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Fragments of Late Eocene Earth-impacting asteroids linked to disturbance of asteroid belt

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ABSTRACT

The onset of Earth's present icehouse climate in the Late Eocene coincides with astronomical events of enigmatic causation. At ∼36 Ma ago the 90–100 km large Popigai and Chesapeake Bay impact structures formed within ∼10–20 ka. Enrichments of ^{3}He in coeval sediments also indicate high fluxes of interplanetary dust to Earth for ∼2 Ma. Additionally, several medium-sized impact structures are known from the Late Eocene. Here we report from sediments in Italy the presence of abundant ordinary chondritic chromite grains (63–250 μm) associated with the ejecta from the Popigai impactor. The grains occur in the ∼40 cm interval immediately above the ejecta layer. Element analyses show that grains in the lower half of this interval have an apparent H-chondritic composition, whereas grains in the upper half are of L-chondritic origin. The grains most likely originate from the regoliths of the Popigai and the Chesapeake Bay impactors, respectively. These asteroids may have approached Earth at comparatively low speeds, and regolith was shed off from their surfaces after they passed the Roche limit. The regolith grains then settled on Earth some 100 to 1000 yrs after the respective impacts. Further neon and oxygen isotopic analyses of the grains can be used to test this hypothesis.

If the Popigai and Chesapeake Bay impactors represent two different types of asteroids one can rule out previous explanations of the Late Eocene extraterrestrial signatures invoking an asteroid shower from a single parent-body breakup. Instead a multi-type asteroid shower may have been triggered by changes of planetary orbital elements. This could have happened due to chaos-related transitions in motions of the inner planets or through the interplay of chaos between the outer and inner planets. Asteroids in a region of the asteroid belt where many ordinary chondritic bodies reside, were rapidly perturbed into orbital resonances. This led to an increase in small to medium-sized collisional breakup events over a 2–5 Ma period. This would explain the simultaneous delivery of excess dust and asteroids to the inner solar system. Independent evidence for our scenario are the common cosmic-ray exposure ages in the range of ca. 33–40 Ma for recently fallen H and L chondrites.

The temporal coincidence of gravity disturbances in the asteroid belt with the termination of ice-free conditions on Earth after 250 Ma is compelling. We speculate that this coincidence and a general correlation during the past 2 Ga between K–Ar breakup ages of parent bodies of the ordinary chondrites and ice ages on Earth suggest that there may exist an astronomical process that disturbs both regions of the inner asteroid belt and Earth's orbit with a potential impact on Earth's climate.

1. Introduction and background

The Late Eocene, ∼37.8–33.9 Ma ago, was the time when Earth's climate changed into the present "icehouse" state after ∼250 Ma of "greenhouse" conditions. Although the major change in climate occurred at the Eocene–Oligocene boundary, an accel-

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erating cooling trend prevailed through the Late Eocene when also the first significant ice sheets on Antarctica formed (Vonhof et al., 2000; Zachos et al., 2001; Bodiselitsch et al., 2004; Lear et al., 2008; Scher et al., 2014; Villa et al., 2014). The Late Eocene was also a period with an enigmatic, enhanced flux of extraterrestrial matter to Earth. The evidence comes primarily from two very large and several medium-sized impact craters, as well as an interval in the sedimentary strata with high concentrations of extraterrestrial ^{3}He (e.g., Montanari et al., 1993; Farley et al., 1998; Glass and Koeberl, 1999; Whitehead et al., 2000; Koeberl, 2009; Kyte et al., 2011; Paquay et al., 2014). The Popigai crater in northern Siberia is 100 km in diameter and the largest known impact crater post-dating the Cretaceous–Tertiary boundary (Vishnevsky and Montanari, 1999; Whitehead et al., 2000; Koeberl, 2009). The second large astrobleme, Chesapeake Bay in the eastern US, is a structure with a diameter of 85–90 km, but the true crater is ∼40 km in diameter, with the larger size reflecting collapse of sediment structures (Poag et al., 2004; Kyte et al., 2011). This impact was thus considerably less energetic than the Popigai impact. The Chesapeake Bay and Popigai structures have radiometric ages of 35.5 ± 0.6 and 35.7 ± 0.2 Ma, respectively (Koeberl et al., 1996; Bottomley et al., 1997). The stratigraphic positions of the distal ejecta layers from the craters indicate that the impact events occurred within ∼10–20 ka (Koeberl, 2009). The ejecta layers occur in the middle part of the sedimentary interval enriched in extraterrestrial ^{3}He, reflecting a ∼2 Ma period of enhanced flux of small (<50 μm) interplanetary dust particles to Earth (Farley et al., 1998). Three well-dated, medium-sized craters with ages ∼40–35 Ma are Haughton, Mistastin, and Wanapitei (Koeberl, 2009), but there are also a number of craters with larger dating uncertainties of which some could be of Late Eocene age (Earth Impact Database, 2015).

The Late Eocene ^{3}He anomaly and associated impacts were originally proposed to reflect a comet shower from a random perturbation of the Oort comet cloud (Farley et al., 1998; Farley, 2009). This scenario was supposed to best explain the ∼2 Ma duration of the enhanced flux of fine-grained ^{3}He-rich dust to Earth. Also the simultaneous delivery of large projectiles and fine-grained interplanetary dust reconciles best with models for cometary events. An asteroid breakup was ruled out because following such an event the ejected dust moves directly to Earth by Poynting–Robinson drag, whereas the km-sized fragments need to drift into an orbital resonance before being redirected to an Earth-crossing orbit. Thus the km-sized asteroids will arrive on Earth typically several million years after the fine-grained dust (Zappalà et al., 1998). Tagle and Claeys (2004, 2005), however, challenged the comet scenario and suggested the breakup of an L-chondritic asteroid in the asteroid belt as an alternative source of Late Eocene ^{3}He and impactors. They based their claims on platinum-group element (PGE) analyses of melt rock in the Popigai crater (Tagle and Claeys, 2004, 2005), but more elaborated evaluation of the PGE data show that they may be consistent with any type of ordinary chondrite (i.e., H, L or LL) (Farley, 2009; Kyte et al., 2011). There are also other uncertainties around PGE signatures, related to element fractionation in the condensing impact plume or during sediment diagenesis (Schmitz et al., 2011). It has also been speculated that following an L-chondritic asteroid breakup, a shower of smaller asteroids to the Earth–Moon system ejected large amounts of ^{3}He-rich fine-grained lunar regolith that settled on Earth (Fritz et al., 2007). The most compelling data so far as to the causes of the Late Eocene events comes from Cr-isotopic analyses of distal ejecta from the Popigai crater (Kyte et al., 2011). These data constrain the origin of this impactor to be an ordinary chondritic asteroid. The authors speculated that the Popigai impactor and excess ^{3}He may be related to the breakup of the Brangäne asteroid, with an assumed H-chondritic composition. Based on astronomical observations this

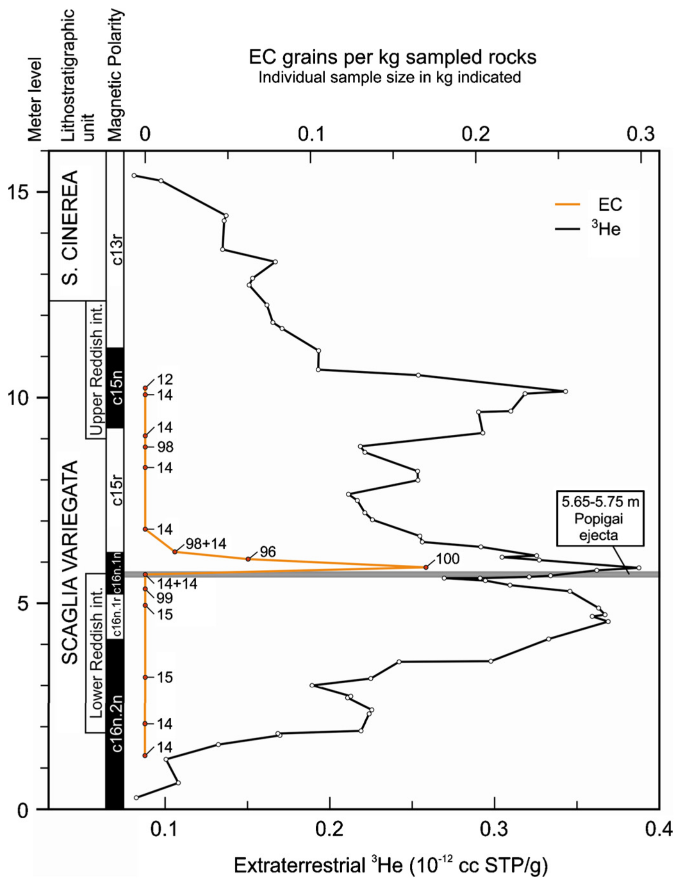

Fig. 1. Profiles for the Massignano section of extraterrestrial ^{3}He concentrations (black curve) (Farley et al., 1998) and the total number of recovered EC grains per kg sediment (orange curve) in this study and by Schmitz et al. (2009). Indicated in numbers on the latter curve are the masses in kilogram of the samples searched for EC grains. Magnetostratigraphy after Jovane et al. (2007).

body broke up at $\sim 50 \pm 40$ Ma (Nesvorný et al., 2005) and is the only major family-forming event involving an S-type (i.e. ordinary chondritic) asteroid that is a potential match for Late Eocene ^{3}He and impactors.

In a previous study we aimed at testing the hypothesis of a Late Eocene major L-chondrite breakup event by searching for L-chondritic chromite grains over the ^{3}He-rich interval in the pelagic sediments of the Massignano section in central Italy (Schmitz et al., 2009). This is the section where some of the most detailed studies of the Late Eocene extraterrestrial events have been performed, including the original reconstruction of the ^{3}He anomaly (Farley et al., 1998) (Fig. 1). A major breakup event in the Late Eocene would have given a chromite signature in the sediment similar to that following the breakup of the L-chondrite parent body in the mid-Ordovician 470 Ma ago (Schmitz et al., 2003; Schmitz, 2013). Slowly formed marine sediments from immediately after this event contain up to ten L-chondritic chromite grains (63–250 μm) per kg of sediment, attesting to a very high flux of L-chondritic matter to Earth. Chromite makes up ∼0.25% of ordinary chondrites and is the only common mineral in this meteorite type that survives weathering on Earth. In our previous study at Massignano we searched for chromite grains in 167 kg of rock from 12 levels within the 14 m stratigraphic range of the ^{3}He anomaly. We found only one ordinary chondritic chromite grain, arguing against a major breakup event similar to that in the mid-Ordovician. The single grain recovered occurred in a sample ∼45 cm above the Popigai ejecta layer. This finding prompted us to continue the search for extraterrestrial spinels, but at a higher resolution. Therefore, in the present study a total of 491 kg of