Two large meteorite impacts at the K/Pg boundary

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ABSTRACT

The end Cretaceous mass extinction has been attributed to a single asteroid impact at Chicxulub on the Yucatán peninsula, Mexico. The discovery of a second smaller crater at Boltysh in the Ukraine with a similar age has raised the possibility that a shower of asteroids or comets impacted Earth close to the K/Pg boundary. Here we present palynological and $\delta^{13}C$ 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 those in mid North America. We conclude that the Boltysh crater pre-dated Chicxulub by approximately 2ky – 5ky a timescale 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 its discovery (Alvarez et al., 1980; Smit, 1999), The discovery of the circa 180 km diameter Chicxulub crater which has been thought to 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 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 Ir layer (Alvarez et al., 1990), and lack of any signal of heightened extraterrestrial dust, indicated by levels of ^{3}He 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, 2001; Keller et al., 2004).

More recently, Kelley and Gurov (2002) obtained an Ar-Ar age of 65.17±0.64 Ma for the 24km diameter Boltysh impact crater on the Ukrainian Shield, an age subsequently confirmed as being coeval with the K/Pg by palaeontological evidence (Valter and Plotnikova, 2003). Boltysh lay in the northern hemisphere at a similar latitude to the well characterised N. American K/Pg sections at 65.6Ma (Figure 1). However, the experimental error in the Ar-Ar age is too large to conclusively prove an asteroid shower occurred since long term data on terrestrial impacts indicates that one Boltysh sized crater forms on continental crust every million years, nor does it 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 Sheild that formed the Boltysh crater (Figure 2) was unlikely to have contributed substantially to the worldwide devastation at the end of the Cretaceous. It is difficult to know the precise effects but models indicate that the ignition zone extended at least 100km beyond the crater rim (Toon et al. 1997, Kring 1997). The explosion caused by the Boltysh impact deposited an unconsolidated ejecta blanket surrounding the crater which models indicate may have reached between 120m - 350m thick close to the crater rim (McGetchin et al 1973, Collins et al., 2005), and thinned to 1 m thickness between 50 and 80km from the crater rim. The crater itsself subsequently filled with sediments which contain a record of impact and post-impact events (Figure 3). Here, we use the unique record of the Boltysh crater fill sediments 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 curated and have been lost. A 596m 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 resting unconformably on suevite breccias (see supplementary data). Here we describe results from the lowermost 5 m of sediment in the core. The oldest sediments are thin green-grey 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 the deposition of reworked proximal ejecta blanket material by turbidity currents in the anoxic waters of the crater lake. This dominantly laminated unit is truncated by the erosional base of the first of a thick sequence of turbidites with coarse sandstones at the base (578.75m), probably representing the establishment of an effective fluvial drainage system from the ejecta blanket into the crater via marginal deltas.

Palynoflora

The boundary between suevite and sediment is an unconformity orientated at 60°, probably reflecting an uneven crater floor but all other sedimentary 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 (581.9m, and fissure fill at 583.4m) (Figure 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, 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 onto land, a deep, eutrophic crater lake forming shortly afterwards.

These moderately diverse assemblages are overlain by a 0.89m thick interval of sediments which are lithologically similar, but barren of palynomorphs (Figure 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 were indeed recovered from one sample at the base of this zone, but are probably reworked from the underlying pollen rich unit as part of the rip-up clast assemblage. Palynomorphs reappear at 581.01m (0.89m 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 580.60m (1.3m above base) by assemblages of pteridacean spores marking colonisation of the ejecta blanket by a higher biomas early seral succession plant community.

From 580.35m (1.55m above base) mid-successional vegetation is marked by the Normapolles *Plicapollis pseudoexcelsus* and *Interpollis supplingensis* in association with palm pollen (*Arecipites* sp.). Immediately above this (579.6m), penetration of marine water into the crater is marked by common occurrences of the dinocyst *Areoligera* cf. *coronata*. This marine incursion is probably a manifestation of the post K/Pg transgression recorded around Tethys (Guasti et al., 2005). This transgression possibly originated from the Dneiper depression area (Figure 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 haploxylonoid pine pollen increase upsection (above 578.1m), 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 $\delta^{13}C$ values upwards through the section with C content steadily increasing and marked changes recorded in $\delta^{13}C$ values (Figure 3). Carbon contents throughout the lowest 5m 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) with a mean $\delta^{13}C$ value of -30.5‰. C contents then rise slightly (100 to 300 ppm between 581.9m and 580.85m (0.0m to 1.05m above base) and there is a concomitant positive 5.5‰ shift in $\delta^{13}C$ values to a mean of -24.8‰ through the barren interval with significant variability in $\delta^{13}C$ values, probably as a result of a 'nugget effect' caused by individual particles. From 580.9m to 580.6m. a negative excursion in $\delta^{13}C$ values (Figure 3) at 580.7m (1.2m 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 580.6m (1.3m above base) in sediments indicating a wider colonisation of the ejecta blanket by Pteridaceae. Above this, in sediments indicating mid-successional flora, carbon contents progressively increase with occasional spikes and $\delta^{13}C$ values show low variability compared with the underlying sequences, and a mean value of -27.7‰. A second negative $\delta^{13}C$ excursion is apparent at 578.1m (3.8m above base) to -32.9‰.

Table 1 summarizes the mean $\delta^{13}C$ values associated with each palynofloral assemblage identified in the 42/11 core. The isotopic results were subjected to statistical tests to establish the relationship between $\delta^{13}C$ and palynofloral assemblage.

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 $\delta^{13}C$ value of -30.5‰), which is accompanied by an early-mid successional community of ferns and angiosperms (Wing & Hickey, 1984). Parallels with inter lava flow durations in Large Igneous Provinces (Jolley et al, 2008), and from modern lava fields (Vitousek, 2004) suggests that such communities can occur in sedimentary interbeds of 2000 – 5000 yr duration. This comparison suggests that the interval from the impact of the Boltysh meteorite to deposition of the earliest palynoflora observed would have been between 2000 - 5000 yr. The destruction of this post impact early-mid successional flora is recorded in a 0.89m thick sequence that is barren of palynomorphs, exhibiting a significantly higher mean δ^{13}C of -24.9 ± 1.5 ‰ and very low carbon contents. The influx of fern/moss spores at 0.89m 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, it did not experience 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.

Correlation 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 δ^{13}C excursion in bulk organic matter with the influx of fern spores (although it post-dates their earliest appearance). A δ^{13}C 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). These terrestrial δ^{13}C excursions parallel the negative δ^{13}C excursion in carbonate rocks reported in the global stratotype K/Pg section at El Kef, Tunisia (Therrien et al., 2007), and in many other marine sections worldwide. In Boltysh, the negative $\delta^{13}C$ excursion and adjacent fern spike occurs 0.9-1.2m above the base of the barren zone, which is in turn interpreted as recording the destruction of the Boltysh post impact early-mid successional flora by the K/Pg event. The erosion of metamorphic carbon from the proximal ejecta blanket is recorded in the heavier $\delta^{13}C$ values in this zone. In North America the interval between the iridium anomaly and the negative $\delta^{13}C$ excursions and fern spike is <0.01 – 0.3m in sections that preserve a complete record of the K/Pg transition (Therrien et al., 2007).

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 5,000 yr and is thus shorter than the 100ky 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 2-5ky, 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 $D \geq 20$km are formed on the land surface at a rate of 4±2 every 5 Ma (Grieve and Pesonen, 1992) yielding a probabililty of 0.004 that a 20km crater would form somewhere on Earth in a 5ky period, and if the total probability equals P(A ∩ B) then the probability of two craters forming within a 5ky period is <0.001 although it is difficult to assign physical meaning to such a low probability. In addition the fact that the two impacts were not synchronous significantly reduces the probability that they were a binary pair and another mechanism must be sought for closely spaced large terrestrial impacts. Various mechanisms have been proposed for the impact clusters which occurred during the Eocene (Mukhopadhyay et al., 2001), and the Ordovician (Schmitz et al. 1997), focussing 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 (Bottke 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, occurred on Earth separated by as little as 2-

5 ky synchronous with the K/Pg boundary and mass extinction, which would only have 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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Figures

Figure 1 Location map showing impact sites of Chicxulub, Boltysh and the Deccan Traps Large Igneous Province at the time of the K/Pg events.

Figure 2 Map of the Boltysh impact crater, impact effects, and ejecta blanket model. Grey shaded circle represents ejecta thicker than 1m; dark ring represents the edge of the ignition zone.

Figure 3: Lithological, palynological and geochemical data from borehole 42/11, Boltysh impact crater. Base of barren zone = A, base of fern spike = B, floodplain ferns = C, mid succession angiosperms = D, influx marine dinocysts = E, return to freshwater lake = F, oldest pine dominance = G.

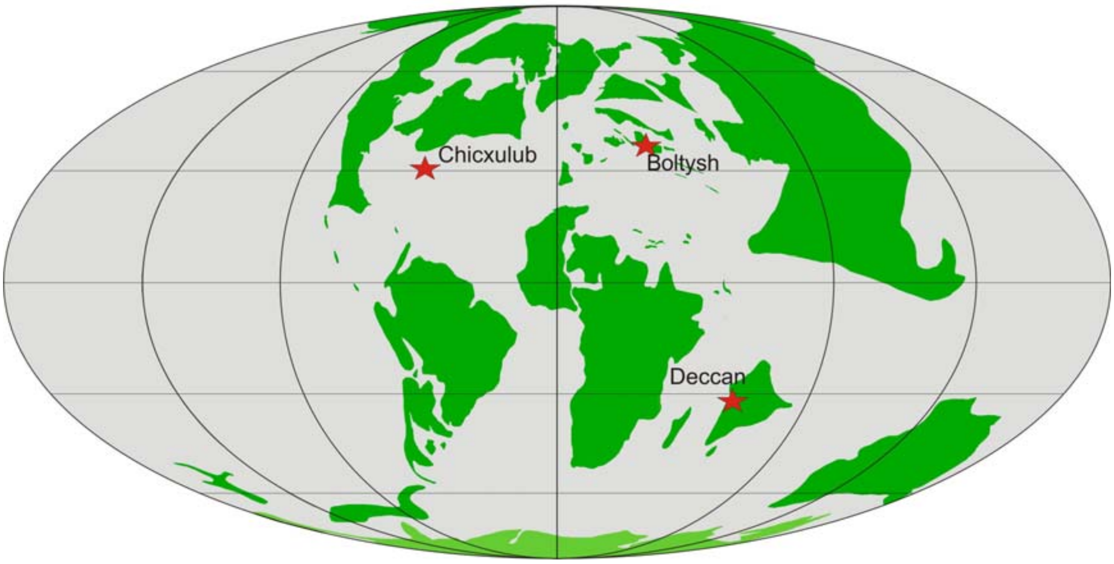
Tables

Table 1 Mean $\delta^{13}C$ values by stratigraphical interval at the base of the core.

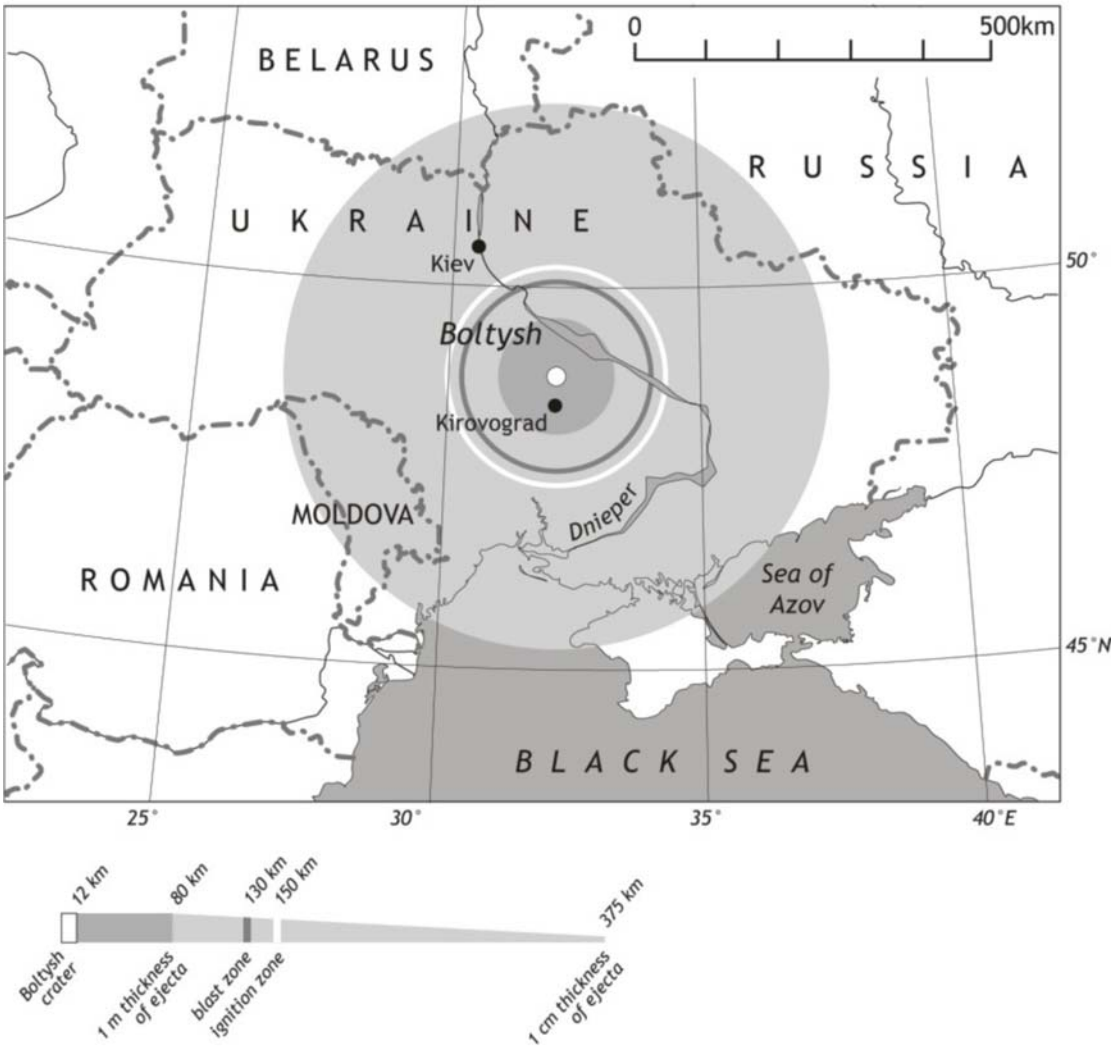
TABLE 1. MEAN δ^{13}C VALUES BY STRATIGRAPHIC INTERVAL AT THE BASE OF THE CORE

Assemblage	Description	Mean δ^{13}C value (‰)	Core depth (m)	Mean difference in δ^{13}C to previous zone (‰)
5	Mid-succession angiosperms	–27.7 ± 2.1	580.4–577.5	–1.2 ($t_{55} = 0.97$, $p = 0.34$)
4	Fern spike—floodplain ferns	–26.5 ± 0.4	580.6–580.4	–0.4 ($t_{9} = 0.37$, $p > 0.5$)
3	Fern spike—fern allies	–26.1 ± 1.9	581.0–580.6	–1.2 ($t_{20} = 1.68$, $p = 0.11$)
2	Barren zone	–24.9 ± 1.5	581.9–581.0	+5.5 ($t_{16} = 7.3$, $p < 0.001$)
1	Early succession *Botryococcus braunii*, Normapolles pollen, *Platycaryapollenites*, Polypodiaceous fern spores	–30.45 ± 0.7	583–581.9	

Jolley et al., Fig 1



Jolley et al., Fig 2



Jolley et al., Fig 3