Two large meteorite impacts at the Cretaceous-Paleogene boundary

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ABSTRACT
The end-Cretaceous mass extinction has been attributed by most to a single asteroid impact at Chicxulub on the Yucatán Peninsula, Mexico. The discovery of a second smaller crater with a similar age at Boltysh in the Ukraine has raised the possibility that a shower of asteroids or comets impacted Earth close to the Cretaceous-Paleogene (K-Pg) boundary. Here we present palynological and δ13C evidence from crater-fill sediments in the Boltysh impact crater. Our analyses demonstrate that a post-impact flora, formed on the ejecta layer, was in turn devastated by the K-Pg event. The sequence of floral recovery from the K-Pg event is directly comparable with that in middle North America. We conclude that the Boltysh crater predated Chicxulub by ~2–5 k.y., a time scale that constrains the likely origin of the bodies that formed the two known K-Pg craters.

INTRODUCTION
The celestial mechanism responsible for the globally distributed iridium-rich clay layer and shocked quartz associated with the end of the Cretaceous Period and a global mass extinction has been debated since the discovery of the layer (Alvarez et al., 1980; Smit, 1999). The discovery of the ~180-km-diameter Chicxulub crater, thought to be the origin of the global layer (Hildebrand et al., 1991), intensified the debate. Alternate hypotheses including a single impacting body (Smit, 1999), a comet shower (Hut et al., 1987), and an asteroid shower (Zappala et al., 1998; Bottke et al., 2007) have been proposed, although the discovery of meteorite fragments in a Pacific Ocean Cretaceous-Paleogene (K-Pg) layer (Kyte, 1998) makes a single asteroid or asteroid shower a more likely explanation. In addition, the asteroid or comet shower hypothesis must be reconciled with the single global iridium (Ir) layer (Alvarez et al., 1990), and lack of any signal of heightened extraterrestrial dust, indicated by levels of 3He in sediments (Mukhopadhyay et al., 2001). For many years following its discovery the Chicxulub structure in Mexico was the only confirmed crater known to have formed at the K-Pg boundary, although there has been controversy over the interpretation of regional deposits close to the crater (Keller et al., 2004).

Two of us (Kelley and Gurov, 2002) obtained an Ar-Ar age of 65.17 ± 0.64 Ma for the 24-km-diameter Boltysh impact crater on the Ukrainian shield. Boltysh is in the Northern Hemisphere at a latitude similar to that of the well-characterized North American K-Pg sections 65.6 m.y. ago (Fig. 1). Data on terrestrial impacts indicate that one Boltysh-sized crater forms on continental crust every million years. However, the experimental error in the Ar-Ar age is too large to constrain whether the two impacts were synchronous, or if not, the order in which they occurred.

The impact on the land surface of the Ukrainian shield that formed the Boltysh crater (Fig. 2) was unlikely to have contributed substantially to the worldwide devastation at the end of the Cretaceous. Models indicate that the ignition zone extended at least 100 km beyond the crater rim (Toon et al., 1997; Kring, 1997) and that an unconsolidated ejecta blanket between 120 and 350 m in thickness was deposited close to the crater rim (McGetchin et al., 1973; Collins et al., 2005). This ejecta thinned to 1 m between 50 and 80 km from the crater rim. The crater subsequently filled with the sediments (Fig. 3) we used to test both the physical effects of terrestrial impacts and the single-impact K-Pg boundary hypothesis.

NEW DRILL CORE
The Boltysh crater was drilled in the 1960s–1980s, but the cores were not recorded, and have been lost. A 596 m cored borehole (hole 42/11) drilled by us in 2008 to the west of the central peak, in the deepest part of the crater, recovered a complete sequence of sedimentary rocks unconformably overlying suevite breccias (see the GSA Data Repository1).

Figure 1. Location map showing impact sites of Chicxulub and Boltysh, and Deccan Traps large igneous province at time of Cretaceous-Paleogene (K-Pg) events.

Figure 2. Map showing location of Boltysh impact crater, impact effect zone, and area of ejecta blanket. Gray shaded circle represents ejecta thicker than 1 m; dark ring represents edge of ignition zone.

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1GSA Data Repository item 2010232, methods, and statistical treatment of carbon isotope results (Tables DR1–DR5), is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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Geology, September 2010; v. 38; no. 9; p. 835–838; doi: 10.1130/G31034.1; 3 figures; 1 table; Data Repository item 2010232.
Within the basal 5 m of sedimentary rocks, the oldest are thin green-gray silty sands, which are also present in intra-suevite fissures and as rip-up clasts in overlying coarse turbidite sandstones. These sandstones pass upsection into crudely bedded fine silty sandstones and laminated siltstones interpreted as proximal ejecta blanket material reworked and deposited by turbidity currents in the anoxic waters of the crater lake. This unit is truncated by the erosional base of the first of a thick sequence of turbidites with coarse sandstones at the base (578.75 m), probably representing the establishment of an effective fluvial drainage system from the ejecta blanket into the crater via marginal deltas.

**PALYNOFLORA**

The 60° unconformity between suevite and sediment is probably due to an uneven crater floor, as all other bed boundaries are nearly horizontal. The oldest palynofloras of the 42/11 core are recovered from immediately above the suevite, and in a fissure fill of the same sediment lower down the section (581.9 m, and fissure fill at 583.4 m) (Fig. 3). They are dominated by *Botryococcus braunii*, a Chlorophycean algae indicative of eutrophic freshwater lakes (Tappan, 1980). Recovered along with these algae is a moderately diverse palynoflora of pollen and spores including species of Normapolles pollen, and fagaceous and *Platycarya*-type pollen, which are derived from scrubby angiosperms (Batten, 1981; Jolley et al., 2008). Polypodiaceous fern spores and *Calamaspora (Equisetum)* are also common in what is interpreted as temperate early mid-successional vegetation growing on the proximal ejecta field. The lack of any marine component in this palynoflora supports an interpretation that the Boltysh meteorite impacted land, a deep, eutrophic crater lake forming shortly afterward.

These moderately diverse assemblages are overlain by a 0.89-m-thick interval of sediments that are lithologically similar, but barren of palynomorphs (Fig. 3). These sediments have no indication of post depositional oxidation, indicating that the lack of organic material is a depositional feature. A small number of pollen grains recovered from one sample at the base of this zone are probably reworked from the underlying pollen-rich unit as part of the rip-up clast assemblage. Palynomorphs reappear at 581.01 m (0.89 m above base), where *Echinatisporis* species (*Selaginella* or spikemoss) occur with low frequencies of polypodiaceous fern spores. This influx of fern and spikemoss spores is replaced at 580.60 m (1.3 m above base) by assemblages of pteridacean spores marking colonization of the ejecta blanket by a higher biomass early seral succession plant community.

From 580.35 m (1.55 m above base) mid-successional vegetation is marked by the Normapolles *Plicapollis pseudoexcelsus* and *Interpollis*...
supplingensis in association with palm pollen (Arecoptes sp.). Immediately above this (579.6 m), penetration of marine water into the crater is marked by common occurrences of the dinocyst Areoligera cf. cornuta. This marine incursion is probably a manifestation of the post K-Pg transgression recorded around the Tethys Ocean (Guasti et al., 2005). This transgression possibly originated from the Dnieper depression area (Fig. 2), and transformed the Boltysh ejecta blanket vegetation, resulting in a mosaic of early and early-mid successional communities of pteridacean ferns, Normapolles, and palms. Numbers of angiosperm and haploxylo-noid pine pollen increase upsection (above 578.1 m), recording maturing community succession. This interval saw freshwater conditions return to the lake, marked by the influx of Botryococcus braunii.

CARBON ISOTOPE STRATIGRAPHY

Bulk sedimentary carbon contents and isotopic compositions in the lowermost 5 m of sediments in the 42/11 core from immediately above the suevite reveal a variation in wt% C and δ13C values upward through the section, the C content steadily increasing and marked changes recorded in δ13C values (Fig. 3). Carbon contents throughout the lowest 5 m of section are low, indicating a low biomass within the crater lake drainage, and a lack of deposition of carbonaceous sediments.

Immediately above the suevite C contents are very low (<100 ppm); the mean δ13C value is −30.5‰. The C contents then rise slightly (100–300 ppm between 581.9 m and 580.85 m; 0.0–1.05 m above base) and there is a concomitant positive 5.5‰ shift in δ13C values to a mean of −24.8‰ through the barren interval with significant variability in δ13C values, probably as a result of a “nugget effect” caused by individual particles. From 580.9 m to 586.6 m a negative excursion in δ13C values (Fig. 3) at 580.7 m (1.2 m above base) to −28.9‰ occurs within sediments, indicating an influx of fern spores. This is followed by a return to more positive values at 580.6 m (1.3 m above base) in sediments, indicating a wider colonization of the ejecta blanket by Pteridaceae (Table 1). Above this, in sediments indicating mid-successional flora, carbon contents progressively increase with occasional spikes and δ13C values show low variability compared with the underlying sequences, and a mean value of −27.7‰. A second negative δ13C excursion is apparent at 578.1 m (3.8 m above base) to −32.9‰.

DISCUSSION

Borehole 42/11 records minor weathering of the Boltysh impact suevite prior to the formation of a crater lake and deposition of the oldest sediments (associated with a mean δ13C value of −30.5‰), accompanied by an early-mid successional community of ferns and angiosperms (Wing and Hickey, 1984). Parallels with inter-lava flow durations in large igneous provinces (Jolley et al., 2008) and from modern lava fields (Vitousek, 2004) suggest that such communities can occur in sedimentary interbeds of 2–5 k.y. duration. This comparison suggests that the interval from the impact of the Boltysh meteorite to deposition of the earliest pteridoflora observed would have been between 2 and 5 k.y. The destruction of this post-impact flora by the K-Pg event is recorded in a 0.89-m-thick barren sequence, exhibiting a significantly higher mean δ13C of −24.9‰ ± 1.5‰ and very low carbon contents. The influx of fern and/or moss spores at 0.89 m above the base, and their succession by fern communities, highlights parallels with the North American record of the Chicxulub impact. While the fern spike record in Boltysh is closely comparable to other K-Pg boundary examples, Boltysh did not have deposition of carbonaceous sediments or of common fungal spores (Vajda and McLoughlin, 2004), probably because the low biomass vegetation following the Boltysh impact and the subsequent period of little or no vegetation meant that there was insufficient rotting organic matter to support saprophytic organisms.

Comparison of the fern spike in the Boltysh record with the first phase of recovery after the K-Pg in North America is supported by the coincidence of the negative δ13C excursion in bulk organic matter with the influx of fern spores (although it postdates their earliest appearance). A δ13C excursion of similar magnitude (−1‰ to −2.8‰) is observed in terrestrial K-Pg sequences coincident with a fern spike in the Western Interior of North America (Schimmelmann and Deniro, 1984; Beerling et al., 2001). A similar excursion has been measured in a higher plant biomarker from the marine Caravaca section, Spain (Arinobu et al., 1999). In Boltysh, the negative δ13C excursion and adjacent fern spike occur 0.9–1.2 m above the base of the barren zone, which is in turn interpreted as recording sedimentation after K-Pg event biotic devastation. The erosion of metamorphic carbon from the proximal ejecta blanket is recorded in the heavier δ13C values in this zone. Calculating an absolute duration for the total fern spike period in the Boltysh core is difficult because sedimentation is cyclic, the duration being within two turbidite units. However, it is unlikely to have exceeded 5 k.y., and is thus shorter than the 100 k.y. suggested for the equivalent interval in New Zealand (Vajda and Raine, 2003), but it is comparable to the duration of early successional vegetation on some volcanic terrains (Wolfe and Upchurch, 1987; Chadwick et al., 1999).

IMPLICATIONS FOR CELESTIAL DYNAMICS AT THE K-PG BOUNDARY

The very short period of time, as little as 2–5 k.y., between two large asteroid impacts on Earth close to the K-Pg boundary constrains the likely impactor delivery mechanism since it necessitates a high probability of delivering several large bodies into the inner solar system within a few thousand years. Average cratering rates indicate that craters with diameters D ≥ 20 km are formed on the land surface at a rate of 4 ± 2 every 5 m.y. (Grieve and Pesonen, 1992), yielding a probability of 0.004 that a 20 km crater would form somewhere on Earth in a 5 k.y. period. If the total probability equals P(A ∩ B) (where P is probability, A is impact 1, and B is impact 2), then the probability of 2 craters forming within a 5 k.y. period is <0.001. Because the two impacts were not synchronous, the probability that they were a binary pair is significantly reduced, and another mechanism is required for closely spaced large terrestrial impacts. Various mechanisms have been proposed for impact clusters in the Eocene.

<table>
<thead>
<tr>
<th>Assemblage</th>
<th>Description</th>
<th>Mean δ13C value (‰)</th>
<th>Core depth (m)</th>
<th>Mean difference in δ13C to previous zone (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Mid-succession angiosperms</td>
<td>−27.7 ± 2.1</td>
<td>580.4–577.5</td>
<td>−1.2 (t9 = 0.97, p = 0.34)</td>
</tr>
<tr>
<td>4</td>
<td>Fern spike—floodplain ferns</td>
<td>−26.5 ± 0.4</td>
<td>580.6–580.4</td>
<td>−0.4 (t9 = 0.37, p = 0.5)</td>
</tr>
<tr>
<td>3</td>
<td>Fern spike—fern allies</td>
<td>−26.1 ± 1.9</td>
<td>581.0–580.6</td>
<td>−1.2 (t9 = 1.68, p = 0.11)</td>
</tr>
<tr>
<td>2</td>
<td>Barren zone</td>
<td>−24.9 ± 1.5</td>
<td>581.9–581.0</td>
<td>+5.5 (t9 = 7.3, p &lt; 0.001)</td>
</tr>
<tr>
<td>1</td>
<td>Botryococcus braunii, Normapolles pollen, Platyxipylon pollens, Polypodiaceous fern spores</td>
<td>−30.45 ± 0.7</td>
<td>583–581.9</td>
<td></td>
</tr>
</tbody>
</table>

Note: t—number of samples; p—probability.
(Mukhopadhyay et al., 2001), and the Ordovician (Schnitzius et al., 1997), focusing on a large collision in the asteroid belt during the Ordovician and either a comet shower (Hut et al., 1987; Mukhopadhyay et al., 2001) or an asteroid shower (Claeys et al., 1992; Fritz et al., 2007) in the Eocene.

A comet shower is an unlikely explanation for the K-Pg given the global Ir anomaly and discovery of an asteroid fragment (Kyte, 1998), but the very short period between the Chicxulub and Boltysh impacts is also difficult to explain using current models for asteroid showers. A model of the likely spread of terrestrial impact ages from asteroids expelled from different resonance bands in the asteroid belt (Zappala et al., 1998) demonstrated that the resonance most likely to produce a short burst of asteroidal bodies is the J5:2 band (5 asteroid orbits per 2 orbits of Jupiter). The J5:2 resonance band is thought to have been responsible for the rapid delivery of many meteorites and possibly larger bodies during the Ordovician Period (Nesvorny et al., 2002). However, no large asteroid family has been identified that might be related to the K-Pg boundary and an alternative hypothesis that the K-Pg events were the result of a disruption of the Baptistina asteroid family close to the J7:2 band (Botte et al., 2007) is unlikely to have resulted in two near simultaneous impacts.

In summary, the evidence from sediment filling the Boltysh impact crater indicates that at least two large meteorite impacts, separated by as little as 2–5 k.y., synchronous with the K-Pg boundary and mass extinction, occurred and resulted in one identifiable global layer. While there is strong evidence that they were asteroidal impacts, the celestial mechanism responsible is as yet unclear.

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