it is important to note that the scale of the impact is not necessarily reflected in the size of the Os excursion (Morgan, 2008). Other major climate events that have been proposed to be associated with impacts, such as the Paleocene-Eocene

Thermal Maximum (PETM; e.g., Schaller et al., 2016; Figure 1d), and the Younger Dryas (e.g., Kennett et al., 2009; Figure 1f) are not associated with any clear excursion toward unradiogenic values, despite relatively high sample resolution (e.g., Paquay et al., 2009). Rather, the PETM shows a positive excursion of Os isotope values associated with enhanced weathering during the event (Ravizza et al., 2001).

Ocean drilling has directly sampled ejecta from several Cenozoic craters in the form of black glassy spherical tektites, created from melt droplets caused by a meteor impact. Tektites from the late Eocene Chesapeake Bay and Popigai impacts were recovered from DSDP and ODP Sites 94 (Gulf of Mexico), 149 (Caribbean), and 612, 903, 904, and 1073 (New Jersey margin) in the Atlantic (Glass, 2002); from DSDP Sites 65, 69, 70, 161, 162, 166, 167, and 292 in the equatorial Pacific (Glass et al., 1985); and from DSDP Site 216 in the Northeast Indian Ocean (Glass, 1985). They have also been found in the South Atlantic at Maud Rise (ODP Site 689; Vonhof et al., 2000). These microtektites include a large number of clinopyroxene-bearing spherules (termed "microkrystites" by Glass and Burns, 1988) found in the Pacific and South Atlantic. An iridium anomaly was reported to occur in association with these ejecta (Alvarez et al., 1982), but higher-resolution work revealed that this iridium anomaly occurs below the microtektite layer (Sanfilippo et al., 1985). This positioning indicates that there were actually two impacts at this time (Chesapeake and Popigai), one that produced an iridium anomaly and microkrystites and a second that did not produce an iridium anomaly and that created chemically distinct microtektites (Glass et al., 1985; Vonhof and Smit, 1999). The iridium anomaly is also found at the Eocene-Oligocene Stratotype Section at Massignano, Italy, where it occurs ~12 m below or ~1 million years before the base of the Oligocene (Montanari et al., 1993). Nevertheless, some researchers have inferred a causal relationship between these impacts and latest Eocene cooling and faunal change (e.g., Keller, 1986; Vonhof et al., 2000; Liu et al., 2009), which would imply a climate feedback that amplified the short-term cooling directly caused by the impact (Vonhof et al., 2000).

> "Rock samples collected by IODP and its sister organization, the International Continental scientific Drilling Program (ICDP), have provided insights into impact cratering processes and the effects of events of different magnitudes on the climate and the biosphere, supplying an exceptional record of processes that are ubiquitous across the solar system (and, presumably, beyond)."

THE CHICXULUB IMPACT AND ITS PHYSICAL EFFECTS

The most important impact of the Phanerozoic, and the one that has been best studied by scientific ocean drilling, is the Chicxulub impact. The hypothesis that an impact caused the most recent major mass extinction was founded on elevated iridium levels in the K-Pg boundary clays within outcrops in Spain, Italy, and Denmark (Alvarez et al., 1980; Smit and Hertogen, 1980). The impact hypothesis was initially quite controversial, and one of the early objections was that iridium had only been measured at a few sites across a relatively small area of western Europe and may have reflected a condensed interval and not a discrete impact (Officer and Drake, 1985). Researchers then began to investigate and document other K-Pg boundary sites around the globe, many of which were DSDP/ODP drill sites (Figure 2). High iridium abundances were soon found at other sites (e.g., Orth et al., 1981; Alvarez et al., 1982), and the identification of shocked minerals within the K-Pg layer added irrefutable proof that it was formed by an extraterrestrial impact (Bohor et al., 1984). When a high-pressure shock wave passes through rocks, common minerals such as quartz and feldspar are permanently deformed (referred to as shock metamorphism) and produce diagnostic features (e.g., Reimold et al., 2014) that, on Earth, are only found in association with impacts and nuclear test sites. Since 1985, many ODP and IODP drill sites have recovered (and often specifically targeted) the K-Pg boundary (Figure 2), further contributing to our understanding of this event and demonstrating that ejecta materials were deposited globally (Figure 3).

The Chicxulub impact structure, on the Yucatán Peninsula, Mexico, was first identified as a potential impact crater by Penfield and Carmargo-Zanoguera (1981), and then as the site of the K-Pg impact by Hildebrand et al. (1991). These authors noted that the size of the shocked quartz and thickness of the K-Pg boundary deposit increased globally toward the Gulf of Mexico, and they located the Chicxulub crater by its association with strong, circular, potential field gravity anomalies. Core samples from onshore boreholes drilled by Petróleos Mexicanos ("Pemex") confirmed the crater's impact origin. Although some authors have argued against a link between Chicxulub and the K-Pg boundary (see Keller et al., 2004, 2007, for mature forms of that position), accurate $^{40}Ar/^{39}Ar$ dating of impact glass within the K-Pg layer (Renne et al., 2013, 2018), as well as dating of microcrystalline melt rock (Swisher et al., 1992) and shocked zircon (Krogh et al., 1993; Kamo et al., 2011) from Chicxulub and the K-Pg layer, clearly demonstrate that Chicxulub is the site of the K-Pg impact. Hildebrand et al. (1991) also noted that Gulf of Mexico DSDP Sites 94, 95, 536, and 540 contained deepwater gravity flows and turbidity-current deposits adjacent to Campeche Bank, and DSDP Sites 603B, 151, and 153, as well as outcrops along the Brazos River in Texas, contained potential tsunami wave deposits (Bourgeois et al., 1988), all of which suggested these deposits were a result of the Chicxulub impact. Increasingly, opponents of the impact hypothesis have accepted an end-Cretaceous age for the Chicxulub crater, and have focused their arguments on the Deccan Traps in India as the sole or contributing cause of the mass extinction (see Chenet et al., 2009; Punekar et al, 2014; Mateo et al., 2017; and Keller et al., 2018, and references therein for a recent summary; Schulte et al., 2010, remains the best rebuttal of these arguments).

Many studies have subsequently confirmed that at sites proximal to Chicxulub

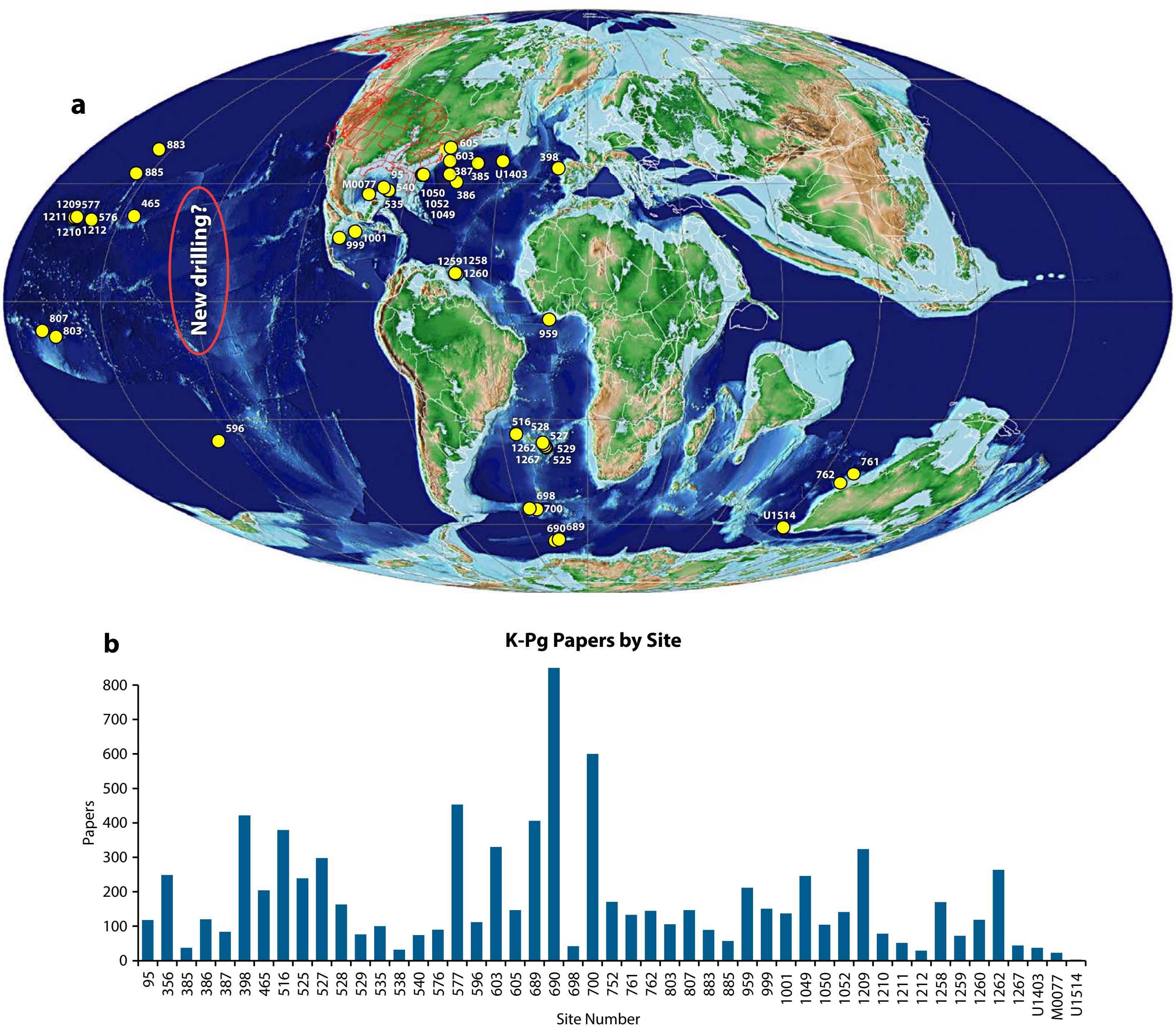


FIGURE 2. (a) Map of DSDP/ODP/IODP Sites that recovered the K-Pg boundary, up to Expedition 369. The base map is adapted from the PALEOMAP Project (Scotese, 2008). (b) Number of K-Pg papers by site, according to Google Scholar as of November 30, 2018 (search term: Cretaceous AND Tertiary OR Paleogene OR Paleocene AND 'Site ###'). As with any such search, there are some caveats, for example, inclusion of papers that match the search terms but are not strictly about the K-Pg, and papers that are missing because they are not cataloged by Google Scholar. However, this is a good approximation of the reams of articles that have been written about the K-Pg based on DSDP, ODP, and IODP cores, and the clear impact (sorry) of scientific ocean drilling on the K-Pg literature. n = 8,679, but there are duplicates because some papers cover multiple sites. The most recent site is U1514 (n = 3).

(<2,000 km), the impact produced multiple resurge, tsunami, gravity flow, and shelf collapse deposits (e.g., Bohor and Betterton, 1993; Bralower et al., 1998; Grajales-Nishimura et al., 2000; Schulte et al., 2010; Hart et al., 2012; Vellekoop et al., 2014). Well logs, DSDP cores, and seismic data show margin collapse deposits reach hundreds of meters thick locally, making the K-Pg deposit in the circum-Gulf of Mexico the largest known single event deposit (Denne et al., 2013; Sanford et al., 2016). Complex stratigraphy (Figure 3) and a mixture of nannofossil and foraminiferal assemblages of different ages that contain impact-derived materials characterize proximal deepwater DSDP and ODP sites in the Gulf of Mexico (DSDP Sites 95, 535–538, and 540) and the Caribbean (ODP Sites 999 and 1001), all exhibiting sequential deposition of material from seismically driven tsunamis, slope collapses, gravity flows, and airfalls (Sigurdsson et al., 1997; Bralower et al., 1998; Denne et al., 2013; Sanford et al., 2016). Bralower et al. (1998) termed this distinct assemblage of materials the K-Pg boundary "cocktail."

At intermediate distances from Chicxulub (2,000–6,000 km), the K-Pg boundary layer is only 1.5–3 cm thick, as observed in North America (Smit et al., 1992; Schulte et al., 2010), on Demerara Rise in the western Atlantic at ODP Site 1207 (K.G. MacLeod et al., 2007; Schulte et al., 2009), and on Gorgonilla Island, Colombia (Bermúdez et al., 2016). At the first two locations, it has a dual-layer stratigraphy. The lower layer contains goyazite and kaolinite spherules, which have splash-form morphologies such as tear drops and dumbbells, and is overlain by the "boundary clay" that contains the iridium anomaly and nickel-rich spinels (Smit and Romein, 1985; Bohor et al., 1989, 1993; Bohor and Glass, 1995). The similarity between spherules found in Haiti (~800 km from Chicxulub) and those found in the lower layer in North America has led to their joint interpretation as altered microtektites (Smit and Romein, 1985; Sigurdsson et al., 1991; Bohor et al., 1993; Bohor and Glass, 1995). Large-scale mass wasting has also been documented along the North Atlantic margins of North America and Europe, including on Blake Plateau (ODP Site 1049), Bermuda Rise (DSDP Sites 386 and 387), the New Jersey margin (DSDP Site 605), and the Iberian abyssal plain (DSDP Site 398) (Klaus et al., 2000; Norris et al., 2000).

At distal sites (>6,000 km), the K-Pg boundary becomes a single layer with a fairly uniform 2–3 mm thickness, and it has a chemical signature similar to the upper layer in North America (e.g., Alvarez et al., 1982; Rocchia et al., 1992; Montanari and Koeberl, 2000; Claeys et al., 2002). See, for example, DSDP Site 738 on the southern Kerguelen Plateau (Thierstein et al., 1991), DSDP Site 577 on Shatsky Rise (Zachos et al., 1985), DSDP Site 525 in the South Atlantic (Li and Keller, 1998), ODP Site 761 on Exmouth Plateau (Pospichal and Bralower, 1992), and ODP Site 1262 on Walvis Ridge (Bernaola and Monechi, 2007). The most abundant component (60%–85%) of the distal ejecta layer is microkrystites with a relict crystalline texture (Smit et al., 1992) that are thought to have formed from liquid condensates within the expanding plume (Kyte and Smit, 1986). Ubiquitous alteration of these microkrystites means that they are now primarily composed of clay (smectite, illite, and limonite). Some spherules contain skeletal magnesioferrite spinel (Smit and Kyte 1984; Kyte and Smit, 1986; Robin et al., 1991) that appears to be the only pristine phase to have survived diagenetic alteration (Montanari et al., 1983; Kyte and Bostwick, 1995). Shocked minerals are present in the K-Pg layer at all distances from Chicxulub, and are co-located with the elevated iridium unit (Smit, 1999).

DSDP, ODP, and IODP sites (Figure 2) have all been employed in mapping the global properties of the K-Pg layer. Sites close to the crater appear to have a slightly lower total iridium flux at $10–45 \times 10^{-9}$ g cm^{-2} (e.g., Rocchia et al., 1996; Claeys et al., 2002; K.G. MacLeod et al., 2007), as compared to a global average of $\sim 55 \times 10^{-9}$ g cm^{-2} (Kyte, 2004). Maximum iridium concentrations are quite variable (<1 to >80 ppb; Claeys et al., 2002). Attempts have been made to locate the ultimate carrier of the iridium in the sediment layer, but it is evidently too fine-grained to be identified with conventional techniques. Siderophile trace elements in the distal and upper K-Pg layer exhibit a chondritic distribution (Kyte et al., 1985), the isotopic ratio of the platinum group element osmium is extraterrestrial (Luck and Turekian, 1983; Meisel et al., 1995), and the chromium isotopic composition indicates that the impactor was a carbonaceous chondrite (Kyte, 1998; Shukolyukov and Lugmair, 1998).

The most common explanation for the origin of the microtektites at proximal and intermediate sites is that they are formed from melted target rocks that were ejected from Chicxulub and solidified en route to their final destination (e.g., Pollastro and Bohor, 1993; Alvarez et al., 1995). Ejecta at distal sites and within the upper layer at intermediate sites, including the shocked minerals and microkrystites, are widely thought to have been launched on a ballistic trajectory from a rapidly expanding impact plume (Argyle, 1989; Melosh et al., 1990). There are, however, several observations that are difficult to reconcile with these explanations. For example: (1) microkrystites within the global layer all have roughly the same mean size (250 μm) and concentration (20,000 cm^{-2}) (Smit, 1999), whereas shocked minerals show a clear decrease in number and size of grains with increasing distance from Chicxulub (Hildebrand et al., 1991; Croskell et al., 2002); (2) if shocked quartz were ejected at a high enough velocity to travel to the other side of the globe, the quartz would anneal on reentry (Alvarez et al., 1995; Croskell et al., 2002); and (3) if the lower layer at intermediate sites were formed from melt droplets ejected from Chicxulub on a ballistic path, the thickness of the lower layer would decrease with distance from Chicxulub, whereas across North America, it is close to constant. The interaction of reentering ejecta with Earth's atmosphere appears to be necessary to explain all of these observations, with the ejecta being redistributed laterally by atmospheric heating and expansion (Goldin and Melosh, 2007, 2008; Artemieva and Morgan, 2009; Morgan et al., 2013).

Differences in the K-Pg boundary layer around the globe have been used to infer different angles and directions for the Chicxulub impactor. Schultz and D'Hondt (1996) argued that several factors, including the dual-layer stratigraphy and particularly large fragments of shocked quartz in North America, indicated an impact direction toward the northwest. However, comparable 2 cm thick K-Pg layers at sites to the south of Chicxulub at equivalent paleodistances have been identified (Schulte et al., 2009; Bermúdez et al., 2016), and it now appears that the ejecta layer is roughly symmetric, with the number and size of shocked quartz grains decreasing with distance from Chicxulub (Croskell et al., 2002; Morgan et al., 2006). One asymmetric aspect of the layer is the spinel chemistry: spinel from the Pacific (e.g., DSDP Site 577) is characterized by higher Mg and Al content than European (e.g., Gubbio, Italy) and Atlantic spinel (e.g., DSDP Site 524; Kyte and Smit, 1986). The higher Mg-Al Pacific spinel represents a higher temperature phase, and thus the impact direction must have been toward the west, because the plume would be hottest in the downrange direction (Kyte and Bostwick, 1995). However, thermodynamic models of sequential condensation within the cooling impact plume suggest the opposite: that the spinels from Europe and the Atlantic represent the higher temperature phases and, thus, that the impact direction was toward the east (Ebel and Grossman 2005). An argument that sought to use position of crater topography relative to the crater center (Schultz and D'Hondt, 1996) has been questioned through comparisons with Lunar and Venutian craters

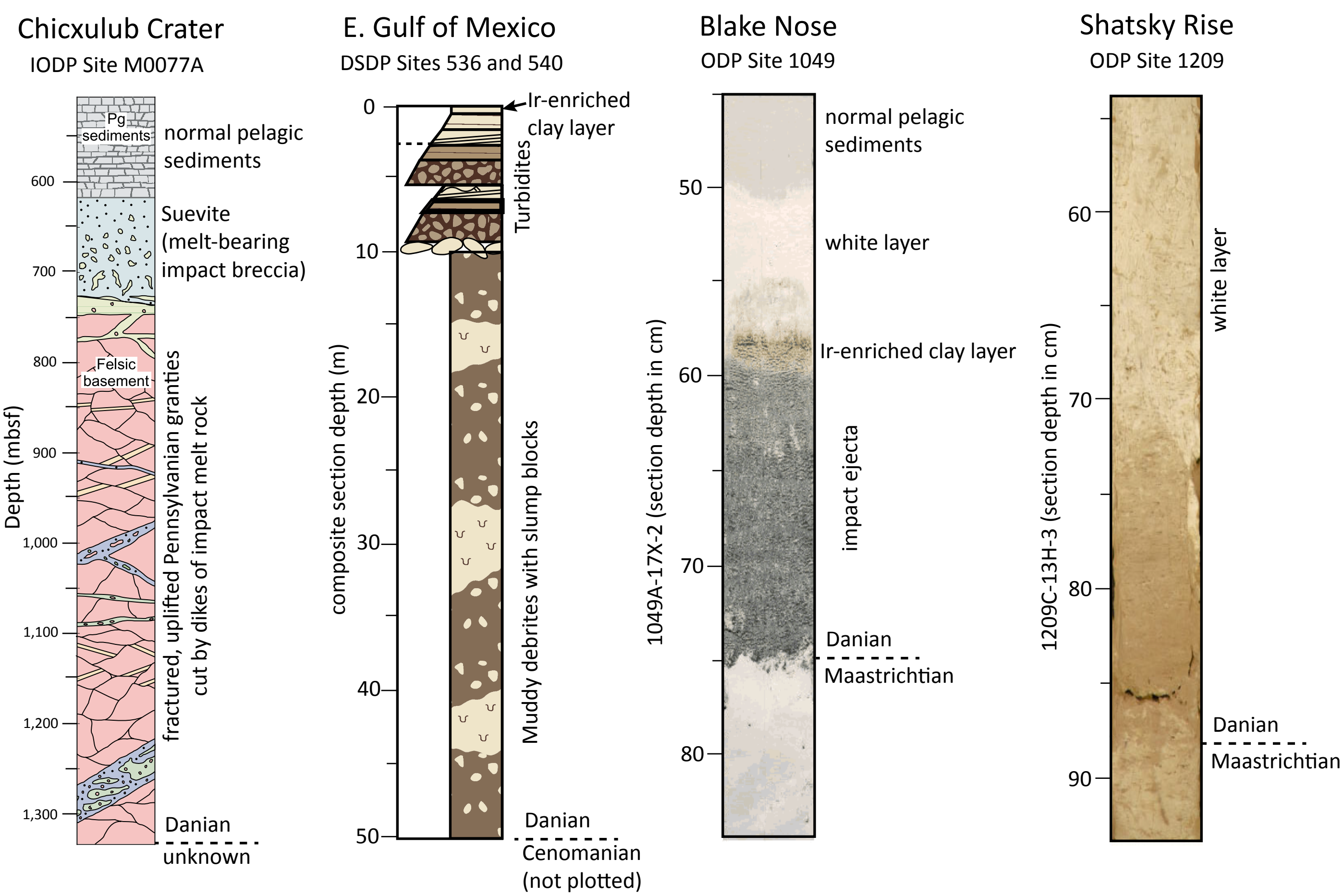


FIGURE 3. Representative K-Pg boundary sections from scientific ocean drilling cores. The peak ring of the Chicxulub crater itself shows pelagic post-impact sediments overlaying downward-coarsening suevite on top of impact melt rock, which in turn overlays fractured pre-impact granite cut by impact dikes (Morgan et al., 2016). Eastern Gulf of Mexico cores show the proximal deep-sea expression of the boundary layer, with massive slumps caused by platform margin collapse overlain by turbidites associated with secondary mass wasting, overlain by fallout of iridium-rich clay (Sanford et al., 2016). Blake Nose represents the dual-layer stratigraphy of many mid-distance localities, with impact ejecta overlain by an iridium-rich clay layer (Schulte et al., 2010). Shatsky Rise is typical of distal deep-sea sites, with a color change the only core-scale evidence of the impact (Schulte et al., 2010). The Chicxulub crater illustration is redrawn from Morgan et al. (2016), the eastern Gulf of Mexico image is redrawn from Sanford et al. (2016), and the Blake Nose and Shatsky Rise core photographs are from the IODP Janus database.

with known impact trajectories (Ekholm and Melosh, 2001; McDonald et al., 2008). The best estimate of impact direction to date, based on three-dimensional numerical simulations of crater formation that incorporate new data from IODP Site M0077 in the Chicxulub crater, indicates that an impact toward the southwest at a ~60° angle produces the best match between the modeled and observed three-dimensional crater structure (Collins et al., 2017).

OCEAN DRILLING PERSPECTIVE ON MASS EXTINCTION AND THE SUBSEQUENT RECOVERY OF LIFE

Paleontologists have long recognized a major mass extinction at the end of the Cretaceous with the disappearance of non-avian dinosaurs, marine reptiles, and ammonites, although the first indication of the rapidity of this event came from microfossils. The earliest studies of the extinction of the calcareous microfossils across the K-Pg boundary came from outcrops on land (e.g., Luterbacher and Premoli-Silva, 1964; Perch Nielsen et al., 1982; Percival and Fischer, 1977; Romein, 1977; Smit, 1982; M.J. Jiang and Gartner, 1986; Hollis, 1997; Harwood, 1988; Hollis and Strong, 2003). However, the full taxonomic scope of the extinction and how it related to global biogeography and ecology is largely known from scientific ocean drilling (e.g., Thierstein and Okada, 1979; Thierstein, 1982; Pospichal and Wise, 1990; N. MacLeod et al., 1997; Bown et al., 2004). Deep-sea sites also serve as the basis for our understanding of the subsequent recovery of life (Bown, 2005; Coxall et al., 2006; Bernaola and Monechi, 2007; S. Jiang et al., 2010; Hull and Norris, 2011; Hull et al., 2011; Koutsoukos, 2014; Birch et al., 2016; Lowery et al., 2018). The K-Pg boundary has been recovered in dozens of cores from all major ocean basins, including some from the earliest DSDP legs (Figure 2; Premoli Silva and Bolli, 1973; Perch-Nielsen, 1977; Thierstein and Okada, 1979; see summary of terrestrial and marine K-Pg sections in Schulte et al., 2010). Deep-sea cores generally afford excellent microfossil preservation, continuous recovery, and tight stratigraphic control, including magnetostratigraphy and orbital chronology (Röhl et al., 2001; Westerhold et al., 2008).

Studies of deep-sea sections have exposed the severity of the mass extinction among the calcareous plankton, with over 90% of heterotroph foraminifera and autotroph nannoplankton species becoming extinct (Thierstein, 1982; D'Hondt and Keller, 1991; Coxall et al., 2006; Hull et al., 2011). The extinction was highly selective, as siliceous groups experienced relatively low rates of extinction (Harwood, 1988; Hollis et al., 2003). Among the calcareous plankton groups, survivors include high-latitude and nearshore species (D'Hondt and Keller, 1991; Bown, 2005), suggesting that these species adapted to survive variable environments in the immediate aftermath of the impact. Benthic foraminifera survived the impact with little extinction (Culver, 2003).

A key component of the post-extinction recovery of life on Earth is the revival of primary productivity. Photosynthesis favors ^{12}C over ^{13}C, enriching organic material in the former. Sinking of dead organic matter in the ocean removes ^{12}C from the upper water column; thus, under normal conditions, there is a carbon isotope gradient from the surface waters to the seafloor. After the Chicxulub impact, this vertical gradient was non-existent for ~4 million years (e.g., Coxall et al., 2006). This phenomenon was originally interpreted as indicating the complete or nearly complete cessation of surface ocean productivity (Hsü and McKenzie, 1985; Zachos et al., 1989; the latter from DSDP Site 577 on Shatsky Rise), a hypothesis that became known as the Strangelove Ocean (after the 1964 Stanley Kubrick movie; Hsü and McKenzie, 1985). D'Hondt et al. (1998) suggested that surface ocean productivity continued, but the extinction of larger organisms meant that there was no easy mechanism (e.g., fecal pellets) to export this organic matter to the deep sea—a modification of the Strangelove Ocean hypothesis that they called the Living Ocean hypothesis (D'Hondt, 2005; see also Adams et al., 2004). The observed changes in carbon isotopes can be explained by just a slight increase (from 90% to 95%) in the fraction of organic matter remineralized in the upper ocean (D'Hondt et al., 1998; Alegret et al., 2012), although a more precipitous drop in export productivity (Coxall et al., 2006) has also been suggested. The lack of a corresponding benthic foraminiferal extinction indicates that the downward flux of organic carbon may have decreased somewhat but remained sufficiently elevated to provide the carbon necessary to sustain the benthic community (Hull and Norris, 2011; Alegret et al., 2012). Research on barium fluxes in deep-sea sites across the ocean shows that, in fact, export productivity was highly variable in the early Danian (the age that immediately followed the end of the Cretaceous, when K-Pg extinction begins), with some sites recording an *increase* in export production during the period of supposed famine in the deep sea (Hull and Norris, 2011).

However, any shift in the surface-to-deep carbon isotope gradient does have significant implications for biogeochemical cycling. The extinction of pelagic calcifiers such as planktic foraminifera and calcareous nannoplankton caused profound changes in the cycling of carbon from the surface to the deep sea. Pelagic calcifiers are a key component of the carbon cycle as they export carbon in the form of $CaCO_3$ from the surface ocean to the seafloor. The near eradication of these groups must have made surface-to-deep cycling less efficient, explaining the decreased carbon isotope gradient (Hilting et al., 2008; Alegret et al., 2012; Henehan et al., 2016). This also led to the weakening of the marine "alkalinity pump" (D'Hondt, 2005; Henehan et al., 2016). The resulting carbonate oversaturation improved carbonate preservation in the deep sea, which can be observed as a white layer that overlies the K-Pg boundary at numerous sites, including the eastern Gulf of Mexico (DSDP Site 536; Buffler et al., 1984), the Caribbean (ODP Sites 999 and 1001; Sigurdsson et al., 1997), Shatsky Rise in the western Pacific (Figure 3; ODP Sites 1209–1212; Bralower et al., 2002), and in the Chicxulub crater (IODP Site M0077; Morgan et al., 2017).

Records from cores across the ocean basins indicate that the post-extinction recovery of export productivity (e.g., Hull and Norris, 2011) and calcareous plankton diversity (e.g., S. Jiang et al., 2010) was geographically heterogeneous, with some localities recovering rapidly and others taking hundreds of thousands (for productivity) to millions (for diversity) of years to recover. Among the nannoplankton, Northern Hemisphere assemblages are characterized by a series of high-dominance, low-diversity "boom-bust" species (Bown, 2005), while Southern Hemisphere assemblages contain a somewhat more diverse group of surviving species (Schueth et al., 2015). In general, diversity of Northern Hemisphere assemblages took longer to recover (S. Jiang et al., 2010). Recovery of export productivity likewise appears to have been slower in the North Atlantic and Gulf of Mexico (e.g., S. Jiang et al., 2010; Hull and Norris, 2011; Alegret et al., 2012), suggesting that sites proximal to the impact crater had a slower recovery. Some authors (e.g., S. Jiang et al., 2010) attributed this to direct environmental effects of the impact, such as the uneven distribution of toxic metals in the ocean. If recovery is slower closer to the crater, then it should be slowest in the crater itself. However, recent drilling within the Chicxulub crater shows rapid recovery of life, with planktic and benthic organisms appearing within just a few years of the impact and a healthy, high-productivity ecosystem established within 30,000 years of the impact, much faster than estimates for other Gulf of Mexico and North Atlantic sites (Lowery et al., 2018). This rapid recovery rules out an environmental driver for heterogeneous recovery and instead suggests that natural ecological factors, including incumbency, competitive exclusion (e.g., Hull et al., 2011; Schueth et al., 2015), and morphospace reconstruction (Lowery and Fraass, 2018), were the dominant controls on the recovery of the marine ecosystem. The recovery of diversity took millions of years to even begin to approach pre-impact Cretaceous levels (Bown et al., 2004; Coxall et al., 2006; Fraass et al., 2015). This delay in the recovery of diversity appears to be a feature of all extinction events (Kirchner and Weil, 2000; Alroy, 2008) and bodes ill for the recovery of the modern biosphere after negative anthropogenic impacts of, for example, ocean acidification and hypoxia, subside.

UNIQUE INSIGHT INTO THE CHICXULUB CRATER

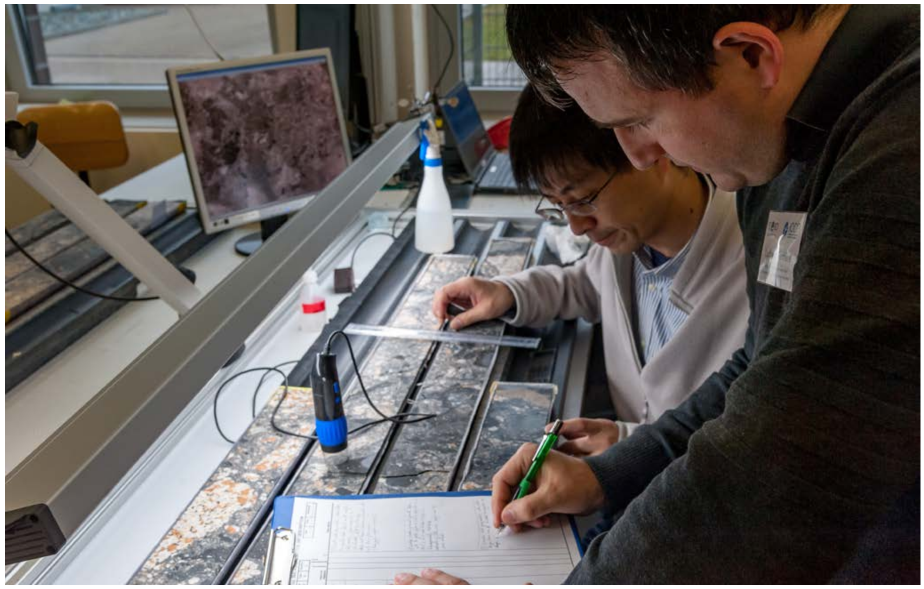
In 2016, the joint IODP-ICDP Expedition 364 drilled into the peak ring of the Chicxulub impact crater at Site M0077 (Morgan et al., 2017). Peak rings are elevated topography that protrude through the crater floor in the inner part of large impact structures. Prior to drilling, there was no consensus on the nature of the rocks that form peak rings or their formational mechanism (Baker et al., 2016). To form large craters like Chicxulub, rocks must temporarily behave in a fluid-like manner during crater formation (Melosh, 1977; Riller et al., 2018). Two hypotheses, developed from observations of craters on other planets, provided possible explanations for the processes by which peak rings form. The first, the dynamic collapse model (first put forward by Murray, 1980) predicted that the Chicxulub peak ring would be formed from deep crustal rock, presumably crystalline basement. The second, the nested melt-cavity hypothesis (conceived by Cintala and Grieve, 1998) predicted that the Chicxulub peak ring would be underlain by shallow crustal rock, presumably Cretaceous carbonates. Thus, Expedition 364 was able to answer a major question about impact cratering processes simply by determining what rock comprises the peak ring (Figure 3). Geophysical data acquired prior to drilling indicated that there are sedimentary rocks several kilometers beneath the Chicxulub peak ring, and that the peak-ring rocks have a relatively low velocity and density, suggesting that they are highly fractured (Morgan et al., 1997; Morgan and Warner, 1999; Gulick et al., 2008, 2013; Morgan et al., 2011).

The discovery that the peak ring was formed from fractured, shocked, uplifted granitic basement rocks supports the dynamic collapse model of peak-ring formation (Morgan et al., 2016; Kring et al., 2017). Structural data from wireline logging, CT scans, and visual core descriptions provide an exceptional record of brittle and viscous deformation mechanisms within the peak-ring rocks. These data reveal how deformation evolved during cratering, with dramatic weakening followed by a gradual increase in rock strength (Riller et al., 2018). The peak-ring rocks have extraordinary physical properties: the granitic basement has P-wave velocities and densities that are, respectively, ~25% and ~10% lower than expected, and a porosity of 8%–10%. These values are consistent with numerical simulations that predict the peak-ring basement rocks represent some of the most shocked and damaged rocks in an impact basin (Christeson et al., 2018). Site M0077 cores and measurements have been used to refine numerical models of the impact and provide new estimates on the release of cooling climatic gases by the Chicxulub impact. Previous studies estimated that the Chicxulub impact released anywhere from 30–1,920 Gt of sulfur from the evaporite-rich target rocks and formed sulfate aerosols in the atmosphere that block incoming solar radiation (see Tyrrell et al., 2015, and references therein)—a recent global climate model indicates that a modest injection of 100 Gt of sulfur may have resulted in a 26°C drop in global temperatures (Brugger et al., 2017). New impact models calibrated with data from Site M0077 suggest that between 195 Gt and 455 Gt of sulfur were released and may have led to even more radical cooling during the so-called "impact winter" (Artemieva et al., 2017). However, it appears that only the most extreme estimates of sulfur release would have driven ocean acidification severe enough to explain the extinction of calcareous plankton (Tyrrell et al., 2015), suggesting that the sharp reduction in sunlight for photosynthesis drove the extinction.

NEW CHALLENGES

The scientific community's understanding of the Chicxulub impact event and the K-Pg mass extinction has grown immensely since Smit and Hertogen (1980) and Alvarez et al. (1980) proposed the impact hypothesis, and many of the advances were the direct result of scientific ocean drilling data. However, there is still a great deal that we do not know. New K-Pg boundary sites from undersampled regions (the Pacific, the Indian Ocean, and the high latitudes) are essential to reconstruct environmental gradients in the early Paleocene and to understand geographic patterns of recovery and global environmental effects as well as what drives them. IODP Site U1514, on the Naturaliste Plateau on the Southwest Australian margin (Figure 2), drilled in 2017 on Expedition 369 (Huber et al., 2018), is a perfect example of the kind of new site we need to drill—at a high latitude and far from existing K-Pg boundary records.

New data from the Chicxulub crater have resulted in refined impact models that suggest the asteroid impacted toward the southwest (Collins et al., 2017), in contrast with previously inferred directions that placed the Northern Hemisphere in the downrange direction. Although the most proximal Pacific crust at the time of impact has since been subducted, very little drilling has been conducted on older crust in the central and eastern Pacific (red circle in Figure 2). New drilling on seamounts and rises on the easternmost Cretaceous crust in the equatorial Pacific could shed new light on the environmental and biological consequences of the Chicxulub impact in a close-by and downrange location. Samples from these locations may finally yield some fragments of the impactor.



Impact Petrologists Ludovic Ferrière (Natural History Museum, Austria) and Naotaka Tomioka (JAMSTEC) at the visual core description table at the IODP Bremen Core Repository during the onshore science party for IODP Expedition 364, Chicxulub: Drilling the K-Pg Impact Crater. *Photo credit: V. Diekamp, ECORD/IODP*

In the end, the Chicxulub structure remains an important drilling target to address questions that can only be answered at the K-Pg impact site. IODP Site M0077, which was drilled at the location where the peak ring was shallowest, recovered a relatively thin Paleocene section with an unconformity present prior to the Paleocene-Eocene boundary. Seismic mapping within the crater demonstrates that the Paleocene section greatly expands into the annular trough (Figure 4), providing an exciting opportunity to study the return of life to the impact crater at an even higher resolution than Lowery et al. (2018) achieved. Additionally, continuous coring within an expanded Paleocene section and the underlying impactites would better constrain climatologic inputs from the vaporization of evaporites.

Equally intriguing is the interaction of impact melt rock, suevite, and post-impact hydrothermal systems for studying how subsurface life can inhabit and evolve within an impact basin. Such settings were common on early Earth and provide an analog for the chemical evolution of pre-biotic environments as well as biologic evolution in extreme environments. Full waveform images (Figure 4) suggest tantalizing morphologic complexities within the low-velocity suevite layer above the high-velocity central melt sheet that are tempting to interpret as ancient hydrothermal vent systems of the kind often seen at mid-ocean ridges. Drilling into the Chicxulub melt sheet would be ideal for studying the hydrogeology and geomicrobiology of impact melt sheets buried by breccias as a (new) habitat for subsurface life, providing an opportunity for scientific ocean drilling to sample the best analog for the habitat in which life may have initially formed on early Earth and on rocky bodies across the solar system and beyond.

The successful cooperation between IODP and ICDP during Expedition 364 serves as a model for future drilling in the Chicxulub crater as well as for future IODP mission-specific platform expeditions. High-quality marine seismic data from an offshore portion of the Chicxulub crater (Morgan et al., 1997; Gulick et al., 2008; Christeson et al., 2018) permitted detailed characterization of the subsurface before drilling even

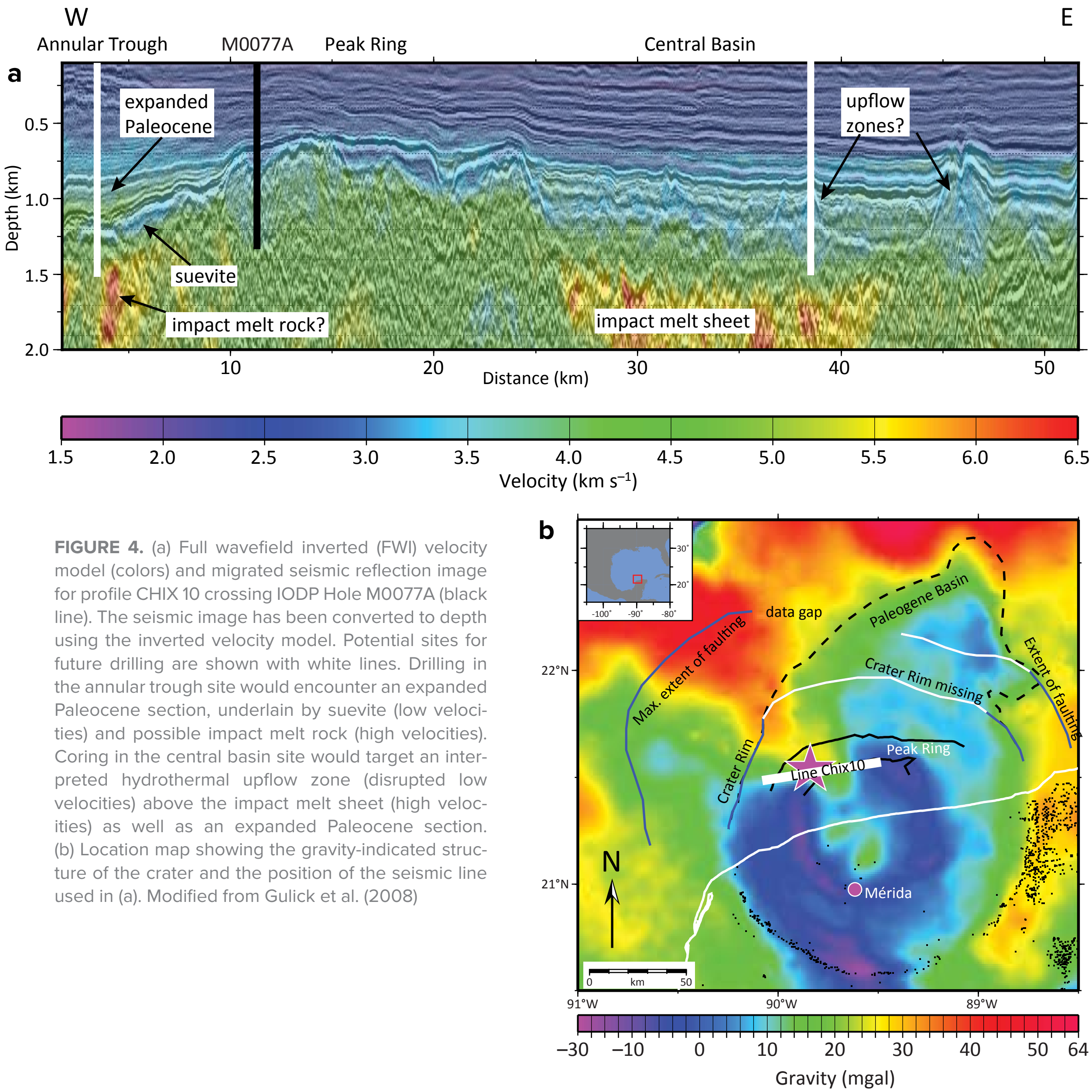


FIGURE 4. (a) Full wavefield inverted (FWI) velocity model (colors) and migrated seismic reflection image for profile CHIX 10 crossing IODP Hole M0077A (black line). The seismic image has been converted to depth using the inverted velocity model. Potential sites for future drilling are shown with white lines. Drilling in the annular trough site would encounter an expanded Paleocene section, underlain by suevite (low velocities) and possible impact melt rock (high velocities). Coring in the central basin site would target an interpreted hydrothermal upflow zone (disrupted low velocities) above the impact melt sheet (high velocities) as well as an expanded Paleocene section. (b) Location map showing the gravity-indicated structure of the crater and the position of the seismic line used in (a). Modified from Gulick et al. (2008)

began (Whalen et al., 2013). In turn, this allowed Hole M0077A to precisely target not just the peak ring but a small depression on top of the peak ring expected to contain earliest Paleocene age sediments that provided the basis for unprecedented study of this unique interval at ground zero (Lowery et al., 2018, and a number of upcoming papers). As we plan for the next 50 years of scientific ocean drilling, we should look for additional opportunities to leverage the clarity and resolution of marine seismic data with the precision drilling possible from a stable platform provided by ICDP (Expedition 364 achieved essentially 100% recovery; Morgan et al., 2017).

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