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Iridium profiles and delivery across the Cretaceous/Paleogene boundary

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ABSTRACT

We examined iridium (Ir) anomalies at the Cretaceous/Paleogene (K/Pg) boundary in siliciclastic shallow marine cores of the New Jersey Coastal Plain, USA, that were deposited at an intermediate distance (~2500 km) from the Chicxulub, Mexico crater. Although closely spaced and generally biostratigraphically complete, the cores show heterogeneity in terms of preservation of the ejecta layers, maximum concentration of Ir measured (~0.1–2.4 ppb), and total thickness of the Ir-enriched interval (11–119 cm). We analyzed the shape of the Ir profiles with a Lagrangian particle-tracking model of sediment mixing. Fits between the mixing model and measured Ir profiles, as well as visible burrows in the cores, show that the shape of the Ir profiles was determined primarily by sediment mixing via bioturbation. In contrast, Tighe Park 1 and Bass River cores show post-depositional remobilization of Ir by geochemical processes. There is a strong inverse relationship between the maximum concentration of Ir measured and the thickness of the sediments over which Ir is spread. We show that the depth-integrated Ir inventory is similar in the majority of the cores, indicating that the total Ir delivery at time of the K/Pg event was spatially homogeneous over this region. Though delivered through a near-instantaneous source, stratospheric dispersal, and settling, our study shows that non-uniform Ir profiles develop due to changes in the regional delivery and post-depositional modification by bioturbation and geochemical processes.

1. Introduction

The discovery of anomalously high abundance of iridium (Ir) and other platinum group elements (PGEs) at the Cretaceous/Paleogene (K/Pg) boundary led to the hypothesis that the Earth was impacted by an ~8–10 km diameter asteroid, causing severe environmental disturbance (Alvarez et al., 1980; Smit and Hertogen, 1980). The impact hypothesis was supported by the subsequent discovery of shocked minerals (Bohor et al., 1987), impact spherules, and Ni-rich spinels (Smit and Kyte, 1984). Discovery of the buried Chicxulub crater, ~180–200 km in diameter in Yucatan Peninsula, Mexico (Hildebrand et al., 1991) also substantiated that the source of Ir and other PGEs is extraterrestrial.

An extraterrestrial source is not the only means of yielding high Ir concentrations at the K/Pg boundary. Deccan flood basalts in modern-day India spanning the K/Pg boundary have been suggested as a source for the Ir anomalies at the boundary (Officer and Drake, 1985). Emplacement of Deccan basalts took ~600 kyr primarily during Chron C29r (Courtillot et al., 1986). Previous studies have suggested that the main pulse began ~340 kyr prior to the K/Pg boundary (Robinson et al., 2009), and ended at the K/Pg boundary (Chenet et al., 2007; Keller et al., 2008), though more recent studies suggest the largest pulse began at about the time of the boundary (Renne et al., 2015) or 250 kyr before the boundary (Schoene et al., 2015). The suggestion that the origin of anomalies in Ir and other platinum group elements (PGEs) are volcanic rather than extraterrestrial has been challenged by mea-

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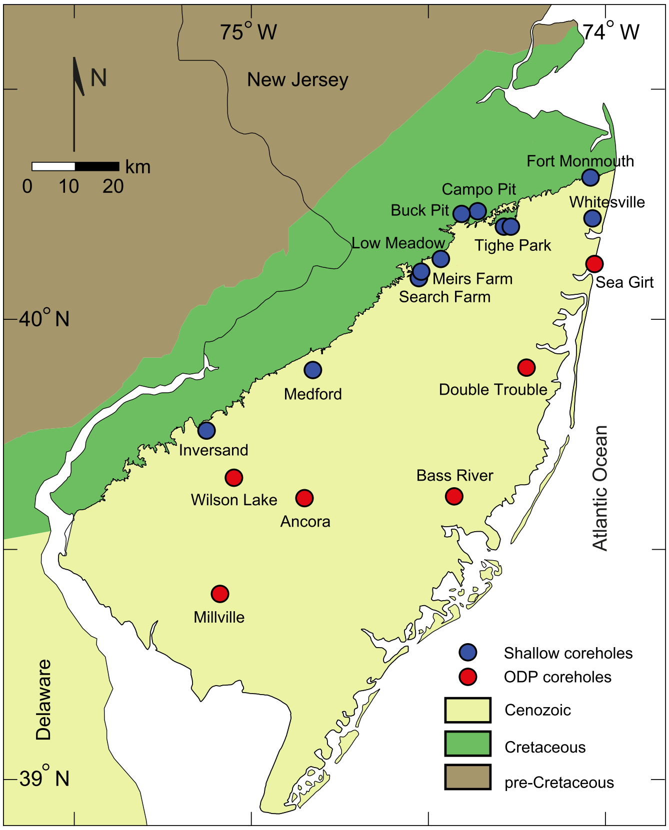

Fig. 1. Geological map of the New Jersey Coastal Plain showing coreholes that sampled the K/Pg boundary. ODP Leg 174AX and ODP Leg 150X cores are shown as red circles. Shallow cores are shown in blue circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

surements of sedimentary PGE ratios, showing similarity to those of meteorites rather than terrestrial basalts (Evans and Chai, 1997; Evans et al., 1993; Koeberl, 2002). In addition, Sawlowicz (1993) and Shukla et al. (2001) proposed that the contribution of Deccan basalts was too small and local to explain the global inventory of Ir at the K/Pg boundary.

Iridium anomalies, mostly associated with ejecta layers (Smit, 1999; Schulte et al., 2010), have been recorded in more than 85 K/Pg boundary sites globally (Claeys et al., 2002; Schulte et al., 2010). The global occurrence of an Ir anomaly suggests that dust and vapor from the impacting bolide and target rock rich in high-PGE meteoritic material were transported to the stratosphere creating a homogeneous cloud encircling the Earth. Then, Ir-rich material settled down from the atmosphere on scales of months (Toon et al., 1982) and slowly settled through the water column (Claeys et al., 2002).

Outside the Gulf of Mexico, i.e., in the intermediate and distal sites from the Chicxulub crater, there is no correlation between the peak Ir concentration and distance from the impact site (Claeys et al., 2002). The original Ir-rich deposits can be redistributed due to remobilization by sedimentary processes including bioturbation and geochemical remobilization that can account for the site to site differences in Ir concentrations (Sawlowicz, 1993; Claeys et al., 2002), as well as the shape of the Ir anomaly profiles (Hull et al., 2011). In some K/Pg boundary sites the Ir anomaly is concentrated in a thin (~1 cm) interval, whereas at other locations it spreads over as much as several meters of section (Smit, 1999; Claeys et al., 2002). Even geographically close sites show different maximum concentrations of Ir and/or different thicknesses over which the Ir enrichment is spread.

The New Jersey Coastal Plain (NJCP) contains a record of the K/Pg extinction (Olsson, 1960), Ir anomaly, and spherules in both outcrops and in cores (Olsson, 1987; Landman et al., 2007; Miller et al., 2010; Esmeray-Senlet et al., 2015; Vellekoop et al., 2016). Shallow cores (<25 m) drilled adjacent to outcrops of the K/Pg boundary localities (Buck Pit 1, Tighe Park 1, Search Farm 1, Meirs Farm 1, Inversand, and Fort Monmouth 3) and deeper cores drilled onshore by Ocean Drilling Program (ODP) 174AX (Ancora, Double Trouble, and Bass River) provide important constraints on the impact-related features across the K/Pg boundary (Fig. 1). Previously, a 6-cm-thick spherule layer immediately above the K/Pg boundary was reported at Bass River with reworked clay clasts and an Ir peak of 2.4 ppb (Olsson et al., 1997). Landman et al. (2007) reported a ~0.5 ppb Ir anomaly from an outcrop section from Tighe Park, Freehold, NJ below a 20-cm thick bed containing Cretaceous markers. Miller et al. (2010) documented Ir anomalies at Buck Pit 1, Tighe Park 1, Search Farm 1, Meirs Farm 1, and Bass River to investigate the stratigraphic relationship between the Ir anomalies and the extinction level. Updip sites yield lower Ir anomaly peak concentration (~0.5 ppb) compared to the downdip Bass River site and each core shows a different shape of Ir profile, despite being deposited in close proximity.

We conducted additional Ir measurements in the Ancora, Double Trouble, Inversand, and Fort Monmouth 3 sites (Fig. 1) in order to quantify Ir concentrations and investigate potential Ir mobility in the New Jersey sections. Here we address two main questions combining new data with the previous results. First, how did vertical redistribution of Ir by sedimentary processes like bioturbation or geochemical remobilization affect the shape of Ir profiles in the NJCP cores, deposited in shallow marine settings at intermediate distances (~2500 km) from the Chicxulub crater? Second, could the variations in peak Ir anomaly concentrations in NJCP cores, ranging from low to moderate, be attributed to bioturbation, geochemical remobilization, redeposition, or simply concentrations of background values? We analyze the shape of Ir profiles by modeling Ir anomalies under a range of mixing conditions with a Lagrangian advection–diffusion sediment mixing model (Hull et al., 2011) and compare the mixing model parameters with physical observations in the cores. In order to place these Ir profiles in a biostratigraphic context, we combine published planktonic foraminiferal and organic-walled dinoflagellate data with additional palynological analyses on Tighe Park 1, Buck Pit 1, and Inversand. Finally, we evaluate the similarities and differences in depth-integrated anomalies (total vertical accumulation) among the NJCP cores, and discuss the relevance of this quantity relative to the more-frequently-used peak Ir concentrations.

2. Analytical techniques

Concentrations of Ir were measured using Sector Field Inductively Coupled Plasma Mass Spectrometry at the Institute of Marine and Coastal Sciences, Rutgers University. Pre-concentration and isolation of Ir from the sediment samples were carried out using a NiS fire-assay technique modified after Ravizza and Pyle (1997). In this method, sediment samples were dried at 105 °C overnight, and ~1 g subsample was finely ground and homogenized using an acid-cleaned agate mortar and pestle. The resulting powder was then mixed with pure Ni powder and sublimed sulfur (2:1 mass ratio), borax (2:1 ratio to sediment mass), and a ^{191}Ir enriched isotope spike prepared in 6.2N HCl and calibrated against an independent NIST-traceable certified ICP-MS primary Ir standard solution (High-Purity Standards). This mixture is then heated to 1000 °C in a muffle furnace for 75 min to allow fusion. After fusion and rapid cooling, the glassy sample was broken to release a bead of NiS containing scavenged Ir. Beads are then dissolved in 6.2N HCl at 190–200 °C on a hot plate until H_2S evolution stops, then

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