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Nano particles as the primary cause for long-term sunlight suppression at high southern latitudes following the Chicxulub impact — evidence from ejecta deposits in Belize and Mexico

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1. Introduction

The discovery of a crater buried beneath the town of Chicxulub on the Yucatán Peninsula (Penfield and Camargo, 1981) provided the pivotal evidence supporting the assertion that the end-Cretaceous mass extinction was indeed caused by the impact of an asteroid or comet (Hildebrand and Boyton, 1990; Hildebrand et al., 1991; Pope et al., 1991) as proposed by Alvarez et al. (1980). The extinction of over 70% of species, including the dominant dinosaurs on land, is now attributed to this asteroid impact (Schulte et al., 2010 and references therein). The impact site has been well preserved from erosion by burial beneath more than 1000 m of younger strata (Pope et al., 1991). Thus, expensive drilling programmes are required to access the sedimentary successions within the crater. After more than 30 years of investigations by multiple research groups, well-founded geochemical and mineralogical data have been generated that support the extra-terrestrial cause of the end-Cretaceous event. Such data include the presence of anomalous concentrations of iridium, the presence of high-temperature and high-pressure phases in shocked quartz, and the presence of Ni-rich spinel in the clay layer separating the Cretaceous from the Paleogene (Schulte et al., 2010 and references therein). The presence of metal oxides and hydroxides in nano-phases in the ferruginous layer within the K-Pg boundary clay at Mimbral in Mexico (Wdowiak et al., 2001) and mid-Waipara and Compressor Creek in New Zealand (Ferrow et al., 2011), has been presented as additional mineralogical evidence of the precise position of the ejecta layer.

The Chicxulub ejecta layer is amongst the best preserved proximal ejecta deposit of any large-scale crater on Earth, and it provides an ideal opportunity to study impact processes. In 1995 and 1996, beds containing spherules related to the Chicxulub ejecta blanket were found at two sites in Belize: at Albion Island in the northern part of...
the country and at Armenia, in the foothills of Maya Mountain in the Cayo district of the central region (Fig. 1), at distances of 365 and 470 km from the crater centre, respectively (Ocampo et al., 1996).

Since this initial discovery, further outcrops have been identified and described in detail in several studies (e.g., Ocampo et al., 1996; Vega et al., 1997; Pope et al., 1999; Fouke et al., 2002; Keller et al., 2003a,b; King and Petruny, 2003; Pope et al., 2005). Significant differences expressed in the mineralogy and texture of the ejecta layer at the various sites have prompted an ongoing dispute concerning the causal mechanisms behind the heterogeneity of the ejecta deposits. The two dominant hypotheses raised to explain this heterogeneity invoke: (1) different depositional processes following the impact (Ocampo et al., 1996; Wdowiak et al., 2001; Bauluz et al., 2004; Ocampo et al., 2006; Wigforss-Lange et al., 2007; Schulte et al., 2010 and references therein), and (2) multiple impact events (Keller et al., 2007).

This study aims to examine the Fe-bearing phases of the ejecta deposits focussing on the spheroid bed of the Albion Formation, which is exposed at several sites in Belize and Mexico within a 500 km radius of the crater centre. Results from petrography, Mössbauer spectroscopy, powder X-ray diffraction (XRD) and palynology, are used to assess differences and similarities between the different parts of the spheroid bed, and between samples from the spheroid bed at various sites along the Mexican/Belize border. Additionally, we compare these data with one sample from the underlying Cretaceous Barton Creek dolomite. Further, the global distribution of the ejecta is discussed and linked to the end-Cretaceous biotic turnover with particular focus on the Gondwanan vegetation.

2. Geological setting

Belize is situated on the east coast of the Yucatan Peninsula in Central America, southeast of the Chicxulub crater (Fig. 1). The geology of northern Belize is not well documented due to the paucity of natural outcrops in this tropical, low relief region and because dissolution-induced collapse and recrystallization of carbonates and evaporites have destroyed many of the original textures, bedding and fossils. However, quarrying activities on Albion Island in Rio Hondo (Hondo River), northern Belize, provides excellent bedrock exposures in this particular region (Figs. 1–3).

Proximal ejecta deposits were first recognized in a quarry on Albion Island, northern Belize, approximately 365 km southeast of the centre of the Chicxulub impact structure; the geographical name was subsequently employed to name the Albion Formation (Ocampo et al., 1996). The deposits are now known to be exposed at several places along the Mexico–Belize–Guatemala border, e.g., in Ramonal North, Ramonal South, Agua Dulce, Alvaro Obregón, the Albion Island Quarry, Armenia and Santa Teresa (Fig. 1). The deposits incorporate the basal spheroid bed containing carbonate accretionary lapilli and altered impact glass, overlain by a diamictite bed consisting of coarser material including displaced carbonate boulders up to 8 m in diameter and associated sparse dolomite spheroids.

The target rock consists of a 3-km-thick succession of limestones, marls, dolomites, evaporites and sandstones overlying a crystalline basement. The ejecta deposits rest directly on the fractured and karstified Maastrichtian Barton Creek Formation. This dolomitic unit was formed on a carbonate platform and has been interpreted to represent the deposits of a shallow, back-reef lagoon environment (Flores, 1952a,b; Vega et al., 1997).

The impactor, inferred to be a carbonaceous chondrite (Shukolyukov and Lugmair, 1998) approximately 10 km in diameter (Alvarez et al., 1980), excavated a 180–200 km diameter crater in the volatile-rich carbonate platform and the underlying crystalline basement down to the base of the crust (Kring, 2007). The globally distributed ejecta and fallout deposits generated by this event are recognized by the presence of shocked quartz, tektites and geochemical anomalies, such as iridium enrichment (Alvarez et al., 1980).

3. Material and methods

3.1. Material

Samples from four sections in Belize and Mexico were studied for petrology, geochemistry and palynology. The samples were collected by A. Ocampo between 1994 and 2005, and represent mainly the ejecta deposits (spheroid bed), together with one sample from the underlying Cretaceous Barton Creek Formation for comparison. The base of the Albion Formation and its contact with the underlying Barton Creek Formation are well exposed at Ramonal South. Eight samples were selected for Mössbauer analysis, three samples for XRD, and four samples for palynology and, petrographic analyses were carried out on thin sections from three samples (Figs. 4, 5).

Ramonal North is located at ~340 km from the crater centre and is close to the village of Ramonal, Quintana Roo, Mexico (Fig. 1), where a road-cut exposes 3.6 m of the spheroid bed incorporating calcitic silt matrix with abundant green altered glass clasts 2–40 mm in diameter. The bed also contains abundant spherical to slightly oblate pink carbonate lapilli 5–25 mm in diameter. One sample (RN-68) was selected from this deposit for Mössbauer analysis (Fig. 2).

Ramonal South locality is situated a few hundred metres south of Ramonal North (Fig. 1). The Barton Creek Formation is exposed at this site and has been affected by extensive karst weathering. This heavily recrystallized limestone with iron oxide staining, calcite deposits, solution cavities and travertine deposits has a local surface relief of 3–5 m. Overlying the Barton Creek Formation at Ramonal South is a 2-m-thick spheroid bed. At Ramonal South, this basal unit is overlain by a 5-m-thick diamictite bed incorporating limestone cobbles and boulders (up to 3 m in diameter) supported in a calcitic silt matrix (Fig. 2). Samples selected for Mössbauer analysis from this unit were taken from the spheroid bed at 1.60 m above the contact with the underlying Barton Creek Formation (sample RS-160) and from the topmost part of the spheroid bed, approximately 2 m above the contact (sample RS-SPH).
Albion Island locality is situated in Belize at a distance of 365 km from the crater's centre (Figs. 1, 2). The succession exposed in Albion Quarry (Fig. 3) incorporates the Cretaceous Barton Creek Formation and the Paleogene Albion Formation. Immediately overlying the Barton Creek Formation is the spheroid bed, which at this site contains carbonate accretionary lapilli and altered impact glass. The spheroid bed is overlain...
by a coarse diamictite bed hosting carbonate boulders up to 8 m in diameter, associated with sparse dolomite spheroids (Fig. 2). One sample from the topmost part of the Barton Creek Formation (sample AI-143) was analysed for Mössbauer spectroscopy and XRD (Fig. 2). Two samples were further selected from the spheroid bed for Mössbauer analysis (AI-97 and the “saddle breccia” Al-SH), and XRD analysis was also carried out on sample AI-97.

The Armenia section is located at a distance of 470 km from the crater centre, and south of the Belizean capital Belmopan (Fig. 1). An approximately 17-m-thick succession spanning the Cretaceous–Paleogene boundary is exposed here along the Hummingbird Highway. The basal part of the succession comprises the uppermost part of the Maastrichtian Barton Creek Formation and is composed mainly of a 5-m-thick indurated regolith deposit. This is overlain by a deep red–green calcitic clay (0.5–1.5 m thick) hosting small angular to rounded pebbles and granules. At the top of this clay, and immediately underlying the basal contact of the lowermost Paleocene spheroid bed, fossil roots are present suggesting that it represents soil formed on the weathered surface of the Barton Creek Formation at the end of the Cretaceous. A 5-m-thick spheroid bed consisting of altered glass and accretionary lapilli overlies the palaeosol. Overlying the spheroid bed at Armenia is a 5-m-thick portion of the diamictite bed consisting of matrix-supported limestone pebble and cobble conglomerate (Fig. 2). The contact with the underlying spheroid bed is sharp and lacks evidence of mixing or weathering. One sample (AR-118) from the red–green clay layer was selected for Mössbauer analysis (Fig. 2) and one sample (AR-104) for XRD derives from the spheroid bed.

3.2. Analytical methods

3.2.1. Mössbauer spectroscopy and powder X-ray diffraction

Seven samples were selected for Mössbauer spectroscopy (Figs. 2, 6–8) and three of these were powdered and analysed by powder X-ray diffraction (XRD). Mössbauer spectra were recorded at 20 K and 300 K (room temperature) using a constant-acceleration Mössbauer spectrometer with a $^{57}$Co in Rh source. This type of spectroscopy is element specific and was employed to study the Fe-containing minerals. The spectrometers were calibrated using a thin foil of natural iron, and isomer shifts are given with respect to the centre of the calibration spectrum. Thin absorbers were prepared by mixing the sample with a...
petroleum jelly in a 5 mm thick and 10 mm diameter sample support (Rancourt, 1994). The spectra were fitted using the Lorentzian site analysis software programme in the Recoil package.

X-ray powder diffraction was used to study mineral phases in the samples. Data were obtained using a PW 1710 Philips diffractometer equipped with a Cu tube and a diffracted beam monochromator.

3.2.2. Petrology

Hand specimens representing the Barton Creek Formation and the spheroid bed (Fig. 4) from all four localities were studied and described. Additionally, thin sections from the spheroid bed and the red–green clay from Ramonal North, Albion Island and Armenia were studied by transmitted light microscopy for petrographic constituents (Fig. 5).

3.2.3. Palynology

As part of a pilot study, since carbonaceous ejecta deposits would not normally be a target for palynological analyses, five samples were processed according to standard palynological procedures at Global GeoLab Ltd, Canada: Albion Island Cretaceous dolomite (AI-143); Albion Island spheroid bed (AI-97a, AI-97b); Armenia Cretaceous red–green clay (AR-118) and Armenia spheroid bed, (AR-104). Fifteen grams of sediment were first treated with dilute hydrochloric acid (HCl) to remove calcium carbonate, and subsequently macerated by immersion in 45% hydrofluoric acid (HF). The organic residue was sieved using a 10 μm mesh and mounted in epoxy resin on glass microscopy slides. As the organic recovery was very low, all palynomorphs in the residue were identified.

4. Results and interpretation

4.1. Petrology and palynology

Petrological analysis of the red–green clay, underlying the spheroid bed at Armenia shows that the red clay is calcitic and contains ~10% 0.2–3 mm diameter, rounded limestone clasts. The red–green clay is topped by a palaeosol containing lenticular clay clasts in sharp contact with the overlying spheroid bed. The organic matter recovered from the red clay (sample AR-118) via palynological processing shows sparse occurrences of tricolpate angiosperm pollen, fern spores and the alga Botryococcus. The presence of fossil root fragments show that these deposits are terrestrial lateritic palaeosols, representing land when covered by the ejecta from the impact.

Highly vesicular glass fragments comprise about 20–30% of the overlying spheroid bed at Armenia. These glass fragments enclose some zonal altered glass cores that are possibly the products of shock-melted quartz. Accretionary lapilli, mainly composed of carbonates, comprise approximately 10–20% of the spheroid bed sample from this site. These lapilli range from ~1 mm to 6 cm in diameter and possess lithic cores, some of which are composed of altered glass (Figs. 4, 5). The unit also contains...
4.2. Mössbauer spectroscopy and powder X-ray diffraction

The Mössbauer spectra reveal simple combinations of paramagnetic doublets and magnetically ordered sextets or more complex superpositions of paramagnetic doublets and spectral components exhibiting magnetic relaxation. Sample RS-SPH from the Ramonal South spheroid bed (Fig. 8) exhibits no typical magnetically ordered components at 300 K but a clear sextet can be identified at 20 K. This sextet has a magnetic hyperfine field of 49.6 T and quadrupole shift of −0.1 mm/s indicating the presence of goethite (α-FeOOH).

The lower sample from Ramonal South (RS-160, Fig. 8) exhibits a magnetically ordered sextet and a doublet having the same relative spectral areas at 300 and 20 K. The hyperfine parameters of the sextet (magnetic hyperfine field of 52.7 T and quadrupole shift of −0.04 mm/s) identifies this component as an impure haematite (α-Fe₂O₃) with a crystallite size of several nanometres. At 300 K, the doublet has an isomer shift (0.36 mm/s), quadrupole splitting (0.55 mm/s) and linewidth (0.35 mm/s) typical of smectites.

Sample RN-68 from Ramonal North only exhibits a paramagnetic component at both 300 K and 20 K indicating the absence of iron oxides in this sample (i.e., below detection level). The behaviours of the two samples from the spheroid bed at the Albion Island section (Al-SB, Al-97) are similar to that of the sample from the Ramonal South spheroid bed, again indicating the occurrence of goethite (Fig. 6). At high resolution, the 300 K spectrum of the spheroid bed sample Al-SB exhibits a very broad relaxation component that combines with the paramagnetic doublet due to ferric iron in the smectite. This feature indicates that the goethite has a crystallite size for which magnetic relaxation at room temperature is significant — such goethite crystals are often referred to as nano-sized.

The red–green clay from the Armenia section (Figs. 1, 7) is dominated by a paramagnetic doublet that can be assigned to ferric iron in smectite. In addition, a weak-intensity sextet pattern is evident in the 20 K lines (1, 2, 5 and 6 are resolved) and in the 300 K spectra (lines 2 and 5 are resolved). The magnetic hyperfine field of the sextet (52.5 T at 20 K) identify this as due to a small amount of haematite.

Fig. 7. Mössbauer spectra measured at 300 and 20 K of selected samples from Armenia, central Belize. Note different velocity scales in spectra. Arrows 2 and 5 in the 300 K spectrum of the red–green clay indicate lines 2 and 5 in a magnetically ordered sextet assigned to haematite. Iron oxides have been identified based on the hyperfine parameters of the magnetically ordered sextets (see text).
In summary, the Mössbauer results show the presence of goethite and haematite within the spheroid bed (Figs. 6–8). However, the two oxides do not co-occur in any of the samples, i.e., samples contain either haematite or goethite possibly indicating that a single factor controls which mineral precipitates. A further possibility is that some exposures have been more weathered and that the haematite is a weathering product of goethite, as suggested by Brooks et al. (1985).

5. Discussion and conclusion

The results of this study of the spheroid bed at Albion Island, Ramonal South and Ramonal North are consistent with studies at Mimbral, Mexico, by Wdowiak et al. (2001), which revealed that the spheroid bed is characterised by the presence of goethite in nanophase. Comparisons between our low-temperature (20 K) Mössbauer data from the spheroid bed at Albion Island and Ramonal South, and that from the spheroid bed at Mimbral investigated by Wdowiak et al. (2001), show that the latter contains finer particles probably reflecting that site’s more distal location from the crater. Moreover, our study confirms the observation that goethite is the dominant Fe-oxide nanophase associated with the K–Pg boundary spheroid bed in Yucatan. Whilst goethite dominates in the North American K–Pg clay layer (Moscow Landing, Madrid East, Berwind Canyon, Starkville South), haematite dominates the European K–Pg boundary clays (Caravaca, Contessa, Petriccio and Stevns Klint; Wdowiak et al., 2001).

The elevated levels of iridium, chromium, nickel and gold from the impactor, and arsenic and carbonate from the evaporitic target rock, reveal contributions from Chicxulub even at very remote New Zealand K–Pg sites, such as Moody Creek Mine (Vajda et al., 2001; Vajda and McLoughlin, 2004). In the marine K–Pg boundary section at Woodside Creek, New Zealand, the boundary clay is 8 mm thick with an iridium-enriched 2 mm basal layer also containing grains of shocked quartz and three types of spheroids (A–C; Brooks et al., 1985). Spheroid types A and B primarily comprise microcrystalline goethite, whereas type C includes significant amounts of haematite. Brooks et al. (1985) suggested that spheroids of types A and B are weathering products of pyrite. This was also suggested by Bauluz et al. (2004) where Fe and O were identified at Woodside Creek and considered to be “alteration.
products of diagenetic pyrite". We suggest that the goethite in these spherules more likely represents Fe nano-phase oxide. We propose that the goethite formed by the processes initiated by the impact in Yucatan but further studies of the minerogenesis sequence are needed.

It is possible that the difference in the Fe-oxides between the European and North American sites is related to proximity to the impact site; those sites close to the impact containing goethite and more remote sites containing haematite. If this is the case, then the variation in the Fe-bearing phases could reflect fundamental differences in depositional mechanisms whereby goethite was deposited during the expansion of the vapour plume cloud in the atmosphere and haematite was crystallized during re-entry of particles ejected from the atmosphere. However, it is also possible that the variance in the Fe-phases evident at the various K–Pg boundary sites in Europe, North America and the Gondwana continents simply reflects the different types of target rocks that were disseminated within the rapidly expanding vapour plume. This is supported by the presence of goethite within the New Zealand K–Pg boundary clay (Ferrow et al., 2011). It is further supported by the geochemical composition of glass shards from various parts of the world showing that two types of impact glasses occur; one dark and Si-rich and another, yellow and Ca-rich. The Si-rich glass represents the crystalline deeper part of the target rock and the Ca-rich glass represents the upper evaporitic part of the target (Bauluz et al., 2004) as the impactor excavated a crater penetrating the 3-km-thick succession of carbonates, evaporites, sandstones and the underlying crystalline basement (Morgan et al., 1997). Both types of glass are present in Mexico (Mimbral) and Haiti (Beloc) (Kring and Boynton, 1991; Koeberl and Sigurdson, 1992), whilst the K–Pg boundary clay in Denmark (Stevns Klint) contains only Si-rich glass (Bauluz et al., 2000). Geochemical studies of glass shards from Southern Hemisphere sites, such as Woodside Creek and the nearby locality at Flaxbourne River in South Island, New Zealand (Bauluz et al., 2004), show that these shards are smaller than those identified from Stevns Klint (Denmark) and that they have high values of Ca (25%), making them geochemically similar to the Ca-rich impact glass found at Mimbral. Mexico (Keller et al., 2003a). Although the palaeontological evidence indicates severe disruption to the biota globally (Vincent et al., 2013), these observations do not negate the possibility of a low-angle impact hypothesis, in which the Northern Hemisphere would have received greater amounts of impact debris.

The GSSP for the K–Pg boundary is located on a Gondwana continent, at Oued Djerfane, west of El Kef, Tunisia, where it is marked by a >50-cm-thick, dark boundary clay with a rusty iridium-enriched layer at the base and a significant faunal and floral turnover (Molina et al., 2006). The paleo-position of Tunisia places it relatively close to the impact site, which possibly explains the substantial thickness of the boundary clay.

5.1. Implications for the end-Cretaceous biota

The end-Cretaceous event is undoubtedly the best-studied impact-induced global mass-extinction and, as such, serves as a model for biotic responses to extremely abrupt events throughout Earth’s geological history and the fundamental scenario for such an event is summarized in Fig. 9. Although the instantaneous effects of the impact caused local to regional destruction of biological communities by various high-energy processes (e.g., heat release, wildfires, shock waves, tsunamis and earthquakes), global communities were affected mainly by the longer term (years–decades) consequences, such as global cooling induced by aerosols formed in the atmosphere.

The local biota within the Yucatan Peninsula, both those organisms inhabiting the shallow marine environment and terrestrial settings at the time of impact, were evidently instantaneously exterminated. The Barton Creek Formation hosts a range of foraminiferal taxa including miliolids and rotaliids (Flores, 1952a) and macrofossils include rudist bivalves, gastropods and crabs (Vega et al., 1997), but well-preserved fossils are otherwise scarce due to recrystallization (dolomitization). Our results show that algal groups, such as Botryococcus, and dinoflagellates, were present in the Late Cretaceous lagoons and in the sea covering the carbonate platform at Yucatan. The presence of fossil algae both in the target rock and in the matrix of the spheroid bed indicate that some microfossils were reworked from the underlying Barton Creek Formation and resisted the high temperatures, pressures and transport processes following the Chicxulub impact.

Sparse paleontological data are available from terrestrial settings close to the impact site. The only available fossils are roots preserved in palaeosols that indicate the presence of vegetation growing on thin soils developed on the Late Cretaceous carbonates/evaporates. The local vegetation may have been adapted to arid conditions (Craggs et al., 2012) and was inevitably devastated by the impact and covered by vast deposits of molten rock and ejecta debris excavated from the crater. The ejecta deposits thin with distance from the crater, and other factors controlled extinctions at locations remote from the impact site. Whilst ejecta deposits may attain thicknesses up to 45 m at the localities studied herein, the thinnest layer identifiable by an iridium anomaly on a global basis is only a few millimetres thick and occurs in terrestrial Southern Hemisphere high-latitude settings, such as in New Zealand (Moody Creek Mine: Vajda et al., 2001; Vajda and McLoughlin, 2004; Vajda, 2012).

The target rock represented a shallow sea to slope setting with water depths ranging from 100 m to as deep as 2.5 km on the eastern flank according to Gulick et al. (2008) implying that a larger quantity of water vapour was produced than previously contended. Some studies have proposed that the ejecta deposits were chiefly directed towards North America based on the crater shape combined with palaeontological

![Fig. 9. Schematic illustration of the scenario following an asteroid impact induced extinction, and how it was manifested for the Cretaceous–Paleogene event.](image-url)
data from the North American interior that imply that the asteroid impacted from the southeast to the northwest at a 20–30° angle and mainly affected the Northern Hemisphere biota (Schultz and D’Hondt, 1996). However, later high-resolution studies across the K–Pg boundary in New Zealand have revealed that a major disruption to the biota also occurred in Gondwanan high-latitude settings.

It might be argued that this difference in ejecta distribution should also be reflected in the magnitude of the biotic response. The low quantities of clay (devitrified glass) at some remote sites, combined with the evidence of catastrophic changes to the vegetation (Vajda et al., 2001; Vajda and McLoughlin, 2004; Schulte et al., 2010), imply that the long-term sunlight suppression was probably caused by aerosols formed from the vast amount of H2O and S-containing vapour injected into the atmosphere. Recent studies have shown that sulphur trioxide (SO3) dominated over sulphur dioxide in the vapour cloud and that SO3 enhanced the formation of sulphuric aerosol particles following the asteroid impact (Ohno et al., 2014). Both sulphuric acid and nanoparticles may have acted as cloud condensation nuclei (CNN) for water in the atmosphere.

As the nanoparticles partly form by cooling of the plume, they are available almost immediately, and for as long as they are in the atmosphere they will be expected to scatter the sunlight relatively effectively. The sulphuric acid nuclei will form following a photochemical reaction between water and sulphur dioxide depending on the sunlight. The hydrous aerosols may have nucleated around nano-sized particles, such as the nano-phase Fe-oxides described from the ejecta deposits in this study and from other K–Pg boundary layers globally.

As excavated material, together with the remnants of the asteroid, was vapourized and ejected ballistically into the stratosphere, a global heat pulse was generated by ejecta re-entering the troposphere. Several studies have concluded that the atmosphere was heated globally to temperatures where only organisms with abilities/possibilities to shelter from the heat were able to survive (Melosh et al., 1999; Kring and Durda, 2002; Robertson et al., 2004 and references therein), although the existence and extent of the global heat pulse is still intensely debated. After this initial phase (time-frame of hours) with intense infra-red radiation, the principal lethal factor became the effects of dust-loading on climate and photosynthesis (Toon et al., 1982, 1997; Pope, 2002) with the large quantities of atmospheric sulphur aerosols prolonging the cooling. This process had devastating effects on the biota as far away as remote Gondwanan settings. The major killing agent would have been related to the massive drop in primary productivity induced by the suppressed light levels.

This is manifested by the presence of a fern-spine in New Zealand K–Pg boundary successions revealing a mass-kill of vegetation and initial recovery of pioneer plants in southern high latitudes after a prolonged time of darkness (Vajda et al., 2001, 2004; Vajda and McLoughlin, 2004; Ferrow et al., 2011). Long-term effects persisted in New Zealand as evidenced by Araucariaceae conifers (dominant elements of the Late Cretaceous flora in large areas of the pre-impact Gondwanan continents) being replaced by Podocarpaceae upon recovery of the seed-plant communities (Pole and Vajda, 2009; Vajda and Bercovici, 2012). A similar long-term vegetation turnover has been described from Argentinean K–Pg boundary deposits where the tree-sized conifers (Cheirolepidiaceae) briefly dominated the post-impact floras that later saw the recovery of Podocarpaceae and Araucariaceae (Barreda et al., 2012). Although the palaeontological evidence indicates severe disruption to the biota globally, these observations do not negate the possibility of a local low-angle impact hypothesis, in which the Northern Hemisphere would have received greater amounts of impact debris. The paleo-position of Tunisia places it relatively close to the impact site, which possibly explains the substantial thickness of the boundary clay at the K–Pg GSSP.

In Antarctica, a K–Pg boundary layer has been detected based on an iridium anomaly within a layer of the nearshore marine succession on Seymour Island (Askin and Jacobson, 1996) and subsequent palynological studies have shown that the succession indeed spans the boundary. However, high-resolution studies are required to decipher the details of the biological turnover on Antarctica. Likewise, a sedimentary succession on Campbell Island on the southern fringe of the Zealandia continent, which during the Late Cretaceous was still possibly attached to West Antarctica, appears to include the K–Pg boundary (Wannamper et al., 2011). However, geochemical studies are needed to confirm its position.

Several IODP drill-cores from the Pacific region show the presence of a K–Pg boundary layer based on the presence of iridium, shocked quartz and spherules (Zinsmeister et al., 1989; Schulte et al., 2010) but micropalaeontological studies have yet to be performed in order to evaluate the biotic consequences at these sites. Although we have only glimpses into the Southern Hemisphere record of biotic extinction and recovery, there is sufficient evidence to show that the extinction event was genuinely global. Several authors have invoked catastrophic heating and wildfires following the Chicxulub impact (Melosh et al., 1999; Kring and Durda, 2002; Robertson et al., 2004 and references therein), but the existence and extent of the global heat pulse are still intensely debated. After this initial phase (time-frame of hours) with intense infra-red radiation, the principal lethal factor became the effects of dust-loading on climate and photosynthesis (Toon et al., 1982, 1997; Pope, 2002).

The low quantities of clay (devitrified glass) at some sites, combined with the evidence of catastrophic changes to the vegetation (Vajda et al., 2001; Schulte et al., 2010), implies that long-term sunlight suppression was probably caused by aerosols formed from the vast amount of H2O and S vapour injected into the atmosphere. These aerosols may have nucleated around nano-sized particles, such as the nanophase Fe described in this study.

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References


