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Late Eocene impact craters and impactoclastic layers—An overview

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ABSTRACT

Multiple bolide impact events, possibly related to a comet or asteroid shower over a duration of ~2–3 m.y., may have played an important role in the deterioration of the global climate at the end of the Eocene. Upper Eocene marine sediments around the world contain evidence for at least two closely spaced impactoclastic layers, i.e., layers containing impact debris such as tektites and microtektites, shocked minerals, and rock fragments. The upper layer correlates with the North American tektite strewn field (mostly on the eastern side of North America), and the 85-km-diameter Chesapeake Bay crater (USA) has been suggested as its source crater, whereas the lower, microkrystite layer (with clinopyroxene-bearing spherules) was most likely derived from the 100-km-diameter Popigai impact crater (Russia). In summary, at least five impact structures with late Eocene ages are known. Disturbances in the climate at that time are documented, and connection with the impact events is likely. This contribution provides a short review of late Eocene impact craters and ejecta layers.

Keywords: late Eocene impacts, ejecta, Chesapeake Bay crater, Popigai crater, tektites.

INTRODUCTION

The late Eocene was a time interval of major changes characterized by an accelerated global cooling, with a sharp temperature drop of ~2 °C near the Eocene-Oligocene (E-O) boundary, and significant stepwise floral and faunal turnovers (see papers in this volume). These global climate changes, which are recorded by a gradual increase of marine oxygen isotope values and biotic crises, are commonly attributed to the expansion of the Antarctic ice cap following its gradual isolation from other continental masses. However, multiple bolide impact events documented from this time (e.g., Farley et al., 1998; Montanari and Koeberl, 2000, and references therein) may have played an important role in the deterioration of the global climate during the end of the Eocene Epoch (e.g., Vonhof et al., 2000; Bodiselitsch et al., 2004). It is clear, however, that the major climate change at the Eocene-Oligocene boundary, ~1.5 m.y. later, was most likely unrelated to the late Eocene impact events (e.g., Zanazzi et al., 2007; Katz et al., 2008; Miller et al., this volume). Also, the eruption of the Ethiopian Traps happened even later, in the early Oligocene (Touchard et al., 2002), and is thus completely unrelated to the late Eocene climate events.

There is abundant evidence for multiple impact events in the late Eocene, in terms of both impact craters and ejecta layers (Figs. 1 and 2). The first ejecta layer to be recognized was the North American tektite strewn field, with locations on or near the eastern part of the North American continent, which contains both tektites and microtektites (see following). Later, other (mostly recrystallized) microspherules of almost the same age were found in deep-sea sediments at a variety of locations around the world. Both layers were originally thought be in the middle to the early part of magnetic chron C15, although it now appears

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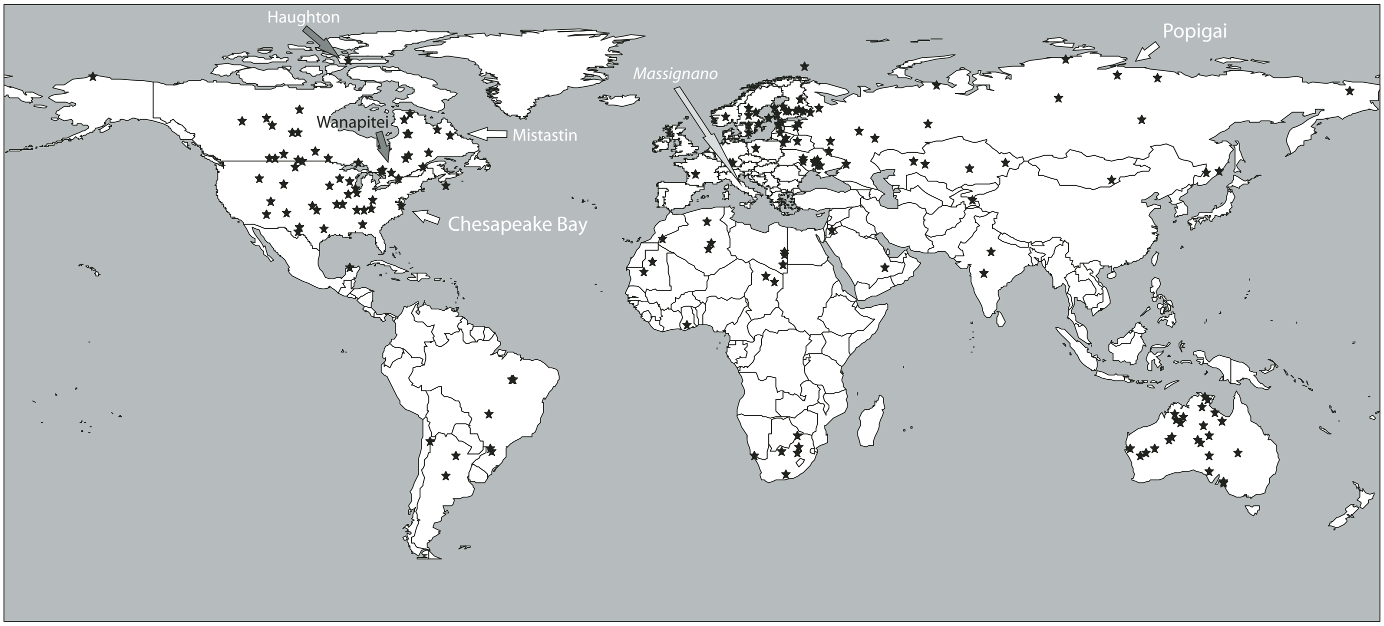

Figure 1. Late Eocene impact craters and structures (marked) on a global map of all well-documented craters and impact structures (crater coordinates modified from the Earth Impact Database at http://www.unb.ca/passc/ImpactDatabase/). Arrow points to the Eocene-Oligocene global stratotype section and point (GSSP) at Massignano, Italy.

that the older layer is in chron C16n. Some of these deposits have been known for much of the twentieth century but were only confirmed as being of impact origin within the past 40 yr or so. Research over the past 20 yr has led to the identification of source craters for these ejecta deposits. Thus, there are currently at least five impact craters known that are of late Eocene age, representing a relatively large number within a short time span. The two largest impact structures are Popigai, Russia, and Chesapeake Bay, USA, with respective diameters of 100 and 85 km, and there are several smaller craters with similar ages (see Fig. 3 for a time line). The present contribution provides a brief review of the late Eocene ejecta layers and coeval impact structures, and possible connections to environmental changes.

TEKTITES, MICROTEKTITES, AND MICROKRYSTITES

The North American tektite strewn field includes tektites found on land and microtektites found in deep-sea sediments. In this strewn field, tektites, which are glassy distal impact ejecta (cf. Koeberl, 1986, 1994, 2007) found on land, occur in two main areas, namely the bediasites in Texas, named after the town of Bedias, in the northeast corner of Grimes County, ~20 miles west of Huntsville, and the georgiaites in Georgia (e.g., Albin et al., 2000). In addition, two samples have been found in Cuba and Martha's Vineyard, respectively, but it is uncertain if these are genuine locations. In addition, tektite fragments were found underwater at Deep Sea Drilling Project (DSDP) Site 612 (see following), and microtektites were found on land at Barbados. Microtektites have been found in late Eocene marine sediments on Barbados and in sediment cores recovered from the Gulf of Mexico, Caribbean Sea, and northwestern Atlantic Ocean (e.g., Glass and Zwart, 1979; Glass et al., 1985, 1998; Sanfilippo et al., 1985; D'Hondt et al., 1987; Keller et al., 1987; Glass, 2002). On the basis of stratigraphic, compositional, isotopic, and age data, they were identified to be part of the North American tektite field. Chemical analyses (Koeberl and Glass, 1988), Sr and Nd isotopic studies (Ngo et al., 1985), and age data (Glass et al., 1986) showed that, without doubt, the Barbados tektites are North American tektites. From their Rb-Sr/Sm-Nd isotopic studies, Shaw and Wasserburg (1982) concluded that the source rocks from which the North American tektites were derived was crustal material that formed very late in the Precambrian (Sm-Nd model age = 0.62–0.67 Ga), which excludes most of the Precambrian shield areas of North America as well as sediments derived from these areas. The Rb-Sr data are in agreement with derivation from a sedimentary source rock.

The North American microtektites are associated with unmelted impact ejecta including shocked quartz and feldspar with multiple sets of planar deformation features, coesite, stishovite, and reidite (a high-pressure polymorph of zircon) (Glass, 1989; Glass and Wu, 1993; Glass et al., 1998; Glass and Liu, 2001). In 1987, microtektites, tektite fragments, and impact debris were discovered in a relatively thick layer in a core at DSDP Site 612 (e.g., Thein, 1987). The chemical composition of the DSDP Site 612 tektites and microtektites is similar to that of other North American tektites, but there are some important differences, e.g., lower Na and higher K contents in the 612 tektites (Koeberl and

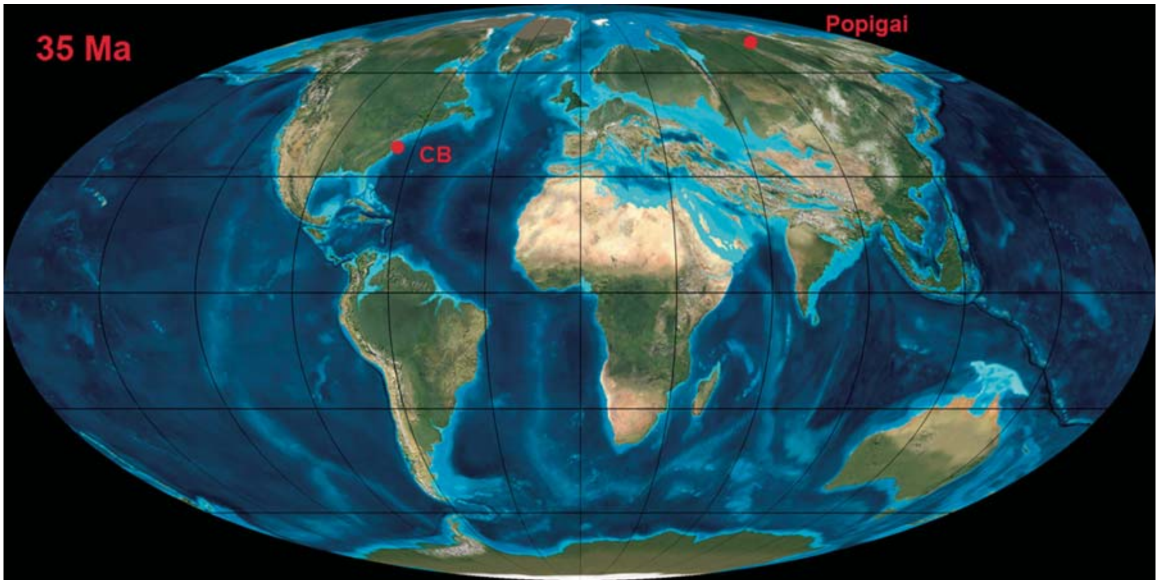

Figure 2. Paleogeographic reconstruction of the plate tectonic setting at 35 Ma (from http://jan.ucc.nau.edu/~rcb7/35moll.jpg; for explanation: http://jan.ucc.nau.edu/~rcb7/globaltext2.html), around the time of formation of the late Eocene impact craters. The locations of the Chesapeake Bay (CB) and Popigai impact structures are indicated.

Glass, 1988). Stecher et al. (1989) found that the Rb-Sr/Sm-Nd isotopic composition of the 612 tektites shows a much wider scatter than that of the North American tektites (but they may still be on a mixing line with the other tektites). Radiometric dating of the DSDP 612 and Barbados tektite fragments indicated an age of ca. 35 Ma for this layer (Glass et al., 1986; Obradovich et al., 1989). This age is consistent with the fission-track, K-Ar, and ^{40}Ar-^{39}Ar ages obtained for the North American tektites (e.g., Zähringer, 1963; Storzer and Wagner, 1971; Albin and Wampler, 1996). The Chesapeake Bay structure has been suggested to be the source of this strewn field based on geographic location, age, composition, and isotopic data (Poag et al., 1994; Koeberl et al., 1996) (see next section for more detailed discussion).

Clinopyroxene-bearing spherules (cpx spherules; microkrystites) are closely associated with the North American microtektites at some locations. Thus, occurrences of cpx spherules in the Indian Ocean and equatorial Pacific were originally interpreted to indicate a major extension of the North American strewn field. However, at a few sites, it is clear that the cpx spherules are slightly older than the North American microtektites, and it is now accepted that they belong to a different impact event. By now, it is clear that the late Eocene microkrystite layer occurs at numerous sites around the world and may be global in geographic extent (Glass et al., 1985, 1998; Keller et al., 1987; Vonhof and Smit, 1999; Glass and Koeberl, 1999a, 1999b; Glass, 2002; Liu et al., 2006). In locations where the North American microtektite layer is present, the cpx spherule layer occurs just below it, but in many cases, the two layers overlap. Based on biostratigraphic data, the cpx spherule layer appears to be ~10–20 k.y. older than the North American microtektite layer (Glass et al., 1998), although a shorter time interval of ~5000 yr is also possible (Glass and Koeberl, 1999a). In the cpx spherules, the most abundant crystalline phase is clinopyroxene, but Ni- and Cr-rich spinel crystals are also present in many of the spherules (e.g., Glass et al., 1985; Glass and Burns, 1987). The cpx spherule layer is, in some cases, associated with an enrichment if the element Ir (e.g., Glass et al., 1985; Keller et al., 1987; Vonhof and Smit, 1999; Kyte and Liu, 2002) and with the extinction of several species of radiolaria (Glass et al., 1985; Sanfilippo et al., 1985). Both the microtektites from the North American strewn field and microkrystites from the cpx-strewn field have major- and trace-element compositions that are close to those of the upper continental crust (e.g., Koeberl and Glass, 1988; Glass et al., 2004a).

Based on similarity in age and Sr and Nd isotopic compositions, it has been suggested (e.g., Whitehead et al., 2000; Deutsch and Koeberl, 2006) that the source crater for the cpx spherule layer may be the 35.7 ± 0.8 Ma (Bottomley et al., 1997), 100-km-diameter Popigai impact crater in northern Siberia. Additional evidence for Popigai as the source of the cpx spherules is found at the Eocene-Oligocene global stratotype section and point (GSSP) at Massignano, Italy, where at the 5.61 m level, shocked quartz and pancake-shaped smectite spherules containing Ni- and Cr-rich spinel crystals are associated with a positive Ir anomaly in late Eocene deposits that have the same age, as far as can be determined, as the cpx spherule layer (Montanari et al., 1993; Clymer et al., 1996; Pierrard et al., 1998). The pancake spherules appear to be diagenetically altered and flattened cpx spherules (Glass et al., 2004b). Langenhorst (1996) suggested that the nature of the shocked quartz is consistent with derivation of this layer (and thus the cpx spherules) from the Popigai

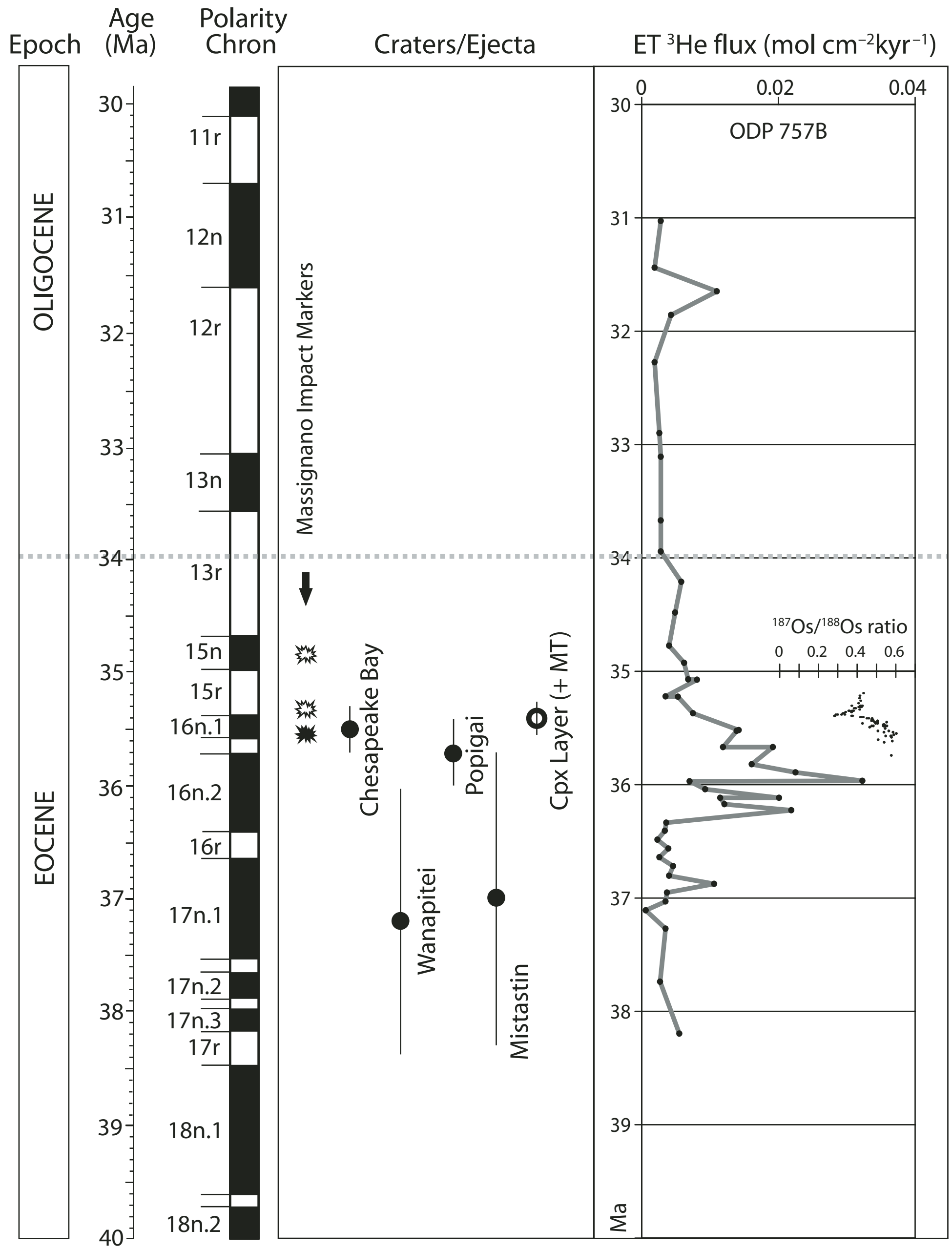

Figure 3. Time line for the late Eocene impact record. Polarity chrons are based on Cande and Kent (1995) and updated after Coccioni et al. (2008; and this volume) and Hilgen and Kuiper (this volume). Preferred age of Eocene-Oligocene boundary is after Coxall et al. (2005), Brown et al. (this volume), Hilgen and Kuiper (this volume), and Hyland et al. (this volume). Data for extraterrestrial ^{3}He are plotted from age-adjusted data in Farley et al. (2006). Crater ages (solid symbols) are from Winzer et al. (1976), Poag and Aubry (1995), Koeberl et al. (1996), Bottomley et al. (1997), Sherlock et al. (2005, 2006), and S. Kelley (2008, personal commun.). Distal ejecta–microkrystite spherule layer (cpx layer, open symbol) age is from Liu et al. (this volume). The age of the North American microtektites ("MT") is indistinguishable from the age of the cpx spherule layer on this scale. Impact markers at Massignano (open symbol: only Ir anomaly; solid symbols: Ir anomaly plus other impact evidence) are from Bodiselitsch et al. (2004) and Coccioni et al. (this volume). In addition, the Os isotopic compositions of deep-sea sediments from Ocean Drilling Program (ODP) Site 1090 are shown (Paquay et al., 2008). Due to differences in the polarity chron measurements at different locations, it is not easy to correlate the stratigraphic positions of the various impact markers across the world. In the case of Massignano, the temporal location of the closely spaced impacts is in lowermost part of foraminiferal zone E15, across the short transitional interval between C16n2 and C16n1 (A. Montanari, 2008, personal commun.).

crater. At Massignano, a second Ir anomaly exists just above the one that is correlative with the pancake spherules, which might be associated with the North American strewn field (Montanari et al., 1993; Montanari and Koeberl, 2000). This second Ir anomaly at Massignano was confirmed by Bodiselitsch et al. (2004). The age of the 5.61 m Ir anomaly was determined to be 35.7 ± 0.4 Ma, by interpolation from several dated volcanic ashes found in the same section (cf. Montanari and Koeberl, 2000). According to the astrochronologic calibration by Brown et al. (this volume), which indicates a mean sedimentation rate for the Massignano section of 8.7 m/m.y., the second Ir peak at 6.19 m would have followed the previous by some 90,000 yr (i.e., close to a short eccentricity cycle), which is a significantly larger time difference than the 5000–20,000 yr of separation estimated between the North American microtektites and the cpx-spherule layer at North American deep-sea sediment sites.

The number of late Eocene microtektite/spherule layers has been a matter of debate, with estimates ranging from two (Glass et al., 1985; Glass and Burns, 1987), to three (Keller et al., 1987), to six or more (Hazel, 1989). Most of the debate is concerned with the number of cpx spherule layers, but Miller et al. (1991) proposed that the microtektite layer at Site 612, off New Jersey, is older than the microtektite layer on Barbados. However, most authors now agree that there are just two layers: (1) the North American microtektite layer and (2) the cpx spherule layer (Glass, 1990; Wei, 1995; Vonhof and Smit, 1999; Montanari and Koeberl, 2000; Whitehead et al., 2000; Marchand and Whitehead, 2002). A detailed review is provided by Glass (2002).

LATE EOCENE IMPACT STRUCTURES: CHESAPEAKE BAY, POPIGAI, AND OTHERS

As noted already, the source of the North American tektite strewn field has now been linked, with a certain degree of confidence, to the 85-km-diameter Chesapeake Bay impact structure (Koeberl et al., 1996; Deutsch and Koeberl, 2006). The size of the Chesapeake Bay structure is generally given as 85 km (Poag et al., 2004); however, some authors suggest that the diameter of the crater before resurge may have been only ~40 km (e.g., Collins and Wünnemann, 2005). Nevertheless, this does not change the fact that the current, measurable crater diameter is 85 km. An impact event that created a crater of this size would be capable of globally distributing its distal ejecta. The late Eocene Chesapeake Bay impact structure is among the largest and best preserved of the known impact craters on Earth (Poag et al., 2004), and it is the largest impact structure currently identified in the United States (Fig. 3). The Chesapeake Bay structure is unique among subaerial and submarine impact craters on Earth because: (1) it is a relatively young structure and, in comparison to other known impact structures of such size, very well preserved; (2) its location on a passive continental margin has prevented the tectonic or orogenic disruption or distortion that is typical of many large terrestrial craters; (3) its original location on a relatively deep continental shelf allowed marine deposition to resume immediately following the impact, which buried the crater rapidly and completely, thereby preventing subsequent erosion; (4) the upper part of the breccia section inside the crater was derived from resurge currents and impact-generated tsunami waves; (5) the breccia body contains a large volume of impact-generated brine; and (6) the crater underlies a densely populated urban corridor whose two million citizens are still affected by crater-related phenomena, such as freshwater availability. Besides glasses and impact debris of the North American tektite strewn field, Chesapeake Bay impact ejecta have also been identified (in the form of shocked minerals) in a quarry in Georgia (Harris et al., 2004).

There is a second large crater with a radiometric age that is indistinguishable from that of the Chesapeake Bay structure and the two ejecta layers, namely the 100-km-diameter Popigai impact structure in Siberia, which has been dated at 35.7 ± 0.8 Ma. The Popigai structure is exposed in Archean crystalline rocks of the Anabar Shield, with overlying Proterozoic to Mesozoic sedimentary sequences, and it is the largest Cenozoic crater on Earth. As noted previously, it is now commonly assumed that the global late Eocene microkrystite layer originated from the Popigai impact event. A detailed geochemical and Sr/Nd isotope survey of target and impact melt lithologies finally established that the very broad range of Popigai target lithologies indeed represents the precursor material for melanocratic and leucocratic microkrystites as well as for the associated microtektites (Kettrup et al., 2003). Also, the isotope compositions and model parameters of the ejecta material allowed Kettrup et al. (2003) to constrain their origin from the uppermost layers at lithologically different and geographically defined parts of the Popigai target area (cf. Whitehead et al., 2002). This explains why the microtektites and microkrystites of the cpx spherule layer display a wider variation in compositions than tektites from other strewn fields.

OTHER LATE EOCENE–AGE CRATERS

There are several smaller late Eocene craters. The locations of the craters are shown in Figure 1, the ages—in comparison to distal ejecta markers and polarity chrons—are plotted in Figure 3, and satellites images of the craters are shown in Figure 4. Mistastin Crater in central Labrador, Canada, is dated at 38 ± 4 Ma (Mak et al., 1976), although Grieve (2006) cited a recalculated age of 36 ± 4 Ma; it is unclear how this age was recalculated. In Figure 3, I use a value of 37.0 ± 2.6 Ma (based on preliminary new Ar-Ar data; S. Kelley, 2008, personal commun.). Mistastin is a heavily eroded complex structure with a diameter of 28 km. Glacial erosion has imparted an eastward elongation to the crater that is particularly evident in the shape of the lake that occupies the central 10 km of the structure. Horseshoe Island, in the center of the lake, is part of the central uplift and contains shocked Precambrian crystalline target rocks. Outside the margins of the lake, there are remnants of the impact melt sheet (with columnar jointing), which contains evidence of shock metamorphism (e.g., Grieve, 1975). The age needs to be redetermined with more modern methods.

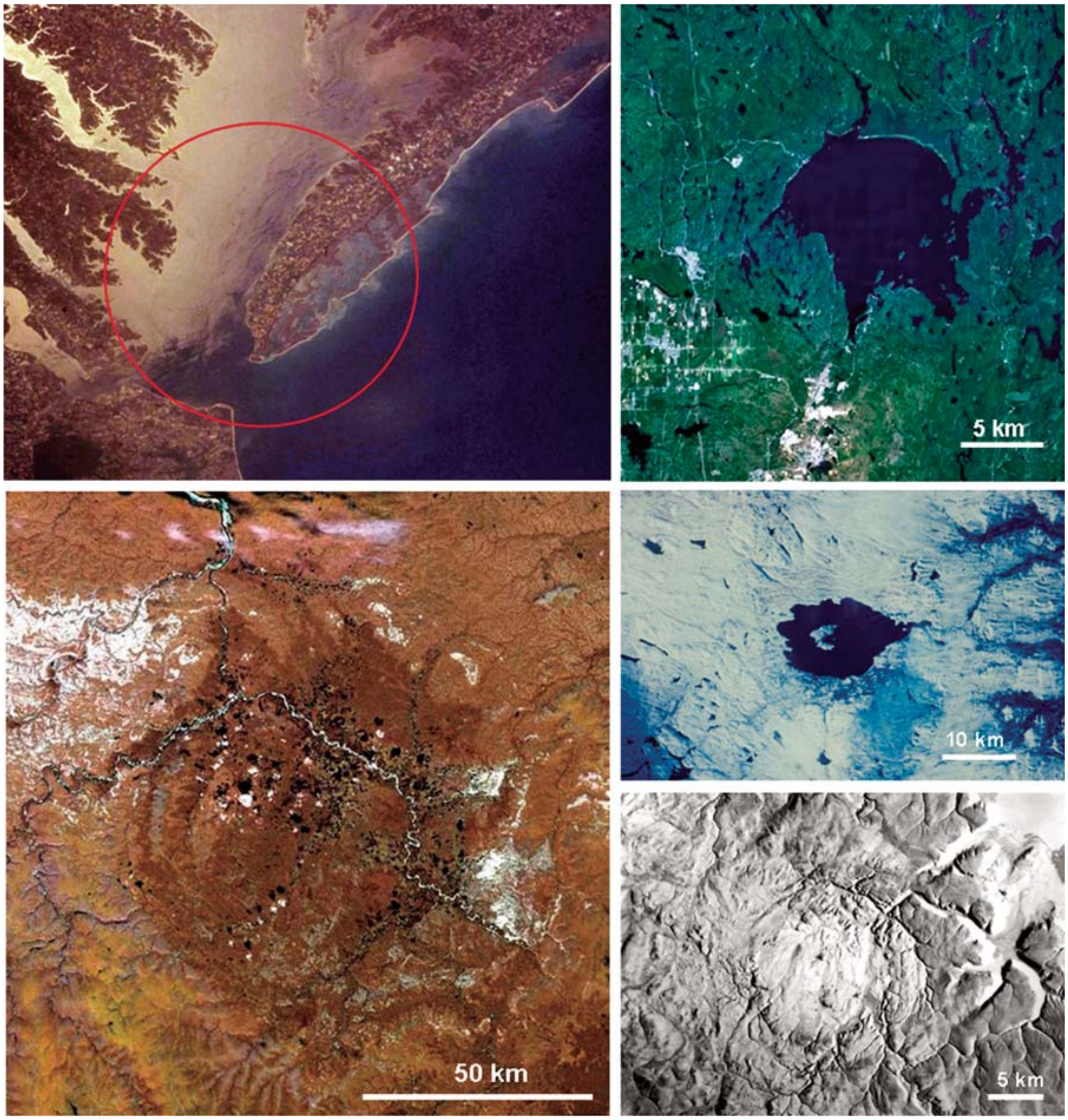

Figure 4. Overview of impact structures of (possibly) late Eocene age. Top left: Chesapeake Bay, USA (Space Shuttle image; circle indicates approximate dimension [85-km diameter] of the structure). Top right: Wanapitei, Canada (Landsat image). Bottom left: Popigai, Russia (Landsat image). Center right: Mistastin, Canada (Space Shuttle image). Bottom right: Haughton, Canada (Radarsat image).

Wanapitei near Sudbury in Canada is dated at 37.2 ± 1.2 Ma (Winzer et al., 1976). The crater is usually listed to have a diameter of 7.5 km. However, it has recently been reclassified as a simple crater because there is no evidence of a central uplift in the submerged crater, and geophysical work by L'Heureux et al. (2005) indicates that if the observed circular structure is due to a meteorite impact, it is at most a 3–4-km-diameter simple crater. This is still an ongoing debate. Wanapitei Lake, which probably fully encompasses the impact structure, has a semicircular shape along the north coast and a highly indented southern margin (Fig. 3). Target rocks are Precambrian crystalline and metasedimentary units of the Southern Structural Province Archean gneisses, Huronian Gowganda (metasedimentary rocks) and Mississagi Formations. They are intruded by Nipissing and younger diabase dikes. The outline of the lake has been enlarged and modified by erosion (e.g., Lazorek et al., 2006; Ugalde et al., 2006).

Petrographic evidence for an impact origin at Wanapitei comes from rock samples that demonstrate shock metamorphic effects (quartzite fragments and the presence of glass) found in glacial drift on the southern shores of the lake (Grieve and Ber, 1994). These include boulders of suevite and glassy breccia, as well as samples of coesite (e.g., Dence et al., 1974; Dressler et al., 1997). There are only a few samples that indicate these shock metamorphic features, none of which were found in their natural or original position or place (Dressler et al., 1997). Shatter cones have been found on certain islands in the southern part of the lake as well as on the shore, but these cannot be unequivocally attributed to the Wanapitei structure due to the close proximity of the Sudbury impact structure.

Sherlock et al. (2005) reevaluated the published age information for the Haughton impact structure, which was believed to have formed close to 23 Ma, during the Miocene age, and reported new late Eocene Ar/Ar laser probe data from shocked basement clasts that are at odds with the published Miocene stratigraphic, apatite fission-track, and Ar/Ar data. Sherlock et al. (2005) found that the age of the Haughton impact structure is close to 39 Ma. This age is not yet confirmed, as the reason for the younger fission-track ages and stratigraphic ages (which agree with each other) are not clear yet, but it is at least conceivable that Haughton is another late Eocene–age impact structure.

The 17-km-diameter Logoisk (Belarus) impact structure, which was earlier dated at 40 ± 5 Ma, has now been provisionally redated at 42.3 ± 1.1 Ma (Sherlock et al., 2006) and thus may not be part of the same late Eocene event.

A CLUSTER OF LATE EOCENE IMPACTS?

Significantly enhanced levels of ^{3}He were found to coincide with the two Upper Eocene impactoclastic layers. This isotope is a proxy for the influx of extraterrestrial dust and is interpreted as indicating that, during the late Eocene, there was a time of enhanced collision activity in the inner solar system, probably resulting in a higher impact rate than usual (e.g., Farley et al., 1998). The data were interpreted to represent a 2.2 m.y. interval of increased flux of interplanetary dust particles (IDPs). The observed higher impact rate and the enhanced flux of interplanetary dust particles during that time can be explained by (1) the arrival of long-period comets to the center of the solar system, resulting from a perturbation of the Oort cloud (Farley et al., 1998), or (2) the occurrence of an asteroid shower, triggered by a major collision in the asteroid belt (Tagle and Claeys, 2004).

High-resolution studies (δ^{13}C, δ^{18}O, and elemental abundances) were conducted by Bodiselitsch et al. (2004) in rocks at and below the E-O boundary GSSP boundary at Massignano, Italy. In addition to an earlier known Ir anomaly at 5.61 m, which is possibly linked to the Popigai impact event, they confirmed the presence of two additional Ir anomalies in the intervals from 6.00 to 6.40 m and from 10.00 to 10.50 m, with maximum values of 259 ± 32 ppt at 6.17 m, and 149 ± 24 ppt at 10.28 m, respectively. The lower Ir anomaly might be derived from the Chesapeake Bay impact event, whereas no impact event is known for the upper one. Similar δ^{13}C and δ^{18}O trends related to the two Ir anomalies indicate that the Ir anomaly at 10.28 m might be also derived from an impact into a continental shelf, similar to the Chesapeake Bay impact event. The δ^{18}O values decrease in the high-Ir layers to –1.16‰ and –1.17‰, respectively, and, together with negative shifts in δ^{13}C in the Ir-rich levels, they indicate a warm pulse superimposed on a general late Eocene cooling trend that is characterized by δ^{18}O values ranging between –0.6‰ and –0.4‰. The release of methane hydrate after an impact in a continental shelf or seafloor, or impacts of ^{12}C-rich comets during a 2.2 m.y. comet shower, respectively, could have produced these more negative carbon and oxygen excursions compared to the continuously decreasing trend documented through the whole late Eocene Massignano section (Bodiselitsch et al., 2004).

As discussed already, there is abundant evidence for the presence of an extraterrestrial component in late Eocene impact ejecta layers. In addition, the melt rocks of the Popigai impact structure show enrichments in characteristic siderophile trace elements, the ratios of which point toward an ordinary chondrite projectile, possibly of the L-chondrite type (e.g., Tagle and Claeys, 2005). Tagle and Claeys (2005) used regression techniques on platinum group element (PGE) data to derive evidence of an L-chondritic projectile for Popigai. Evans et al. (1993) used PGE data to indicate a nonspecified chondrite type for Wanapitei. Goderis et al. (2007) confirmed that the PGE characteristics of melt rocks from the 7.5 km Wanapitei structure point toward ordinary chondrites (possibly even L-chondrites), suggesting that the projectiles for these two impact structures were of the same type. It should be mentioned, however, that the exact projectile identification at Popigai (and possibly at Wanapitei) depends on not only on the quality and number of comparison data for the various meteorite groups, but also on the type of regression calculation used in interelement plots (see Farley, this volume, for a detailed discussion).

It is, therefore, in agreement with the currently available data that two of the late Eocene impact craters were thus formed by the same type of projectile. This hypothesis agrees with the chromium isotope analyses of several samples from Ocean Drilling Program (ODP) Site 709C (Kyte et al., 2004). The positive δ^{53}Cr results exclude carbonaceous chondrites, which make cometary sources less likely. Collisions in the main asteroid belt would result in an increase of the terrestrial impact rate in the form of asteroid showers lasting 2–30 m.y. (Zappalà et al. 1998). This would also be consistent with an asteroid shower between ca. 37 and 34 Ma. However, the association of the layers studied by Kyte et al. (2004) with either Popigai or Chesapeake Bay is not exactly clear. Independent confirmation of a meteoritic component in the late Eocene ejecta layers comes from a study by Paquay et al. (2008), who used the Os isotopic record of marine sediments to derive the projectile sizes. In sediments from ODP Sites 1090 and 1219, these authors also found a decrease in the ^{187}Os/^{188}Os ratio, and a correlated increase in the Ir concentrations, in the age range 35.3–35.6 Ma, with strong peaks in both signals at around 35.43 Ma, and possible secondary peaks at 35.5 Ma. These signals could conceivably be from the Popigai and Chesapeake Bay impacts, respectively.

At the Chesapeake Bay impact structure, the situation is not clear yet. The North American tektites do not seem to contain any distinct enrichment in siderophile elements, and analyses of drill core samples from within the structure have yielded a range of results. Most analyses (e.g., Poag et al., 2004) were below the 1 ppb detection limit for Ir. The highest content of Ir found by Lee et al. (2006) in a clast of impact melt rock from the Sustainable Technology Park (STP) test hole was 0.466 ppb. Lee et al. (2006) reported on osmium isotope ratios and PGE concentrations of impact-melt rocks. They found that the $^{187}Os/^{188}Os$ ratios of impact-melt rocks ranged from 0.151 to 0.518, and that PGE concentrations of some of these rocks were much higher than concentrations in basement gneiss. Together with the osmium isotopes ratios, these data indicate a measurable meteoritic component (0.01%–0.1%) in some impact-melt rocks. However, because the PGE abundances in the impact-melt rocks are dominated by the target materials, interelemental ratios of the impact-melt rocks are highly variable and nonchondritic (Lee et al., 2006). Due to the limitations of the Os isotopic method, the projectile type for the Chesapeake Bay impact structure cannot be constrained by these analyses.

CONCLUSIONS

There is abundant evidence for two large and a number of still poorly constrained (at least two, possibly three or four) smaller impact events during the late Eocene. This coincides with He isotopic evidence of an increased flux of extraterrestrial dust onto Earth over an ~2 m.y. period during this time. The source of the enhanced impact rate and accretion flux is not yet clear, even though the He isotope data were initially interpreted to indicate a comet shower. However, chemical data on the projectile compositions for several of the late Eocene impact craters indicate L-chondritic compositions, which would be difficult to reconcile with a comet source. Disturbances in the climate and, possibly, in cyclostratigraphy coinciding with the impact events have been documented (Brown et al., this volume). At least two important conclusions can be drawn from the study of the late Eocene impact events. First, it is now possible, with the increased resolution of stratigraphic studies and detailed geochemical, isotopic, paleontologic, and petrophysical studies of the rock strata, to determine the global and regional effects of impact events on the Earth system. Second, even a series of fairly large impact events did not lead to any significant mass extinctions, constraining the lower threshold for global biological extinction events above the combined energy of the cluster of late Eocene impacts.

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