Ocean Drilling Perspectives on Meteorite Impacts

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2.2 Ocean Drilling Perspectives on Meteorite Impacts

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Abstract

Extraterrestrial impacts are one of the most ubiquitous processes in the solar system, reshaping the surface of rocky bodies of all sizes. On early Earth, impact structures may have been a nursery for the evolution of life. More recently, a large meteorite impact caused the end Cretaceous mass extinction, killing 75% of species on the planet, including non-avian dinosaurs, and clearing the way for the dominance of mammals and 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 across the solar system and beyond.

Scientific ocean drilling has generated irreplaceable data on impact processes. The Chicxulub impact is the single largest and most significant impact event that can be studied by sampling modern ocean basins, and marine sediment cores have been instrumental in quantifying the climatological and biological effects of the impact. Recent drilling in the Chicxulub Crater has already significantly advanced our understanding of fundamental impact processes, notably the formation of peak rings in large impact craters. These results raise a number of new questions waiting to be addressed with further drilling.

Extraterrestrial impacts have been controversially suggested as drivers for many important paleoclimatic events in the Cenozoic, up to and including the Younger Dryas stadial at the end of the last glacial maximum. However, marine sediment archives (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, major paleoclimatic events are not driven by impacts.

Keywords: Ocean Drilling, Impact Events, Cretaceous-Paleogene, Chicxulub, Mass Extinction

1 Introduction

Large meteorite impacts have had a significant influence on Earth history, possibly driving the early evolution of life (e.g., Kring, 2000; Nisbet and Sleep, 2001; Kring, D.A., 2003) and the composition of the oceans and atmosphere (e.g., Kasting 1993). They also have the potential to completely reshape the terrestrial biosphere (e.g., Alvarez et al., 1980). The Cretaceous-Paleogene (K-Pg) mass extinction, caused by the impact of a meteorite on the Yucatán carbonate platform of Mexico 66 Ma, is the most recent major mass extinction. It ended the dominance of non-avian dinosaurs, marine reptiles, and ammonites, and set the stage for the Cenozoic dominance of mammals that led directly to the evolution of humans (Schulte et al., 2010; Meredith et al., 2011). This mass extinction was likely a direct response to climate change over days to years, and thus provides an important partial analog for the recovery of biodiversity following modern anthropogenic climate change.

The K-Pg impact hypothesis was controversial when first proposed, but careful correlation of K-Pg boundary sections led to its gradual acceptance. The discovery of the Chicxulub Crater in 1991 and its clear genetic relationship with K-Pg boundary ejecta provided confirmation of this hypothesis (Hildebrand et al., 1991; Sigurdsson et al., 1991). Scientific ocean drilling has been instrumental in discovering and documenting the global environmental effects of the impact. Recent drilling by IODP Expedition 364 into the Chicxulub Crater itself has yielded valuable insights into the mechanisms of large impact crater formation and the recovery of life (Morgan et al., 2016; Lowery et al., 2018).

Although the K-Pg is the only mass extinction that is widely accepted to be caused by an extraterrestrial collision, impacts have been suggested at one point or another as drivers for every major 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 signature of extraterrestrial material spurred the search for other impact horizons through the careful examination of many other geologically significant intervals, and so far no other geologic event or transition has met the criteria to indicate causation by an impact (e.g., the presence of Ir and other platinum group elements in chondritic proportions; tektites, shock-metamorphic effects in rocks and minerals; perturbation of marine Os isotopes; and, ideally, an impact crater).

The Deep Sea Drilling Project (DSDP), Ocean Drilling Program (ODP), Integrated Ocean Drilling Program, and International Ocean Discovery Program (IODP) have provided a unique and irreplaceable perspective on the history of the Earth for 50 years. IODP and its sister organization the International Continental scientific Drilling Program (ICDP) provide insights into impact cratering processes and effects of different magnitude events as well as target rocks on the climate and biosphere, providing an exceptional record of processes that are ubiquitous across the solar system (and, presumably, beyond). Here we examine the contributions of scientific ocean drilling into our understanding of impact events, from detailed records of extinction and chemical perturbation in the marine realm to the mechanisms by which rocks are deformed to create peak rings in impact craters. The exciting results of recent drilling in the Chicxulub crater raise new questions, and suggest promising new challenges and avenues of investigation that can only be undertaken by a program like IODP.

2 Marine Record of Impacts

Scientific ocean drilling excels at providing raw material to generate high-resolution composite records of geochemical changes in the ocean through time. One of these proxies is the isotopic ratio of osmium, which records 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, impact events (Peucker-Ehrenbrink and Ravizza, 2000, 2012; Paquay et al., 2008). Extraterrestrial impacts result in a strong, rapid excursion to unradiogenic (i.e., negative) $^{187}Os/^{188}Os$ ratios (Koeberl, 1998; Reimold et al., 2014) (Figure 1A). The only two such excursions in the Cenozoic are Chicxulub (Figure 1B) and the late Eocene (35 Ma; Poag et al., 1994) Chesapeake Bay impact on the North American Atlantic coastal plain (Fig 1C) (Robinson et al., 2009; Peucker-Ehrenbrink and Ravizza, 2012). Other major climate events which are associated with proposed impacts, like the Paleocene-Eocene Thermal Maximum (PETM; e.g., Schaller et al., 2016) (Figure 1D), Miocene Climate Transition (Figure 1E), and 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. It should be noted that the Chesapeake Bay impact is approximately an order of magnitude smaller than the Chicxulub impact (Poag et al., 1992) and is not associated with any significant climatic or biological perturbation. Despite this, the event has a significant Os isotope excursion (Fig. 1C). Thus, an impact strong enough to effect global climate, as has been proposed at various important climatic horizons beyond the K-Pg, would be expected to leave a clear signature in the Os record. Setting aside the debates about whether any particular event coincides with a bollide impact, the lack of an Os isotopic excursion for any of these events calls into question the scale of any proposed contemporaneous impacts, and thus their causal relationship with the events they happen to coincide with.

3 The Chicxulub Impact and Its Physical Effects

The hypothesis that an impact caused the most recent major mass extinction (Smit and Hertogen, 1980) was founded on elevated iridium levels in the K-Pg boundary clays within outcrops in Spain, Italy and Denmark (Alvarez et al., 1980). The impact hypothesis was initially quite widely dismissed, and one of the early objections was that iridium had only been measured at a few sites across a relatively small area and that it was not deposited instantaneously (Officer and Drake, 1985). Researchers then began to investigate and document other K-Pg boundaries around the globe, many of which were DSDP drill sites (Fig. 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 extra-terrestrial 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), producing diagnostic features (e.g. Reimold et al., 2014) that are only found on Earth in association with impacts and nuclear test sites. Since 1985, many ODP and IODP drill sites have penetrated (and often specifically targeted) the K-Pg boundary (Fig. 2), further contributing to our understanding of this event, and demonstrating that ejecta materials were deposited globally (Figure 3).

The Chicxulub impact structure, Yucatán Peninsula, Mexico, was first identified as a potential impact crater by Penfield and Carmargo (1981), and then as the site of the K-Pg impact by Hildebrand et al. (1991). Hildebrand et al. (1991) noted that the size of the shocked quartz and thickness of the K-Pg boundary deposit increased towards the Gulf of Mexico, and located the Chicxulub crater due to its association with strong, circular, potential field anomalies. Core samples from onshore boreholes drilled by Petróleos Mexicanos ("Pemex") confirmed its impact origin. Although Keller et al. (2004, 2007) argue against a link between Chicxulub and the K-Pg boundary, accurate $^{40}Ar/^{39}Ar$ dating of impact glass within the K-Pg layer (Renne et al., 2013; 2018), as well as dating of shocked zircon (Krogh et al., 1993; Kamo et al., 2011) and microcrystalline melt rock (Swisher et al., 1992) 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 DSDP Sites 94, 95, 536 and 540 contained deep water gravity flows and turbidity-current deposits adjacent to the Campeche bank, and DSDP sites 603B, 151 and 153, as well as outcrops along the Brazos River in Texas had potential tsunami wave deposits (Bourgeois et al., 1988), all of which they suggested were caused by the Chicxulub impact.

Many studies have subsequently confirmed that, at sites proximal to Chicxulub, the impact produced multiple resurge, tsunami, gravity flow and shelf collapse deposits, some of which are many meters thick (e.g. Bohor and Betterton, 1993; Bralower et al., 1998; Grajales-Nishimura et al., 2000; Schulte et al., 2010; Vellekoop et al., 2014). Within the Gulf of Mexico basin, well logs, DSDP cores, and seismic data show margin collapse deposits reach 100s 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 and impact-derived materials characterize proximal deep water DSDP and ODP sites in the Gulf of Mexico (DSDP Sites 95, 535, and 540), and Caribbean (ODP Sites 999 and 1001) driven by the sequential deposition of material from seismically driven tsunami, slope collapse, gravity flows and airfall (Bralower et al., 1998; Denne et al., 2013; Sanford et al., 2016). This distinct assemblage of materials was termed the K-Pg "Boundary Cocktail" by Bralower et al. (1998).

At intermediate distances from Chicxulub (2000-6000 km) the K-Pg boundary layer is 1.5 – 3 cm thick, as seen in North America (Smit et al., 1992), the Demerara Rise (western Atlantic) ODP Site 1207 (MacLeod et al., 2007; Schulte et al., 2009) and Gorgonilla Island, Columbia

(Bermúdez et al., 2016), and, at the first two locations, has a dual layer stratigraphy. The lower layer contains goyazite and kaolonite spherules, which have splash-form morphologies such as tear drops and dumbbells (Bohor et al., 1989; Smit and Romein, 1985; Bohor et al., 1993; Bohor and Glass, 1995). The similarity between spherules in Haiti (~800 km from Chicxulub) and the lower layer in North America has led to their joint interpretation as altered microtektites, which were formed from ejected melt droplets (Smit and Romein, 1985; 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 at 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 (> 6000 km) the K-Pg boundary becomes a single layer with a fairly uniform 2-3 mm thickness, and has a similar chemical signature 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). The most abundant component (60-85%) of the distal ejecta layer is spherules with a relict crystalline texture (Smit et al., 1992) which are referred to as microkrystites (Glass and Burns, 1988), and are thought to have been formed from liquid condensates within the expanding plume (Kyte and Smit, 1986). These microkrystites are now primarily composed of clay (smectite, illite, and limonite) owing to their ubiquitous alteration. Some spherules contain skeletal, magnesioferrite spinel (Smit and Kyte 1984; Kyte and Smit, 1986; Robin et al., 1991); spinel is the only pristine phase that appears 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 (Smit, 1999).

DSDP, ODP, and IODP sites (Fig. 2) have all been used for 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 x 10^{-9} gcm^{-2} (e.g. Rocchia et al., 1996; Claeys et al., 2002; MacLeod et al., 2007) compared with a global average of ~55 x 10^{-9} gcm^{-2} (Kyte, 2004), and maximum iridium concentrations are quite variable (< 1 to > 80 ppb, Claeys et al., 2002). Although several attempts have been made to locate the ultimate source of the iridium, the host is too fine-grained to be identified with conventional techniques. The siderophile trace elements in the distal and upper K-Pg layer have a chondritic distribution (Kyte et al., 1985), the isotopic ratio of the Platinum Group Element (PGE) osmium is extra-terrestrial (Meisel et al., 1995), and the chromium isotopic composition indicates the impactor was a carbonaceous chondrite (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 have been ejected from Chicxulub as melt droplets on a ballistic path within an ejecta curtain, 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 of how K-Pg ejecta traveled around the globe. For example: 1) microkrystites within the global layer have roughly the same mean size (250 µm) and concentration (20,000 per 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 re-entry (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. Interactions of ejecta with the Earth’s atmosphere appear to be necessary to explain all of these observations (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 and particularly large fragments of shocked quartz in North America, indicated an impact direction towards the northwest. Subsequently, however, comparable 2-cm thick K-Pg layers at sites to the south of Chicxulub at equivalent paleodistances were identified (Schulte et al., 2009; Bermúdez et al., 2016), and it now appears that the global 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 aspect of the layer that is asymmetric is the spinel chemistry: spinel from the Pacific (e.g., DSDP Site 577) is characterized by higher Mg and Al compared to European (e.g., Gubbio, Italy) and Atlantic spinel (e.g., DSDP Site 524) (Kyte and Smit, 1986). Kyte and Bostwick (1995) concluded that the Pacific spinel represented a higher temperature phase, and thus that the impact direction must have been towards the west because the plume would be hottest in the downrange direction. Subsequently, Ebel and Grossman (2005) used thermodynamic models to predict the sequential condensation within the cooling impact plume and concluded the opposite: that the spinel from Europe and the Atlantic represented the higher temperature phases and, thus, that the impact direction was towards the east. Arguments that sought to use position of crater topography relative to the crater center (Schultz and D'Hondt, 1996) have been questioned through comparisons with Lunar and Venutian craters with known impact trajectories (Ekholm and Melosh, 1998; McDonald et al., 2008). More recently, 3D numerical simulations of crater formation, which incorporate new data from IODP Site M0077 in the Chicxulub crater, indicate that an impact towards the southwest at a ~60° angle produces the best match between the modeled and observed 3D crater structure (Collins et al., 2017).

4 Ocean Drilling Perspective on Mass Extinction

Paleontologists had 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 advances on the extinction of the calcareous and siliceous 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; Jiang and Gartner, 1986; Smit, 1982; Harwood, 1988; Hollis, 1997; Hollis et al., 2003). However, the full taxonomic scope of the extinction and how it related to biogeography and ecology is largely known from ocean drilling (e.g., Thierstein and Okada, 1979; Thierstein, 1982; MacLeod et al., 1997; Pospichal and Wise, 1990; Bown et al., 2004). Deep-sea sites also serve as the basis for our understanding of the subsequent recovery of life (Bown, 2005; Bernaola and Monechi, 2007; Jiang et al., 2010; Hull and Norris, 2011; Hull et al., 2011). The K-Pg boundary has now been recovered in dozens of cores representing all of the major ocean basins, including some from the earliest DSDP legs (Fig. 2) (Premoli Silva and Bolli, 1973; Perch-Nielsen, 1977; Thierstein and Okada, 1979; see summary of key terrestrial sections in Schulte et al., 2010). Deep-sea sections 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 plankton with over 90% of foraminifera and nannoplankton species becoming extinct (Thierstein, 1982; D'Hondt and Keller, 1991; Coxall et al., 2006; Hull et al., 2011). These studies have also shown that the extinction was highly selective, with siliceous groups experiencing relatively low rates of extinction (Harwood, 1988; Hollis et al., 2003). Among the calcareous plankton groups, survivors include high-latitude and near-shore species (Bown 2005; D'Hondt and Keller, 1991) suggesting that these species were adapted to survive variable environments in the immediate aftermath of the impact. Moreover, deep sea benthic foraminifera survived the impact with little extinction, illustrating that deep ocean environments were not perturbed (Alegret et al., 2001; 2012). This is a strong piece of evidence in support of an extremely rapid extinction event, as expected for an impact, as it must have occurred faster than the mixing time of the ocean (~1000 years). Benthic foraminifera would suffer an extinction 10 myr later during the Paleocene Eocene Thermal Maximum (Thomas and Monechi, 2007), a geologically rapid event that was still slow enough to impact the deep sea.

Carbon isotopes across the oceans appear to suggest that the flux of organic carbon to the deep ocean ceased or was very low for ~3 myr, a phenomenon which 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 fertile location for K-Pg studies). This hypothesis 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 to export this organic matter to the deep sea – a modification of the Strangelove Ocean hypothesis that has since been known as the Living Ocean hypothesis. However, several facts about the earliest Danian ocean are incompatible with both of these hypotheses. The lack of a corresponding benthic foraminiferal extinction suggests that the downward flux of organic carbon may have decreased somewhat but remained sufficiently elevated to sustain the benthic community (Hull and Norris, 2011; Alegret et al., 2001). More recent work on biogenic barium fluxes in deep sea sites across the world has shown that, in fact, export productivity was highly variable in the early Danian, with some sites recording an *increase* in export production during the period of supposed famine in the deep sea (Hull and Norris, 2011).

Calcareous plankton communities were geographically heterogeneous in the immediate aftermath of the mass extinction (Jiang et al., 2010). Among the nannoplankton, northern hemisphere assemblages are characterized by a series of high-dominance, low-diversity "boom-bust" species (Bown, 2005); 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 (Jiang et al., 2010) and heterogeneity was maintained for more than 300 kyr. This heterogeneity is likely a result of a combination of factors including incumbency of the surviving population in the southern hemisphere sites as well as environmental and ecological differences following the impact (Schueth et al., 2015).

However, the shift in the surface-to-deep carbon isotope gradient does have significant implications for biogeochemical cycling, and is still ultimately linked to a major disruption and recovery of food webs across the oceans. In the pelagic realm, diminished productivity by nannoplankton and increased bacterial activity (Sepulveda et al., 2009) combined with flourishing production of calcisphere resting stages drastically changed the surface-to-deep carbon isotope gradient (Kump, 1991) and led to an increase in carbonate saturation (Henehan et al., 2016). Pelagic calcifiers like planktic foraminifera and calcareous nannoplankton are a key component of the carbon cycle, exporting carbon in the form of $CaCO_3$ from the surface ocean to the seafloor, where it is buried. The extinction of so many marine calcifiers, and the smaller size of the survivors, led to the weakening of the marine "alkalinity pump" (Henehan et al., 2016), and the resulting oversaturation can be observed in a white layer that overlies the K-Pg boundary in 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 (Fig. 3) (IODP Sites 1209-1212; Bralower et al., 2002), and in the Chicxulub Crater itself (IODP Site M0077; Morgan et al., 2017).

Records from cores across the oceans indicate that the post-extinction recovery of export productivity (e.g., Hull and Norris, 2011) and calcareous plankton diversity (e.g., 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. Recovery appears to be slower in the North Atlantic and Gulf of Mexico (e.g., Alegret and Thomas, 2005;

Jiang et al., 2010; Hull and Norris, 2011), suggesting that distance from the crater correlates to slower recovery. Some authors (e.g., Jiang et al., 2010) attributed this to direct environmental effects of the impact, such as perhaps the uneven distribution of toxic metals in the oceans. If this is true, then the recovery from the K-Pg mass extinction is driven by impact-specific processes and thus can only be used to understand impact-driven extinctions (i.e., just the K-Pg). If recovery is slower closer to the crater, then it should be slowest in the crater itself. However, recent drilling within the Chicxulub crater has shown a rapid recovery of life there, with planktic and benthic organisms appearing within just a few years of the impact and a healthy, high productivity ecosystem established within 30 kyr of the impact, much faster than other Gulf of Mexico and N. Atlantic sites (Lowery et al., 2018). This rules out an environmental driver for heterogeneous recovery and instead suggests that natural ecological factors like incumbency and competitive exclusion (e.g., Hull et al., 2011; Schueth et al., 2015) governed the recovery of the marine ecosystem. The recovery of diversity took millions of years to even begin to approach Cretaceous levels (Coxall et al., 2006; Bown et al., 2004; 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 associated with climate change, over fishing, hypoxia, etc. subside.

5 Unique Insight into the Chicxulub Crater

Joint IODP-ICDP Expedition 364 drilled into the peak ring of the Chicxulub impact crater in 2016 at Site M0077 (Morgan et al., 2017). Peak rings are rings of 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). Two hypotheses, developed from the observation of craters on other planets, proposed explanations of the process by which peak rings form. The first, the dynamic collapse model (first put forward by Murray, 1980) would predict 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), would predict 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 seeing what kind of rock comprises the peak ring. Geophysical data acquired prior to drilling indicate that there are sedimentary rocks several kilometers beneath the peak ring at Chicxulub, 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). Site M0077 sampled the peak ring at Chicxulub to study the rocks that compose them, determine their physical state, better constrain the kinematics and dynamics of large crater formation, and further understand the mechanism by which rocks are weakened to allow bowl-shaped transient cavities to collapse and form relatively wide, flat craters (Gulick et al., 2017).

Immediately after impact the peak ring was located adjacent to a thick sheet of impact melt and Chicxulub was inundated with sea-water (Gulick et al., 2008, *in prep*). Thus, intense hydrothermal activity within the peak ring is expected, which may have been associated with mineralization and/or provided a niche for life forms, in a similar way to oceanic hydrothermal vent systems (Abramov and Kring, 2007). Therefore, cores collected during Expedition 364 can be used to address key questions about the potential habitability of large impact craters, an important analog for early life on Earth. High microbe cell counts and DNA have been found in the peak-ring rocks, demonstrating that the crater currently provides a habitat for a deep biosphere (Cockell et al., *submitted*).

Site M0077 (Fig. 4) was drilled on the outer edge of the peak ring in a small topographic valley where the uppermost peak-ring rocks are formed from a relatively thick (100-150 m) sequence of material with an unusually low seismic velocity (Morgan et al., 2011; Gulick et al., 2017). This site was selected in order to maximize the chance of recovering the earliest Paleocene, obtain a thick section of the low-velocity material that was thought to be impact breccia, and sample several hundred meters of rocks that form the upper peak ring. Coring started at ~500 meters below sea floor (mbsf) and ~110 m of Paleogene sedimentary rocks were recovered before encountering the top of the peak ring, where an unusual 80-cm thick transitional unit lies above a ~130-m thick sequence of suevite (impact melt bearing breccia) and impact melt rocks. Granitoid basement rocks with pre- and post-impact dykes and suevitic intercalations were encountered from ~748 mbsf to the bottom of the hole at 1335 mbsf (Morgan et al., 2016; 2017).

The discovery that the peak ring was formed from fractured, shocked, uplifted basement rocks supports the dynamic collapse model of peak-ring formation (Morgan et al., 2016; Kring et al., 2017). Structural data from the 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., *in review*). 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 new estimates on the release of climatic gases by the Chicxulub impact. Previous models estimated 100 Gt of sulfur (which formed sulfate aerosols in the atmosphere, blocking incoming solar radiation) were released by the impact, which resulted in a 26°C drop in global temperatures (Brugger et al., 2017); new models indicate that between 195 and 455 Gt of sulfur were released, suggesting even more radical cooling during the impact winter (Artemieva et al., 2017).

6 New Challenges

The scientific community's understanding of the Chicxulub impact event and the K-Pg mass extinction has grown immensely since Alvarez et al. (1980) first proposed the impact hypothesis, and many of the advances were the direct result of new 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, understand geographic patterns of recovery and what drives them. Site U1514, on the Naturaliste Plateau on the SW Australian margin (Fig. 2), was drilled in 2017 on Expedition 369 (Huber et al., 2018) and 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, it is sure to provide a new perspective on a number of existing questions.

New data from the Chicxulub Crater have resulted in refined impact models that suggest that the asteroid impacted towards the southwest (Collins et al., 2017) which contrasts 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 on Fig. 2). New drilling on seamounts and rises on the furthest east Cretaceous crust in the eastern equatorial Pacific would shed new light on the environmental and biological consequences of being downrange of the Chicxulub Impact.

Finally, the Chicxulub structure remains an important drilling target to address questions that can only be answered at the K-Pg impact site. Two particular locations will likely bring the greatest return: the annular trough and the central basin. 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 (Fig. 4) providing a potentially exciting opportunity to study the return of life to the impact crater at an even higher resolution than presented in Lowery et al. (2018). Additionally, Expedition 364 has raised new questions as to the quantity of sulfur-rich evaporites that remained in the impact crater as opposed to being vaporized and released to the global environment through the vapor plume (Gulick et al., *in prep*). The sedimentary target rock is 30-50% evaporites yet virtually none were recovered at Site M0077; thus, it is key to have continuous coring within an expanded Paleocene section and the underlying impactites to better constrain climatologic inputs at the onset of the Cenozoic.

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 (Fig. 4) give tantalizing suggestions of vertical flux in the form of morphologic complexities between the high-velocity melt sheet and overlying low velocity suevite layer, which are tempting to interpret as hydrothermal vents, of the kind often seen at mid-ocean ridges. Drilling into the Chicxulub melt sheet is ideal to study the hydrogeology and geomicrobiology of terrestrial impact melt sheets buried by breccias as a habit for subsurface life, providing an opportunity for scientific ocean drilling to sample the best analog for the habitat in which life may have formed on early Earth and on rocky bodies across the solar system and beyond.

The success of the cooperation between IODP and ICDP during Expedition 364 should serve as a model for future drilling in the Chicxulub crater as well as future Mission Specific Platform (MSP) expeditions. The onshore Yaxcopil-1 borehole unexpectedly encountered a Cretaceous megablock because it were essentially drilling blind, with only the regional magnetic and gravity anomaly maps to guide it. High-quality marine seismic data from offshore portion of the Chicxulub crater (Morgan et al., 1997; Gulick et al., 2008; Christeson et al., 2018) allowed for a detailed characterization of the subsurface before drilling even 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 sediments which provided the basis for unprecedented study of this unique interval at ground zero (Lowery et al., 2018; Gulick et al., *in prep* and several other 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 (Exp. 364 achieved essentially 100% recovery; Morgan et al., 2017).

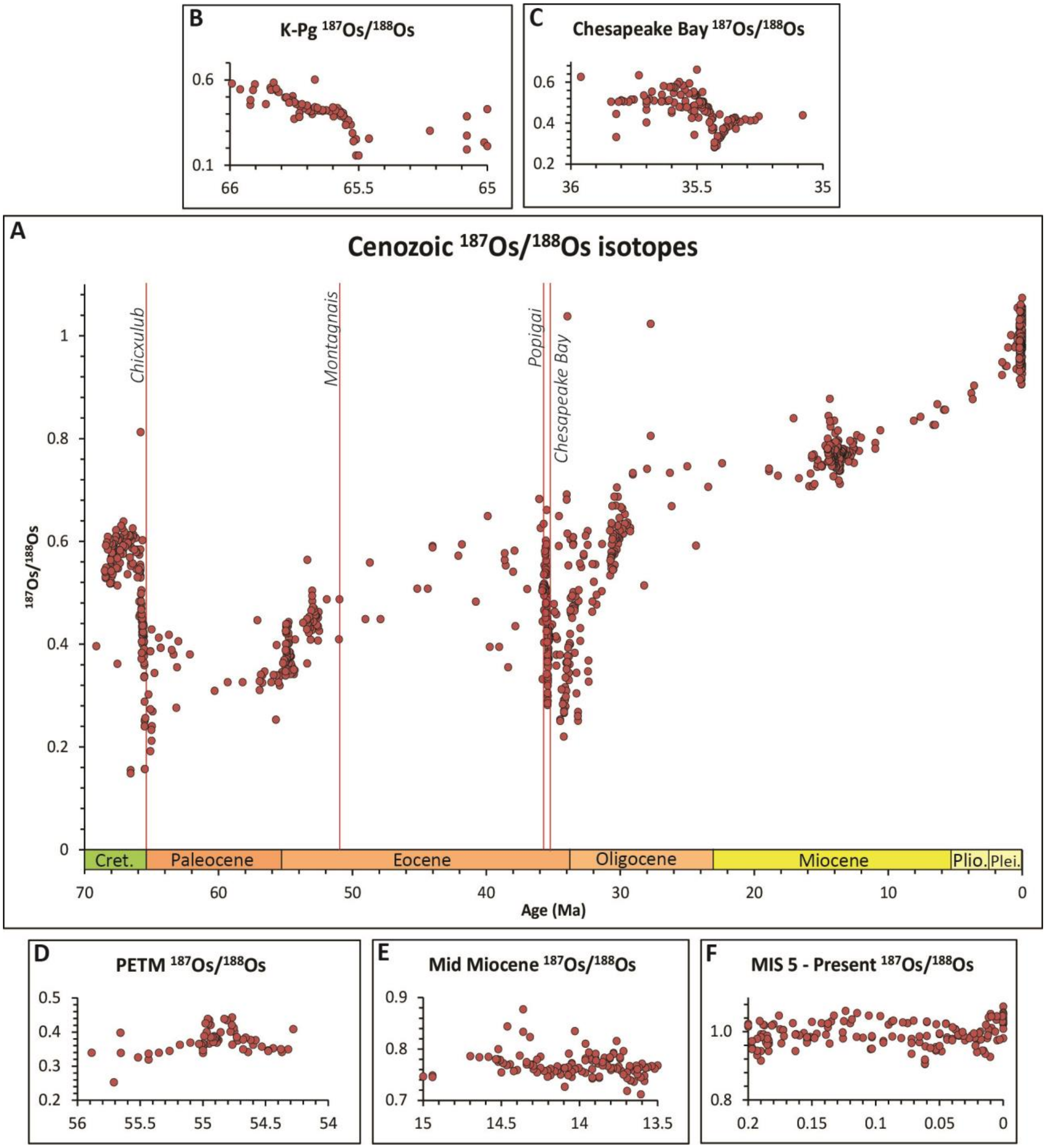

Fig. 1 Marine osmium isotopes through the Cenozoic **(a)**, after Peucker-Ehrenbrink and Ravizza (2012). These data, the majority of which come from DSDP/ODP/IODP cores, record the long-term trend toward more radiogenic (i.e., continental-weathering derived) $^{187}Os/^{188}Os$ ratios in the ocean throughout 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 the Chicxulub impact **(b)** and Chesapeake

Bay impact **(c)**. Other intervals for which impacts have been proposed as important drivers of observed paleoclimatic change lack the diagnostic negative excursion, including the Paleocene Eocene Thermal Maximum **(d)**, Miocene Climate Transition **(e)**, and Younger Dryas **(f)**. Red lines are well-dated large (>35 km crater diameter) impacts, after Grieve (2001).

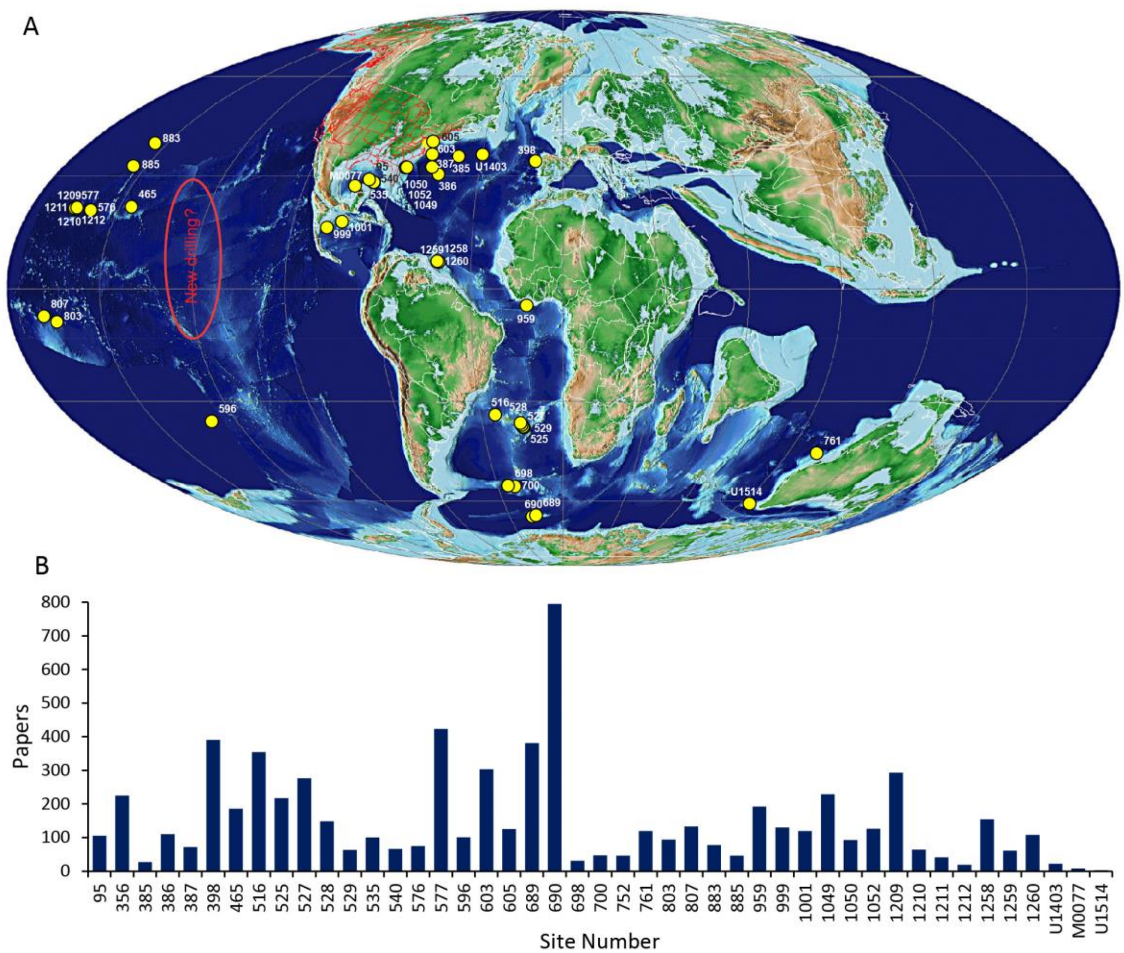

Fig. 2 a) Map of DSDP/ODP/IODP Sites which recovered the K-Pg boundary. Basemap is adapted from the PALEOMAP Project (Scotese, 2008) **b)** Number of K-Pg papers by site, according to Google Scholar as of July 5, 2018. As anyone who's looked up a paper on Google Scholar will recognize, there are some caveats with these data (e.g., inclusion of papers which match the search terms but are not strictly about the K-Pg, papers that are missing because they are not cataloged by Google Scholar, etc.). However, this is a good approximation of the reams of articles that have been written about the K-Pg from DSDP, ODP, and IODP cores, and the clear impact (sorry) of scientific ocean drilling on the K-Pg literature. n = 6797, but includes duplicates from papers which cover multiple sites. Search term: "Cretaceous AND Tertiary OR Paleogene OR Paleocene AND 'Site ###'".

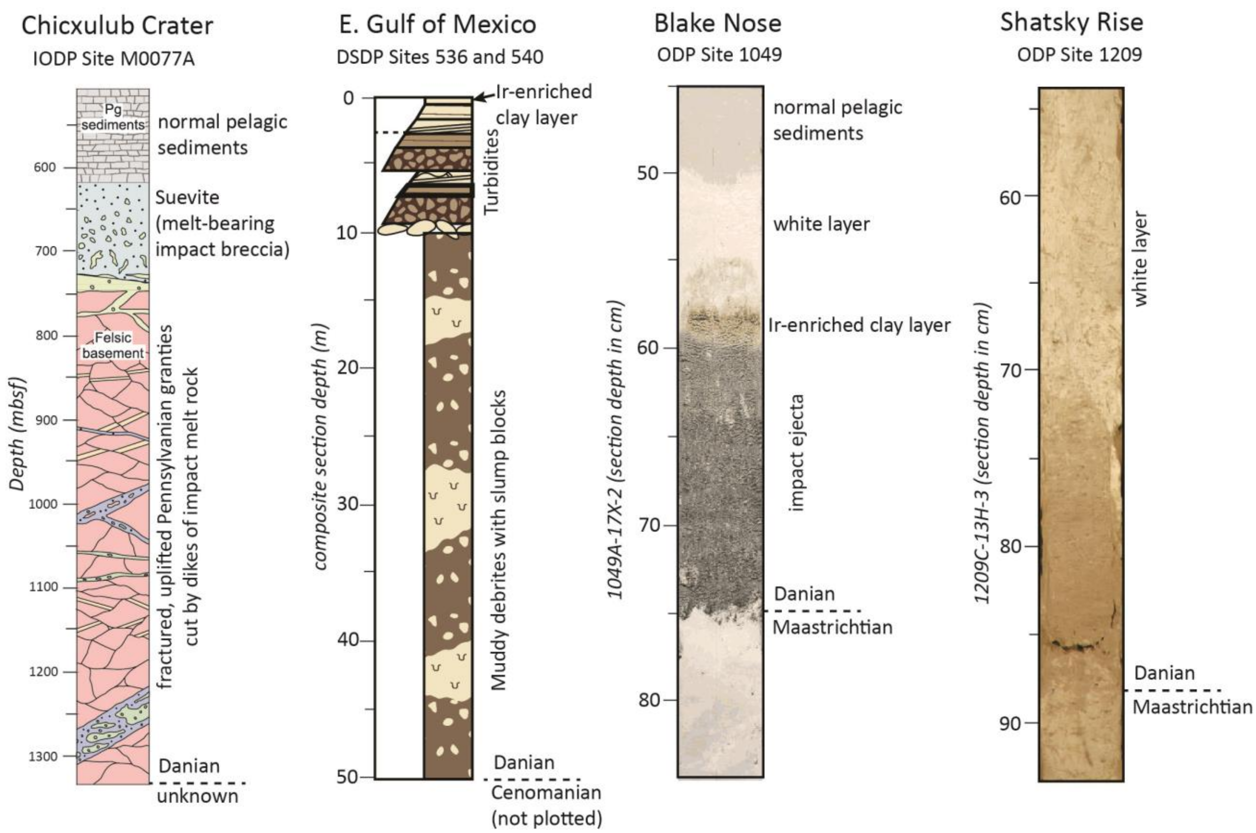

Fig. 3 Representative K-Pg boundary sections from scientific ocean drilling cores. Chicxulub crater is redrawn from Morgan et al. (2016), eastern Gulf of Mexico is redrawn from Sanford et al. (2016), Blake Nose and Shatsky Rise core photographs are from the Janus database.

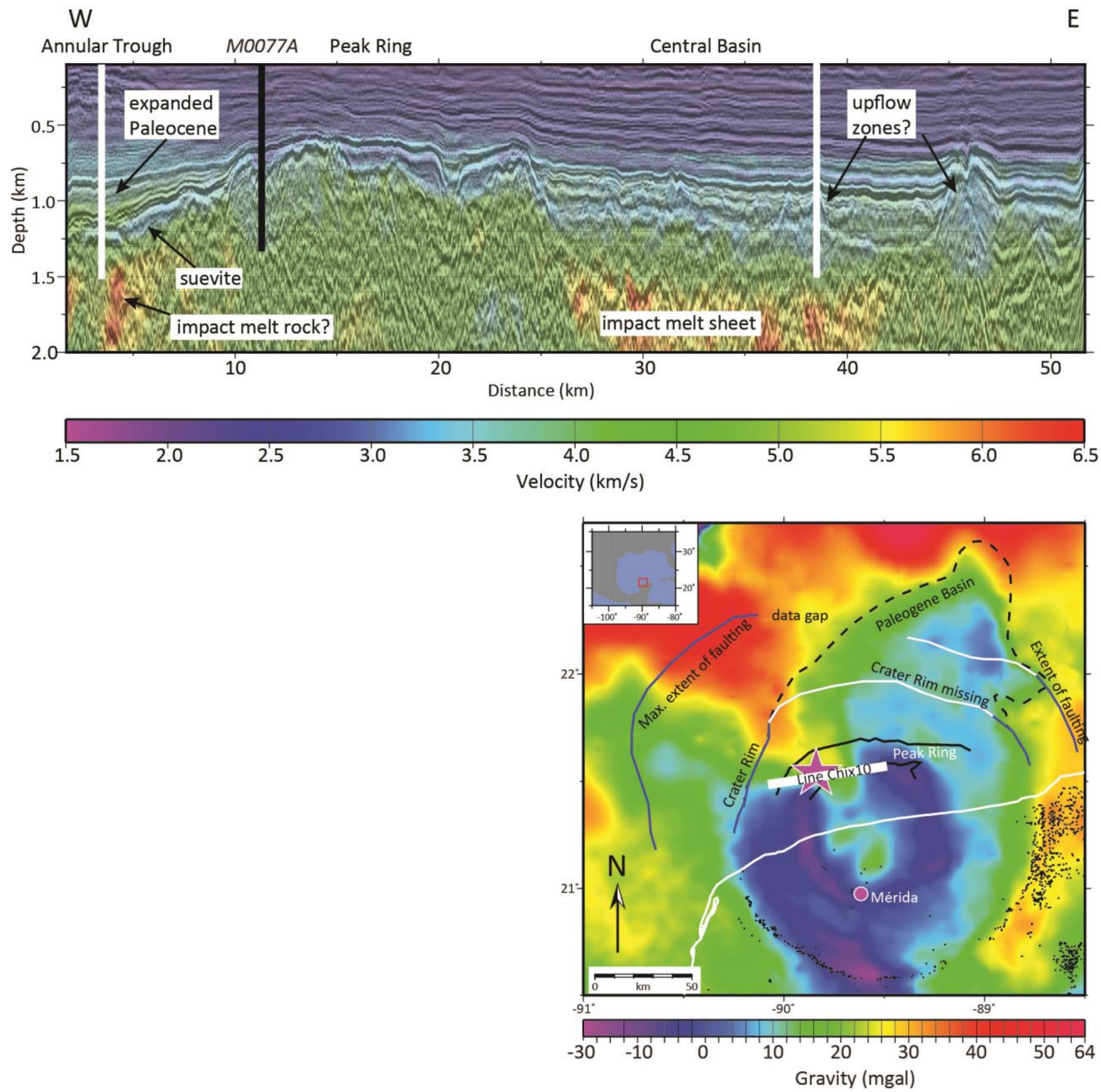

Fig. 4 (a) Full wavefield inverted (FWI) velocity model (colors) and migrated seismic reflection image for profile CHIX 10 crossing site M0077 (black line). The seismic image has been converted to depth using the inverted velocity model. Potential sites for future drilling are shown with white lines. 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).

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