have been interpreted as being primary accretionary lapilli formed in the impact ejecta curtain as condensing water vapour adhered fine dust to spinning grains in the impact debris clouds, forming lapilli similar to those created during volcanic eruptions (e.g. Graup, 1981; Schumacher & Schmincke, 1991). However, the dolomite spheroids from the spheroid bed analysed in the present study are distinct from accretionary lapilli. Their lack of distinct nuclei and concentric layering in cross section (Fig. 3C) may have been the result of fabric-destructive diagenesis (Pope et al., 1999). However, the vermicular crystalline texture in these spheroids, which has not been documented previously in these or other KT impact spheroids (Montanari, 1990), has been preserved (Fig. 7). This implies that the dolomite spheroids either: (1) originally lacked a nucleus and concentric layering; or (2) experienced diagenesis that simultaneously preserved the vermicular fabric and destroyed the nuclei and layering.

Although no evidence was obtained conclusively to support or disprove the mechanism by which the dolomite spheroids were formed, at least three hypothetical scenarios are plausible. The first is that the dolomite spheroids were originally impact glass that was devitrified and altered to clay. As is observed in thin section (Fig. 7A and B), these clays have commonly been replaced by dolomite. Therefore, each clay spheroid may be a pervasively dolomitized clay spheroid. The second hypothesis stems from the assumption that the cloud of vaporized rock (carbonate and silicate) and water created by the bolide impact cooled rapidly as it expanded away from the Chicxulub crater. The condensation of water vapour in this cooling cloud may have triggered the nucleation of calcium and magnesium oxides, forming a dust of highly reactive ‘quicklime’ that accreted and rained out as spheroids (Ocampo et al., 1996). Where these spheroids fell into sea water, they may have been destroyed by rapid hydration, explaining the general lack of large spheroids in marine sections of KT ejecta (Montanari, 1990). In contrast to subaqueous environments, deposition at the terrestrial Albion Island site may have permitted at least short-term preservation of the spheroids until percolating surface water led to pervasive diagenesis. Gradual hydration, conversion to various metastable calcium and magnesium compounds and the eventual formation of dolomite may then have rapidly altered the spheroids. If correct, the vermicular texture may be a product of gas release during hydration of the spheroids.

An analogous series of chemical reactions is observed during the formation of Portland cement. powdered carbonate and silicate rocks are mixed in varying proportions and heated to 1400 °C (Erlin, 1969). Small proportions of water are then added to drive the precipitation of belite (Ca₂SiO₄) in the form of 20- to 40-μm-diameter subspherical cement particles, called ‘clinkers’, containing parallel crystal striations (Petersen, 1983a,b). It may be possible that the vermicular texture is somehow analogous to these parallel crystals. Larger spherical nodules are then formed as the clinkers are bound together by water via both coalescence and accretion processes. Relatively large proportions of water are required in this process to form clinkers without outer rims composed of silicate cements (Taylor, 1997), which is consistent with the observations of the dolomite spheroids.

A third related hypothesis is that the dolomite spheroids formed by mechanisms similar to those that create lunar and meteoritic chondrules. Chondrules are millimetre-sized spherical to subspherical bodies composed of silicate crystallites (‘parallel crystal barring’) that exhibit evidence of melting as well as the incorporation of particulate sulphides and Fe oxides (Roedder & Wielien, 1977; Graup, 1981; Grossman & Wasson, 1983). The parallel crystal barring may somehow be analogous to the vermicular crystallization in the spheroids, in that both crystalline fabrics extend across the host spherical grain. Two types of impact-produced chondrules have been identified, which include fluid drop chondrules composed of shock-melted silicates and lithic chondrules derived from rock fragments (Fredrickson et al., 1973a,b; Graup, 1981; Boss, 1996). Secondary pervasive dolomitization may then have replaced either of these types of chondrules to form the dolomite spheroids.

Depositional history and ⁸⁷Sr/⁸⁶Sr chemostratigraphy of the Albion Formation

Synthesis of the sedimentological and geochemical analyses completed in this study permits an evaluation of the source and transport mechanisms of the Albion Formation ejecta. The ⁸⁷Sr/⁸⁶Sr chemostratigraphy of the spheroid bed exhibits a remarkably symmetrical distribution (Fig. 10). If it can be demonstrated that the Sr in these sediments has not been significantly altered during post-depositional diagenesis, then this trend may reflect variations in the original composition of the impact glass. The δ¹⁸O vs. δ¹³C

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compositions suggest that the spheroid bed has experienced significant diagenetic alteration based on the coincidence of the data with diagenetic reaction trajectories (Fig. 11B). One interpretation is that the spheroid bed sediments were altered via water-rock equilibration with freshwater containing soil-derived CO₂ (Fig. 10B; Allen & Matthews, 1982; Meyers & Lohmann, 1985; Lohmann, 1987; Banner & Hanson, 1990; Goldstein et al., 1991; Fouke et al., 1996a,b). Alternatively, the subset of the spheroid bed δ¹³C vs. δ¹⁸O data that falls along a line (Fig. 11B) may suggest the binary mixing of sea water with freshwater or the mixing of a sea water-derived dolomite with a dolomite precipitated from freshwater (Faure, 1986). Conversely, neither diagenesis nor mixing is suggested by the ⁸⁷Sr/⁸⁶Sr vs. δ¹³C and ⁸⁷Sr/⁸⁶Sr vs. δ¹⁸O cross-plots (Fig. 11B).

Therefore, although unproven, this implies that, while the absolute values of ⁸⁷Sr/⁸⁶Sr in the spheroid bed sediments have been partially altered, their relative trends may still reflect a primary change in the chemistry of the impact glass. If previous interpretations are correct and the clay is derived from melt glass devitrification (Pope et al., 1999), then the higher ⁸⁷Sr/⁸⁶Sr of the clay sample split (Fig. 10) indicates that the original impact glass contained more radiogenic Sr than the dolomite. An associated possibility is that the symmetrical ⁸⁷Sr/⁸⁶Sr trend could have been caused by larger proportions of clay to dolomite in the middle of the spheroid bed, but no such trend was observed in thin section.

Black and yellow impact glasses derived from melting of the siliceous basement at the bottom of the Chixculub crater have been deposited in Haiti (Sigurdsson et al., 1991a; Blum & Chamberlain, 1992; Blum et al., 1993). The black glass, interpreted to be relatively pure crustal melt, has a ⁸⁷Sr/⁸⁶Sr value of 0.70901 (Sigurdsson et al., 1991a). The yellow glass has been interpreted as siliceous melt mixed with carbonate sediments and contains a ⁸⁷Sr/⁸⁶Sr ratio of 0.70799 (Sigurdsson et al., 1991a). The ⁸⁷Sr/⁸⁶Sr values of the spheroid bed dolomite–clay (0.707783–0.707809) and clay (0.707745–0.707872) sample splits are lower than those of the yellow glass ⁸⁷Sr/⁸⁶Sr (Fig. 10; Table 3). However, they are equivalent to higher than the ⁸⁷Sr/⁸⁶Sr of the Upper Jurassic to Upper Cretaceous marine limestone that comprised the impacted Yucatan platform (0.70685–0.70785; Howarth & McArthur, 1997). The intermediate ⁸⁷Sr/⁸⁶Sr composition of the spheroid bed may therefore imply that the original devitrified glass in the ejecta was some type of yellow glass created by mixing silicate melt with impacted carbonates.

As a result, it is possible that the symmetrical ⁸⁷Sr/⁸⁶Sr stratigraphic trend in the spheroid bed represents complex mixing among Sr derived from the impacted crustal rocks (limestone, evaporites, silicate basement), the bolide and sea water at the time of impact. Drill cores indicate that the shallowest depth of siliceous basement at the time of the KT impact was at a depth of ~1.7 km beneath the Yucatan platform (Ward et al., 1995). Therefore, the presence of impact glass in the spheroid bed requires that the Chixculub crater was excavated to at least this depth by the time of spheroid bed deposition to provide a source of siliceous melt. As crater excavation proceeded from the surface to the base of the Yucatan platform, the liberated ⁸⁷Sr/⁸⁶Sr would have been expected to decrease progressively (Howarth & McArthur, 1997). This is not consistent with the symmetrical distribution of ⁸⁷Sr/⁸⁶Sr in the spheroid bed (Fig. 10), suggesting that this trend does not represent progressive crater excavation. Therefore, the implication of the ⁸⁷Sr/⁸⁶Sr chemosтратigraphy in the spheroid bed with respect to cratering and ejecta deposition is uncertain.

An ejecta transport process permitting the fine-grained glass-rich sediments of the spheroid bed to outrun all other ballistic ejecta and be deposited as a thin undisturbed layer beneath the diamicite bed has not yet been identified. However, two models for ejecta dispersal applicable to the diamicite bed have been reconstructed for other impact sites. The first is the ballistic sedimentation model interpreted from the Bunites breccia ejecta blanket from the Ries crater in Germany (Horz et al., 1983). In this model, large ballistically launched clasts and blocks would have fallen back to earth near the crater, forming secondary impacts that triggered ground surge debris flows. Scouring of the earth surface during this process would have incorporated clasts from the Barton Creek Formation bedrock (Oberbeck, 1975). Therefore, if this model is applicable, the diamicite bed debris clasts may be composed of a mixture of primary clasts from the crater site and regionally to locally derived clasts eroded from the Barton Creek Formation. The second ejecta sedimentation model is the ring vortex mechanism for continuous ejecta emplacement (Schultz, 1992; Barnouin-Jha & Schultz, 1996, 1998). In this scenario, the trajectories of ejecta expelled from the impact crater initially form a curtain in the shape of an inverted hollow cone that expands outwards. The ejecta curtain acts as a barrier that
forces the atmosphere away from it, creating ring vortices. Atmospheric drag acts to decelerate the ejecta within the vortex and reduces the velocity of the ejecta curtain, causing the inverted hollow cone to collapse into a turbulent flow of debris that is deposited several crater diameters from the crater rim. If applicable, the diamicite bed should be dominantly composed of clasts derived from the crater rather than from the Barton Creek Formation.

The evidence collected in the present study is inconclusive regarding whether ballistic sedimentation or ring vortex collapse more accurately describes ejecta dispersal from the Chicxulub crater. Ocampo et al. (1996) and Pope et al. (1999) interpreted the majority of diamicite bed clasts to be primary ejecta and thus suggested that the ring vortex model is most applicable. Their interpretation was based on: (1) significant differences in sedimentological composition observed between the Barton Creek Formation limestone and the clasts in the diamicite bed; and (2) rudist biostratigraphy, suggesting that some of the diamicite bed clasts may be Lower Cretaceous. However, significant variations in sedimentological and chemical composition of the limestone would be expected across the broad expanse of the Yucatan platform. Therefore, the differences in dolomite petrography and chemistry may be a product of lateral variations rather than an indication of deep crater excavation. In addition, the bulk rock $^{87}$Sr/$^{86}$Sr from the diamicite bed clasts exhibit consistent upsection decreases (Fig. 10). Therefore, although conjectural at this point, this chronostratigraphic trend in clast $^{87}$Sr/$^{86}$Sr is consistent with increasing depth of excavation within the Yucatan platform. This may imply that at least some of the clasts were primary ejecta derived during cratering from subsurface horizons in the Yucatan platform.

CONCLUSIONS

The depositional and diagenetic history of KT impact ejecta deposited 360 km from the Chicxulub crater at Albion Island, Belize, has been evaluated with CL petrography and isotope geochemistry. The base of the section, exposed in an active quarry on Albion Island, consists of Late Cretaceous Barton Creek Formation marine limestone deposited on the Yucatan carbonate platform before the impact. The overlying 16 m of sediment are KT impact ejecta deposits called the Albion Formation. This unit is composed of a 1-m-thick spheroid bed of fine-grained dolomite and clay-rich sediments with small spheroidal pebbles, and a 15-m-thick diamicite bed composed of a coarse conglomeratic breccia with clasts up to 7-3 m in diameter. A paragenetic sequence of 14 depositional and diagenetic events has been documented in the Albion Island section, which has been used as a contextual framework to interpret bulk-rock $\delta^{18}$O, $\delta^{13}$C and $^{87}$Sr/$^{86}$Sr analyses.

A thin red dolomitized breccia at the uppermost surface of the Barton Creek Formation caps upsection decreases in bulk-rock $\delta^{13}$C and $\delta^{18}$O, indicating that the Albion Island site was subaerially exposed and pervasively dolomitized before the KT impact. Abundant 1-cm-diameter dolomite spheroids in the spheroid bed exhibit unique vermicular crystalline textures and lack the concentric zonations common to other accretionary lapilli in the Albion Formation. These dolomite spheroids are hypothesized originally to have been impact glass, or Ca and Mg oxide dusts that adhered to condensing water particles in the impact vapour cloud and underwent rapid hydration and dolomitization after deposition. The earliest precipitation of dolomite observed in the matrix of the Albion Formation post-dated clays formed by devitrification of impact glass. This indicates that the dolomites comprising the matrix of the Albion Formation are also products of post-depositional diagensis. Bulk-rock $^{87}$Sr/$^{86}$Sr in the spheroid bed exhibit a distinct symmetrical stratigraphic distribution. Comparison with modelled water-rock interaction trends suggests that, although the spheroid bed has experienced extensive diagenetic alteration, variations in $^{87}$Sr/$^{86}$Sr may reflect primary changes in the composition of the original impact glass. The petrography and bulk-rock $^{87}$Sr/$^{86}$Sr of large clasts in the diamicite bed indicate that they were not locally derived from the Barton Creek Formation limestone. However, they may have been eroded from equivalent or older limestone horizons in the Yucatan platform closer to, or within, the Chicxulub crater. The results indicate that both the ballistic and the ring vortex models remain viable models for the interpretation of ejecta dispersal from the Chicxulub impact crater.

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Unravelling the Cretaceous-Paleogene (KT) Turnover, Evidence from Flora, Fauna and Geology

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Abstract. The global devastation of ecosystems as a consequence of a meteorite impact 65 million years ago is clearly detectable in palaeontological and geological records all over the globe. Here we compare and contrast the consequences of the impact expressed in the vegetation, vertebrate fossil record and geological signatures left by the devastation, including information from new proximal KT boundary exposures and new palynological data. The geological evidence of the Chicxulub impact crater shows that the target rock was composed by higher percentages of anhydrite (sulfur source) than carbonates. Atmospheric radiative transfer models suggest that the vaporized target rock rapidly converted into sulfuric acid H₂SO₄ aerosols where it was injected in the stratosphere by the force of the impact and globally distributed. It took at least 10 years for the H₂SO₄ to dissipate, making the Earth’s atmosphere opaque to sunlight, leading to a reduction of solar transmission to 10-20% of normal for that period.

Southern Hemisphere terrestrial Cretaceous-Paleogene boundary sediments in New Zealand reveal that a diverse Late Cretaceous vegetation was abruptly followed by a short interval dominated by fungi, before the pioneer vegetation of ferns re-conquered the soil. The fern dominated interval, so called fern spike is also evident from Northern Hemisphere Cretaceous-Paleogene boundary sections. The massive depletion in spore-pollen diversity is interpreted to reflect devastation of photosynthetic plant communities, a scenario that agrees well with the atmospheric radiative transfer models. The pattern of vertebrate extinctions revealed by the fossil record accords with the temporary, global devastation of photosynthetic plant communities. Vegetation depletion at high latitudes may also explain
the extinction of polar dinosaurs, which apparently were able to withstand relatively cool temperatures and periods of low light intensity: the main reason for their disappearance appears to have been lack of food rather than darkness and cooling.

1 Introduction

Earth history is punctuated by five major mass extinctions (Raup and Sepkoski 1982, 1986; Sepkoski 1990). The latest and perhaps best studied of these mass extinction events is the one that occurred 65 Ma ago as a consequence of a meteorite impact (Alvarez et al. 1980) at the Yucatán peninsula, the so called Chicxulub impact (Hildebrand et al. 1991; Pope et al. 1991). This dramatic event left its signature in the fossil flora, fauna and sedimentological record of the Earth; the biological extinctions defining the Cretaceous-Paleogene boundary. The end Cretaceous mass extinction is also constrained by a sharp geochemical anomaly enabling identification of the boundary commonly at millimetre scale. This provides a robust, independent, calibration point for documenting the biological response to the catastrophe.

A global system approach to mass extinction studies is crucial to gain a greater insight into the environmental mechanisms behind the ecological disruption and biodiversity crisis in the wake of the impact. It may appear that the marine ecosystem was more affected by the mass extinction than its terrestrial counterpart, but perhaps this is partly due to the fact that the terrestrial ecosystem has been less studied and the continental geological and vertebrate record is less complete.

This work aims to review, compare and integrate both published and new results from different fields, such as palynology, vertebrate palaeontology and post-impact sedimentary mechanisms in order to better resolve the processes affecting terrestrial ecosystems and depositional systems at a global scale at the Cretaceous-Paleogene boundary.

2 Geological evidence

The question whether there is a correlation between large impacts craters and extinctions of biota has been dealt with in several studies of impact craters throughout the geological record (Heissig 1986; Aubry et al. 1990;
Dypvik 1996; Kring 1997; Becker et al. 2004). However for the Chicxulub impact there is a clear correlation to a large biotic turnover and mass extinction where the Cretaceous-Paleogene boundary horizon is globally identified as a sharp contact associated with an iridium anomaly in parts per billion (Alvarez 1980). Other features characterizing the boundary horizon is the presence of shocked quartz (Figure 1) and tektites reflecting the geochemical signature of the target rock (Izett 1991; Izett et al. 1991).

The proximal ejecta layers (200-500 km from the crater) consist of vast sediments up to tens of meters in thickness, thinning out with increased distance from the crater. As a comparison the distal boundary layers are only centimetres to millimetres thick in terrestrial and marine settings worldwide (Smit 1999). In these deposits, the first few minutes, hours, days and months after the impact are preserved.

![Fig. 1. A. Grain of shocked quartz (~200μm) found in Belize in the Cretaceous-Paleogene fireball layer. B. Thin section of an accretionary lapilli with a glass core (pink centre) from Albion Formation, Belize. C. Thin section from the diamicrite, Albion Formation, Belize. Shard of vesicular impact glass and foraminifera fragment in a calcareous matrix.](image)

The near ejecta sequence dramatically outcrops in Belize and Southern Mexico, consisting of tens of meters in thickness and some of these exposures have been investigated over the last decade (Ocampo et al. 1996; Ocampo 1997, Vega et al. 1997, Fouke et al. 2002; Keller et al. 2003a, 2003b). The Belize and southern Mexico exposures show proximal ejecta of the Chicxulub impact in the form of a sub-aerial ejecta blanket which is characterized by a two member stratigraphical unit, the so called Albion Formation. The Albion Formation was first defined in Northern Belize at about 300 km from the impact site as the most proximal outcrop of the ejecta blanket (Ocampo et al. 1996; Ocampo 1997). The lower unit of the Albion Formation, also called the Spheroid Bed, contains spherules, altered vesicular glass shards, and other impact debris. The upper unit, the so-called Diamictite Bed, overlays the Spheroid Bed and contains abundant shocked quartz, and is also rich in siderophile elements, most notably iridium. The Albion Formation (Spheroid Bed and Diamictite Bed)
was formed during the first few minutes following the impact and reflects different depositional processes generated by the impact (Figure 2). Subsequently, the Albion Fm was recognized at several new Cretaceous-Paleocene localities in Southern Quintana Roo, Mexico, exposed at Alvaro Obregon, Ramonal, Agua Dulce and Thompson Quarry, to name a few sites. The formation was also identified in Central Belize, Armenia, at a distance of 500 km from the Chicxulub crater where the contact between the Cretaceous dolomite of Barton Creek Fm and the overlying spheroid bed of Albion Fm is found. Interestingly, at a distance of 800 km from the crater, in Santa Teresa, southern Belize, a tektite layer is exposed, similar to the tektites found in Guayal of southern Mexico (Salge et al. 2000).

![Diagram](image)

**Fig. 2.** Scenario immediately following the Chicxulub impact showing the three main transport processes that contributed to the genesis of the Spheroid Bed and Diamictite Bed.

The origin of this two-part stratigraphy is controversial, but at least three major processes were involved in the genesis of these deposits; debris
flow, ballistic ejecta and carbonate vapour condensation (Ocampo et al. 1996). The first to be deposited were the spherules which condensed from the cooling vapour plume, expanding at a rate of approximately 20 km/s. These spherules yield a light oxygen isotopic signature that is consistent with genesis within the expanding vapour plume cloud by condensation and coagulation and subsequently mixing with fragmented rock. Precipitation of these millimetres to centimetre-sized spherical pebbles (spherules) of CaCO₃ and (CaMg)(CO₃)₂ produced the Spheroid Bed, the lower ejecta layer. The Diamictite Bed, which overlies the Spheroid Bed, is mainly composed of larger pebbles and blocks up to 8 m in diameter (many with striations), and was deposited from a debris flow travelling near the ground at a speed of 0.3 km/s. Ballistic material transported at an estimated speed of 2 km/s is also incorporated in the Diamictite Bed (Pope et al. 1994, 1997; Ocampo et al. 1996). The ejecta blanket distribution around the crater remains an important factor in determining the impact angle (Pierazzo and Melosh 2000a,b). The distribution of near ejecta deposits found in southern Mexico and Belize further corroborates the oblique angle of impact. Rock volumes of 300 - 2000 km³ were vaporized at the impact, releasing 2.7 to 8.2 x 10¹⁷ grams of sulfur (Pope et al. 1994, 1997; Iyanov et al. 1996). A minor part of the sulfur was released as SO₂ or SO₃²⁻, but the majority produced sulfuric acid aerosol (Figure 2). The vast quantities of sulfur dioxide released into the atmosphere (Kring et al. 1996), in combination with the atmospheric water vapour, produced H₂SO₄ clouds that were distributed globally in the stratosphere, and attenuated sunlight penetration to the surface to approximately 20% of normal for about 10 years. The sulfuric acid-rich clouds’ capability to remain in Earth’s atmosphere for up to a decade was the prime mechanism inhibiting sunlight penetration to the surface producing near freezing temperatures (Pope 2002).

Previous results based on 3D hydrocode simulations have shown that the impact angle affects the strength and distribution of the shock wave generated and that the volume of melt is directly proportional to the volume of the transient crater generated by the impact (Pierazzo and Melosh 2000a,b). For a crater such as Chixculub, with an impact angle below 45 degrees, the amount of melted target material is less compared to a vertical impact of the same size impactor. However, due to the substantial amount of anhydrite in the target rock, sulfur became more disruptive to the biosphere than impact-generated CO₂ (Pope et al. 1994, 1997; Pierazzo et al. 1998, Pierazzo and Melosh 2000a,b). During the first months to a year after the impact, dust and soot from post impact wild fires played a greater role in blocking sunlight (Wolbach et al. 1988; Kring and Durda 2002), however the sulfuric acid aerosol provided the most
damaging longer-term effect to the biosphere (Pope 2002; Toon et al. 1997; Covey et al. 1994; Pollack et al. 1983).

3 Vegetation response

There is now overwhelming evidence for global disruption of vegetation at the Cretaceous-Paleogene boundary. However, there are important regional differences in the signature of vegetation turnover. The data suggest both massive devastation and mass extinction of plants at many Cretaceous-Paleogene boundary sections in North America (Nichols and Johnson 2002; McIver 1999; Hotton 2002; Norris 2001) but mainly mass-kill of vegetation at Southern Hemisphere high latitudes resulting in dramatic but short-term changes in the relative abundance of plant groups (Vajda et al. 2001; Vajda and Raine 2003; Vajda and McLoughlin 2004).

The floristic turnover is evident at centimetre scale in many terrestrial sections, enabling precise positioning of the Cretaceous-Paleogene boundary. The most characteristic palynological feature of the Cretaceous-Paleogene boundary is the sudden disappearance of a diverse Maastrichtian pollen assemblage, usually followed by a low-diversity succession of ferns in the earliest Paleocene. This so-called fern-spore spike is well-documented in the southern United States where several extinctions and an abrupt decline in angiosperm pollen is followed by an impoverished flora dominated by ferns. The fern-spore spike associated with iridium enrichment in the sediments was first reported by Orth et al. (1981) in material from New Mexico. Subsequently, palynology has been used extensively for high resolution investigations of non-marine midcontinental North American sections, to document the response of terrestrial plants to the this event (Jerrynkiewicz and Sweet 1986; Nichols et al. 1986; Wolfe and Upchurch 1986; Bohor et al. 1987; Lerbekmo et al. 1987; Upchurch and Wolfe 1987; Upchurch 1989; Nichols and Fleming 1990; Sweet et al. 1990, 1999; Wolfe 1991; Sweet and Braman 1992, 2001; Nichols et al. 1992; Braman et al. 1993; McIver 1999; Nichols and Johnson 2002; Hotton 2002; Barclay and Johnson 2004). These studies agree that all North American plant communities experienced severe simultaneous disruption at the Cretaceous-Paleogene boundary. The extinction rate of plants based on the palynoflora ranges from 15% in the Raton Basin (Fleming 1985) to 30% at Morgan Creek and southwestern North Dakota (Nichols et al. 1986; Nichols and Johnson 2002). Megaforal
turnover has been documented from a vast number of sections in southwestern North Dakota where a loss of 57% of the plant species are correlated to the end-Cretaceous extinction (Wilt and Johnson 2004).

There seems to exist a major discrepancy between the turnover traced in the pollen record, compared to extinction seen in the megaflora. In sediments where palynology and megafloras have been compared, an extinction of 80% of the megaflora corresponds to a turnover rate of 30% in the pollen-spore record (Johnson et al. 1989; Johnson 1992; Nichols and Johnson 2002). However, the high extinction rate does not appear to be consistent throughout North America as detailed studies of miospores from a Cretaceous-Paleogene boundary section in Saskatchewan, Canada, demonstrate mass kill of standing vegetation but lacks evidence of mass extinction (McIver 1999). Additionally, some sections in western Canada reveal an anomalous rise in angiosperm pollen abundance following the Cretaceous-Paleogene boundary comparable to the fern-spike identified elsewhere (Sweet et al. 1990). In these localities the pioneer vegetation most probably comprised opportunistic, herbaceous angiosperms instead of ferns.

Well-defined, terrestrial, KT sections are non-existent in Europe but a bryophyte spike (moss spores), comparable to the fern-spike, has been reported from marine KT boundary sections in the Netherlands at Curf Quarry (Herngreen et al. 1998) and in the Geulhemmerberg caves (Brinkhuis and Schoel 1996). The sudden bloom of bryophytes immediately after the KT boundary indicates a major change in the terrestrial ecosystem.

New Zealand, located in the southern hemisphere at the time of impact and far from the Chicxulub crater site, provides an invaluable opportunity to test the global effects of the impact on the biodiversity of the ecosystems. We have recent palynological data from five New Zealand Cretaceous-Paleogene boundary sections (both outcrops and drillcores), all located within the Greymouth Coalfield. The palaeoenvironment consisted of a braided river system covered with swamp vegetation, where silt and mud was sporadically deposited on coal-forming floodplain mires between sandy channel tracts.

The Cretaceous-Paleogene boundary falls within the Paparoa Group, which comprises several coal-bearing intervals (Nathan 1978; Ward 1997). The boundary has been pinpointed by palynology in both marine and terrestrial sediments (Vajda et al. 2001; Vajda and Raine 2003; Vajda and McLoughlin 2004) and is characterized by massive vegetation disruption. The palynological signal through the New Zealand KT sections is nearly identical to those of the southern and central United States. The turnover in the flora is very sudden in the investigated sequences. The latest
Maastrichtian palynoflora includes over 100 species of miospores, but these are suddenly replaced, following the geochemical anomaly, by diversifying fern spores in the earliest Paleocene.

Fig. 3. Spores from the Cretaceous-Paleogene boundary section at Moody Creek Mine, New Zealand, magnification 500x. (a) Laevigatosporites ovatus, spore related to modern Blechnum, a groundfern and first pioneer species recovering after the end-Cretaceous event in Southern Hemisphere, New Zealand sections. (b) Gleicheniidites senonicus, spore related to modern Gleichenia, ground fern and early coloniser (c) Cyathidites minor, of probable tree fern affinities (d) Cibotiidites tuberculiformis, another tree fern component and part of recovery succession following the ground ferns. (e) Tricolpites lilliei, flowering plant pollen and a good stratigraphic marker as it becomes extinct at the KT boundary. (f) Nothofagidites kaitangata, another key species extinct at the KT boundary. (g) Tricolpites phillipsii, a flowering plant pollen and one of first new species to evolve after the KT event, encountered several metres above the KT boundary in New Zealand. (h) Phyllocladidites mawsonii pollen is closely related to those of the modern Huon Pine (Lagarostrobus franklinii) and does not attain pre-event abundance until hundreds to thousands of years after the event.

Extinction of only a few Cretaceous key taxa, such as Tricolpites lilliei and Nothofagidites kaitangata (Figs 3 E-F), at the iridium anomaly horizon, followed by a 4 mm layer only containing fungal spores but barren of plant spores and pollen, typifies the New Zealand KT boundary palynological record (Vajda and McLoughlin 2004). The fungal spores are represented by several genera, e.g., Monoporisporites sp. and Multicellaeasporites sp. and were probably plant saprophytes as the assemblages are of low diversity and are often found associated with fossil
tracheids of conifer wood. Interestingly, iridium values are still at their maximum 5 mm above the boundary when the recovery flora of ground ferns return, suggesting rapid re-establishment of ferns in the aftermath of the Chicxulub impact event (Vajda and McLoughlin 2004).

The pioneer recovery vegetation, following the end-Cretaceous catastrophe consists of *Laevigatosporites ovatus* (Figure 3A) succeeded by *Gleicheniidites* (Figure 3B), both representatives of ground ferns. Younger assemblages are dominated by tree fern spores, e.g., *Cyathidites* and *Cibotioides* (Figures 3C-D).

The period with fern dominance was in New Zealand followed by a stage dominated by the conifer pollen *Phyllocladidites mawsonii* (Figure 3H), closely related to the modern Huon Pine. The evolution of new species was rather slow and only a few new species of pollen appear close above the boundary, e.g., *Tricolpites phillipsii* (Figure 3G) and *Nothofagoides waipawensis*, all belonging to flowering plants.

4 Vertebrate turnover at KT boundary

There has been much debate concerning the extinction of the dinosaurs, and whether their demise was sudden or gradual but there is now substantial support for an abrupt extinction of the non-avian dinosaurs, although doubts are still sometimes expressed about the reality of that mass extinction (Sarjeant and Currie 2001). The argument that dinosaurs did not really become extinct at the KT boundary, because their descendants, the birds, survived, is merely playing on words. The fact that all non-avian dinosaurs disappeared at the KT boundary did have a very profound effect on the composition and structure of terrestrial communities. One of the most striking consequences of that event was the disappearance of all large terrestrial vertebrates. Contrary to what has been claimed (Sarjeant and Currie 2001), the large flightless birds recently reported from the Late Cretaceous of Europe (Buffetaut and Le Loeuff 1998) were archaic forms not related to present-day ratites, or, for that matter, to the Early Paleogene giant flightless Gastornithiformes (Buffetaut 2002), and there is not the slightest evidence that they survived the end-Cretaceous mass-extinction event.

Documentation of faunal diversity from terrestrial ecosystems shows that dinosaurs and pterosaurs were the only major terrestrial vertebrate groups that went completely extinct at the KT boundary event. Most other vertebrate groups were subjected to a mass-kill but no mass extinction is
evident (Milner 1998). The main problem for detailed statistical analyses of vertebrate assemblages is the scarcity of fossils and the few terrestrial KT boundary sections containing vertebrate fossils. The sediments of the western interior of North America provide one of the world’s best records of dinosaur fossils up to the KT boundary boundary. For example, the Hell Creek Formation of Montana and North Dakota and the Lance Formation of Wyoming, USA, contain assemblages of dinosaur fossils extending up to the Cretaceous-Paleogene boundary, which is well constrained by terrestrial palynology and, in some cases, by geochemistry. Data from as many as 53 vertebrate sites from the Hell Creek Formation strongly support a scenario of sudden extinction of dinosaurs (Pearson et al. 2001, 2002). A much-publicised “3 m gap”, supposedly lacking dinosaur fossils at the top of the Hell Creek Formation, was used as evidence that dinosaurs had become extinct (or nearly so) before the KT boundary in North America. Recent research (Sheehan et al. 2000) has shown that in Montana and North Dakota the abundance of dinosaur fossils in the top 3 m of the Hell Creek Formation is comparable to what it is at lower levels in the formation, so that evidence for gradual extinction is absent.

In Europe there are no known dinosaur localities encompassing a well-defined KT boundary. This may be partly a consequence of difficulties in correlating the terrestrial dinosaur-bearing sediments with well-dated marine sediments. However, there are latest Maastrichtian dinosaur localities in the French and Spanish Pyrenees, Aix en Provence (France), Romania, The Netherlands, Belgium, Germany and the Ukraine (López-Martínez et al. 2001). Knowledge of Late Maastrichtian ecosystems in Europe has been greatly improved in recent years by discoveries of stratigraphically well-constrained diverse dinosaur assemblages from the Pyrenees in France (Laurent et al. 2002) and Spain (López-Martínez et al. 2001). Fossil bones of hadrosaurian dinosaurs are most frequently found in the sediments but recent investigations of the Cassagnau locality, southwestern France (Laurent et al. 2002) have revealed, apart from abundant hadrosaur bones, theropod and sauropod dinosaurs, which indicate that at least five dinosaur families inhabited western Europe in the Maastrichtian. The European dinosaur assemblages do not support any gradual decrease in species diversity during the Late Maastrichtian (López-Martínez et al. 2001; Laurent et al. 2002).

On a global scale, a recent examination of dinosaur diversity through the Mesozoic (Fastovsky et al. 2004) shows a steadily increasing rate of diversification. Against this background, fluctuations in known dinosaur diversity during the Campanian and Maastrichtian have little significance, and the data do not suggest a decline in diversity leading to extinction during the last ten million years of the Cretaceous.
Dinosaur fossils are encountered in Maastrichtian sediments from every continent and there have also been sporadic reports of dinosaurs in Paleocene sediments from various parts of the world (e.g., France, United States, Bolivia, China). Some of the older reports are based on misidentifications of non-dinosaurian remains. In all instances when undoubted dinosaur remains have been reported from post-Cretaceous rocks, subsequent studies have shown that either the fossils were reworked, or the purported Paleogene age of the sediments was incorrect. In some instances, accurate placement of the KT boundary is crucial. A recent example of purported Paleocene dinosaurs comes from China. Zhao et al. (2002) claimed evidence of a major extinction at the KT boundary in the Nanxiong Basin, South China, but suggested that dinosaurs in that province survived the KT event by about 250,000 years. The KT boundary is constrained by palynological data. The evidence for dinosaurs surviving into the Paleocene consists of dinosaur nests where the eggshells show an enrichment of iridium. It is suggested that the anomalous trace element concentrations were provided by the food source. Pathological development is traced in the eggs that were produced after the KT event and only a few of them seemed to have hatched due to environmental poisoning. However, the palynological definition of the boundary by Zhao et al. (2002) contradicts previous works, (Zhao 1978, 1993, 1994; Zhao et al. 1991) where the boundary is set higher in the sedimentary succession, at the last occurrence of the eggshells. Both the extinction process by environmental poisoning and the placement of the KT boundary appear highly dubious, and this report from the Nanxiong Basin does not convincingly demonstrate that dinosaurs survived the Cretaceous-Paleogene catastrophe.

Similarly, it has recently been claimed (Fassett et al. 2002) that Paleocene dinosaur remains occur in the Ojo Alamo Sandstone of New Mexico. According to Fassett et al. (2002), persistence of dinosaurs for about one million years after the end-Cretaceous asteroid impact might have resulted from the survival of embryos inside eggs laid just before the disaster. However, this claim is based mainly on palynological evidence for a Paleocene age for the sediments containing the so-called "Lazarus dinosaurs", and renewed sampling has not confirmed it, indicating instead a Maastrichtian age (Sullivan et al. 2002).

Despite various claims to the contrary, there is thus no convincing evidence for the survival of dinosaurs after the KT boundary anywhere in the world.
5 Discussion and summary

Although dinosaurs are the most spectacular victims of the catastrophe, they do not provide the best evidence of the events at that time because their fossil record is much more scanty and discontinuous than that of the marine planktonic organisms or terrestrial palynomorphs. However, there is apparently no significant decline of dinosaur communities prior to the KT boundary (Le Loeuff 2000), and abrupt extinction is likely, albeit difficult to demonstrate because of the nature of the record. It should also be remembered that several groups of vertebrates survived the KT (Buffetaut 1990) with moderate or insignificant damage, among them the ectothermic reptiles, which are known to be sensitive to climate change (Figure 4). A likely scenario involves worldwide food chain collapse (Buffetaut 1984) leading to the extinction of large herbivores and subsequently of the carnivores, which preyed on them, whereas freshwater ecosystems were much less affected because food webs were less immediately dependent on photosynthetic organisms (Sheehan and Fastovsky 1992). Similarly, small continental vertebrates such as mammals and small reptiles, apparently were less affected because they were part of food chains based on organic matter in soils (Sheehan and Fastovsky 1992). Freshwater life may also have been protected from the effects of acid rain due to the formation of larnite, Ca$_2$SiO$_4$ (Maruoka and Koeberl 2003). Larnite was formed as a consequence of contact metamorphism of the limestone in the Chicxulub impact area and was globally dispersed via the stratosphere. Larnite accumulating in freshwater bodies may have buffered the low pH conditions created by the sulfuric acid rain making the environment less lethal for aquatic species compared to the land dwelling biota.

Despite the many questions remaining (e.g., why did small carnivorous dinosaurs disappear while birds survived?), the vertebrate fossil record at the KT boundary is generally in good agreement with the scenario of food chain collapse following devastation of plant communities. From that point of view, the importance of the discoveries from New Zealand, revealing a pattern of vegetation devastation followed by recovery very similar to that recorded in North America, lies in the fact that they strongly suggest that the vegetation crisis was global, and not a local North American phenomenon caused by geographic proximity to the Chicxulub impact. The New Zealand record shows that the Southern Hemisphere was just as badly affected as the Northern Hemisphere. A genuinely global crisis is
needed to explain the world-wide extinction of dinosaurs, and the palynological record appears to support the idea that general food chain collapse following cessation or reduction of photosynthesis is a valid explanation for the observed patterns of terrestrial vertebrate extinctions. The low extinction rate observed in New Zealand vegetation (10-12%) is, however, in contrast to the North American values of 15-30%. The possible explanation is that the high latitude Southern Hemisphere vegetation at the time was dominated by ferns and conifers in contrast to the more light-dependent flowering plants.

Although there is good agreement between the pattern of vertebrate extinctions revealed by fossils and the scenario of food chain collapse, other aspects of the KT extinction are more problematic. Models involving a drastic and relatively protracted drop in temperatures (Figure 5) are not easily reconciled with the fossil record (Buffetaut 1984, 1990), which unambiguously shows that temperature-sensitive organisms, such as ectothermic reptiles (turtles, lizards, crocodilians) were little affected by KT events (Figure 4). In other words, the hypothesis of a severe cold spell is not supported by palaeontological evidence.

Advances in our knowledge of high latitude vertebrate faunas in the Cretaceous are revealing in this regard (Buffetaut 2004). In Arctic North America, climatic cooling from the Turonian to the Maastrichtian resulted in the disappearance of ectothermic reptiles, whereas it apparently did not affect dinosaurs. The opposite pattern is seen at the KT boundary, when ectothermic reptiles survived while dinosaurs disappeared. The hypothesis according to which dinosaurs fell victim to climatic cooling during the last stages of the Cretaceous is therefore highly unlikely.

How to accommodate darkness resulting in a severe reduction of photosynthesis with a continuation of mild climates is an obvious problem. In any case, there is no evidence that climatic cooling played an important part in KT vertebrate extinctions, food chain collapse being a much more convincing scenario. A study made in order to assess the difference in survival rates between plants subjected to prolonged darkness (10 weeks) and warm conditions (15 degrees) versus plants subjected to prolonged darkness and cold conditions (4 degrees, Read and Francis 1992) revealed that more damage was recorded in the 15 degrees dark treatment than in the 4 degrees treatment among evergreen species due to excess respiration. This may demonstrate that prolonged darkness does not have to be combined with low temperatures to produce massive die-back of vegetation.

Plant-insect associations from the Williston Basin of southwestern North Dakota provide evidence for a major extinction of herbivorous insects (Labandeira et al. 2002). This large loss of specialized insect
associations can perhaps explain the higher extinction rate among insect-pollinated angiosperms (flowering plants), compared to conifers and ferns. Furthermore, it should be emphasized that, according to the scenario outlined above, most of the extinctions at the KT boundary must have taken place within a very short time span. Again the New Zealand palynological and geochemical record provides important clues as the recovery succession of ground ferns appears in the layer where the anomalous trace element concentration is still at its peak, suggesting the first recovery of Blechnum-related ferns appeared within a year of the impact, when dust was still settling but light levels were high enough to allow photosynthesis and when temperatures may have been lower.

Fig. 4. Scenario of vertebrate extinction at the KT boundary based on food chain collapse. The iridium anomaly (left) illustrates the consequences of the Chicxulub asteroid impact. The fern spore spike is a marker of floristic devastation caused by cessation or reduction of photosynthesis, itself caused by dust and aerosols injected into the atmosphere by the impact. The food chain to which dinosaurs belong collapses when herbivorous dinosaurs (illustrated by Triceratops) disappear because of lack of food, followed by carnivorous dinosaurs (illustrated by Tyrannosaurus). Members of freshwater ecosystems (crocodile), belonging to different food chains not directly dependent on primary productivity, are not strongly affected. Similarly, some small terrestrial vertebrates (mammal) are able to survive because they belong to food chains based on organic matter in soils. After Buffetaut (1994).

Atmospheric radiative transfer models of sunlight filtration following the Chicxulub impact indicate that the photosynthesis crisis did not last more than a few years (Pope 1994, 1997; Figure 5) and that the longer effect of about 10 years was due to the slow dissipation of the sulfuric acid clouds that enveloped the planet shortly after the impact. The amount of biological evidence is in agreement with this, although more quantitative data are needed: a more protracted crisis would probably have resulted in more extinctions in the plant world, and depletion of organic matter reservoirs in freshwater and soils, which in turn would have led to more
severe extinctions among vertebrates. The apparent lowering of oceanic pH agrees with the more devastating effect that took place on planktic foraminifera, where 75% went extinct. The pattern of vertebrate extinction at the KT boundary does suggest a rather brief but significant reduction of photosynthetic activity, not accompanied by a severe temperature drop. Models of KT boundary events must take these palaeontological constraints into consideration.

![Graph showing changes in insolation and ocean temperature](image)

Fig. 5. Models of the changes in insolation and ocean temperature during the 20 years following impact. The shaded area indicates the period in which dust is the major factor in insolation drop - sulfur aerosols are the primary control on insolation inhibition during the remaining interval.

The models show that vaporization of sulfates by the Chicxulub impact, and the subsequent generation of long-lived sulfuric acid aerosol haze, caused major cooling during the decade after the impact. A few years after the impact, surface temperatures may have dropped below freezing in many areas, especially large continental regions. According to the insolation models, these factors played a key role in the mass extinction that marks the KT boundary (Pope 1999). Recent evidence shows that the Chicxulub impactor was chondritic (Kyte 1998; Shukolyukov and Lugmair 1998) in nature, reducing the contribution of the sulfur from the bolide and
pointing towards the majority of the sulfur contribution being from the
target rock.

The Chicxulub impact event brought rapid and long term effects and the
massive quantities of dust and sulfate aerosols released from the target
rock were a lethal combination for the flora and fauna of the time.

In summary, the processes that brought about this mass extinction 65
Ma are complex and diverse, and only with a multidisciplinary approach
can the enigma of the KT mass extinction be unravelled.

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Author’s contribution to Chapter 6: Provided the geologic data to compare to the 2-D hydrocode model of the Chicxulub impact. Estimated volume of anhydrite. Developed and described stratigraphical model and geological setting. Integrated results and conclusions.
Express letter

Impact winter and the Cretaceous/Tertiary extinctions: Results of a Chicxulub asteroid impact model

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Abstract

The Chicxulub impact crater in Mexico is the site of the impact purported to have caused mass extinctions at the Cretaceous/Tertiary (K/T) boundary. 2-D hydrocode modeling of the impact, coupled with studies of the impact site geology, indicate that between 0.4 and \(7.0 \times 10^{12}\) g of sulfur were vaporized by the impact into anhydrite target rocks. A small portion of the sulfur was released as \(\text{SO}_3\) or \(\text{SO}_4\), which converted rapidly into \(\text{H}_2\text{SO}_4\) aerosol and fell as acid rain. A radiative transfer model, coupled with a model of coagulation indicates that the aerosol prolonged the initial blackout period caused by impact dust only if the aerosol contained impurities. A larger portion of sulfur was released as \(\text{SO}_2\), which converted to aerosol slowly, due to the rate-limiting oxidation of \(\text{SO}_2\). Our radiative transfer calculations, combined with rates of acid production, coagulation, and diffusion indicate that solar transmission was reduced to 10–20% of normal for a period of 8–13 yr. This reduction produced a climate forcing (cooling) of \(-300\ \text{Wm}^{-2}\), which far exceeded the \(+8\ \text{Wm}^{-2}\) greenhouse warming, caused by the \(\text{CO}_2\) released through the vaporization of carbonates, and therefore produced a decade of freezing and near-freezing temperatures. Several decades of moderate warming followed the decade of severe cooling due to the long residence time of \(\text{CO}_2\). The prolonged impact winter may have been a major cause of the K/T extinctions.

1. Introduction

Alvarez and his colleagues [1] originally proposed that the large dust cloud from an asteroid or comet impact blocked out the sun and caused mass extinctions at the end of the Cretaceous. The recent recognition that the Chicxulub structure in northwestern Yucatan is this Cretaceous/Tertiary (K/T) impact site [2,3] allows us to refine the possible extinction mecha-

nisms. A unique aspect of the Chicxulub crater is the presence of thick deposits of anhydrite (\(\text{CaSO}_4\)), which, when impacted, created a massive sulfuric acid aerosol cloud [4,5] that amplified environmental stresses beyond those proposed for the impact dust alone. We combine studies of the Chicxulub geology with a 2-D model of impact dynamics and a 1-D radiative transfer model to explore the biospheric effects of the sulfuric acid aerosol.

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2. Crater geology

The size of the Chicxulub crater is not well constrained. Estimates, based primarily upon circular gravity anomalies, indicate a diameter of \( \sim 180 \text{ km} \) [2,6] or 250–300 km [7]. Our analyses of the crater geology indicate a rim diameter of \( \sim 240 \text{ km} \) [8].

A sequence of carbonates and anhydrites 2.0–2.5 km thick comprises the upper section of target rock near Chicxulub [9–11]. The sequence thickens to the northwest and the total thickness at the center of the impact may be \( > 2.5 \text{ km} \). The average anhydrite composition of the pre-impact sediments, as measured in exploratory oil wells near the crater rim [9], is \( \sim 60\% \) (roughly equivalent to 1,200–1,500 m thickness). Nevertheless, this assessment is based primarily on well cuttings, which may overestimate anhydrite volume. Analyses of cores [10,11] from these same wells record massive anhydrites with interbedded carbonates up to 750 m thick in the lower section near the crater rim, but only minor amounts of anhydrite in the upper section.

3. Impact modeling

In our model of the Chicxulub impact we assume a cylindrical silicate bolide impacting perpendicular to the surface at 20 km/s. More complex bolide geometries and oblique trajectories are difficult to model and 20 km/s is a typical velocity for asteroids. Given the uncertainty of the size of the Chicxulub crater, we chose to model the formation of craters with diameters of 180 km and 300 km. When scaling laws are applied [12] these diameters correspond to bolide diameters of 10 km and 20 km for the two crater sizes. Recent studies [13] indicate an impactor diameter of 32 km, hence our estimates are conservative.

We used a 2-D hydrocode impact model of a two-layer target to estimate the anhydrite volume vaporized by the impact (Fig. 1). We chose a range of anhydrite volumes to account for the variable estimates of the target rock. This range is equivalent to a minimum thickness of 500 m and a maximum of 1,500 m. From the model results we calculated the shock pressures and the mass of sulfur vaporized (Table 1). Shock pressures rapidly decay near the surface, due to a lack of confining pressure, and a large volume of sediments are ejected without being vaporized.

The sulfur is released as \( \text{SO}_2 \) and \( \text{SO}_3 \) [4,5]. A large volume of highly shocked (\( > 100 \text{ GPa} \)) sediments lies directly beneath the bolide (Fig. 1) and our model predicts that it is released to the atmosphere after decompression (\( \sim 10 \text{ s} \) after impact), probably as \( \text{SO}_2 \). A smaller volume (\( \sim 10–20\% \)) of the highly shocked sediments lies outside of the bolide footprint and is released to the atmosphere rapidly. Laser experiments [14]...
that the sulfur is rapidly converted to H$_2$SO$_4$ aerosol, which would occur if the dominant gas species is SO$_3$, or if chemical reactions in the plume produce H$_2$SO$_4$ directly. The second is based on the assumption that large quantities of SO$_2$ are produced, which must be oxidized by sunlight to form SO$_3$ prior to hydration to H$_2$SO$_4$. The two scenarios are not exclusive and both probably occurred.

We adapted a radiative transfer model originally designed for studies of planetary atmospheres [19] to investigate the solar flux through the H$_2$SO$_4$ aerosol cloud. Our model calculates the amount of sunlight reaching the ground, both directly and diffusely through the cloud, based on Mie scattering theory.

Our first scenario involves coagulation and sedimentation. We adapted the coagulation model proposed in previous K/T impact studies [17], which is based on particle collisions due to Brownian motion and 100% cohesion. An initial mean particle size of 0.5 $\mu$m was chosen, based on Pinatubo volcanic H$_2$SO$_4$ aerosol studies [20]. We experimented with smaller sizes but found that the model output was not very sensitive to smaller initial particles. The rapid formation of the H$_2$SO$_4$ aerosols permits acid nucleation on stratospheric dust and soot particles produced by the impact. Therefore, our model examines the effect of impurities by using different imaginary indices of refraction.

The results of a series of model runs is shown in Fig. 2. Model runs with larger aerosol loadings than the one shown produced lower transmission values at the outset but did not prolong the effects. This self-limiting processes is well known for large volcanic eruptions [21]. Our results indicate that light levels dropped below the photosynthesis limit for 6–9 months if the acid droplets were slightly darkened by impurities.

Our second scenario considers the conversion rate of SO$_3$ to H$_2$SO$_4$ aerosol. The model is constructed so that the H$_2$SO$_4$ aerosol is continuously produced photochemically in the upper stratosphere. The lower stratosphere is effectively shielded from the sun; hence H$_2$SO$_4$ does not form at lower levels. Coagulation and sedimentation processes cause the aerosol particle size and
number density, which were modeled in 12 stratospheric layers, to change as they fall. The choice of 12 layers was a compromise between limits on computational time and adequate characterization of changes in particle properties through the stratosphere. The resulting H$_2$SO$_4$ cloud properties represent quasi-steady-state conditions for the lifetime of the SO$_2$ cloud, whereby new particles form in the first layer as those in the 12th layer fall below 10 km and are removed.

Models of Earth [21] and Venus [22] indicate that the rate-limiting factor for aerosol production is the photochemical oxidation of SO$_2$, which is controlled by the abundance of UV light and oxidants. The SO$_2$ conversion rate is proportional to the volume. However, the rate increases more slowly than the volume, so that the rate doubles for an order of magnitude increase in SO$_2$, resulting in a 4–5 times increase in the lifetime [21]. The SO$_2$ oxidation lifetime for our upper sulfur estimate, derived by scaling-up volcanic conversion rates [21], is about 160 yr (Fig. 3). Applying the same scaling to our lower sulfur estimate yields an SO$_2$ oxidation lifetime of 24 yr, while smaller sulfur masses yield correspondingly shorter oxidation lifetimes. Our upper sulfur mass is comparable to the mass of sulfur in the atmosphere of Venus, which studies have shown has an oxidation lifetime of 200 yr [23]. This comparison suggests such scaling is reasonable, although one would expect slightly slower oxidation rates on Venus given the low abundance of oxygen in the atmosphere.

Our impact model indicates that the Chicxulub impact injected large amounts of water vapor into the stratosphere, probably a mass within an order of magnitude of that of sulfur (assuming a maximum 50 m water depth and 5% carbonate porosity). This water may have increased the abundance of oxidants but the effect on the oxidation
rate would be minor because the abundance of oxidants varies with the square root of the water concentration and because oxidation is inhibited by the shielding of UV by the SO$_2$ cloud [21] (a factor accounted for in our SO$_2$ lifetime estimates). Thus, rates may have increased slightly. Oxidants may have ultimately become depleted, thus reducing the H$_2$SO$_4$ production rate and extending the oxidation lifetime of the SO$_2$ cloud.

Given these long oxidation lifetimes, eddy and molecular diffusion will ultimately become important factors in removing unoxidized SO$_2$ from the stratosphere. Turnover of the stratospheric air mass has been calculated by various methods to be between 2.5 and 3.1 yr [24,25]. We used a diffusion e-folding time of 2.5 yr to estimate the minimum diffusion lifetime of the SO$_2$ cloud (Fig. 3). For atmospheric injections of $<10^{15}$ g S diffusion is unimportant but for larger sulfur masses the diffusion lifetime becomes the effective lifetime of the sulfur cloud, because the SO$_2$ reservoir is depleted before oxidation is complete.

5. Conclusions

Our estimates of sulfate vaporization are similar to those of Brett [5] for a 180 km diameter crater, while the upper estimates of Sigurdsson et al. [6] are much too high. Neither of these previous studies considered craters larger than 180 km. Previous K/T impact models [17,18] predicted a 3–6 month blackout with freezing and disruption of photosynthesis due to the silicate dust. The rapid generation of H$_2$SO$_4$ aerosols may have slightly extended this blackout period to 6–9 months. The model results for the SO$_2$ scenario predict that solar transmission would drop to about 20–10% of normal for about 8–13 yr for our lower and upper sulfur estimates, respectively (Fig. 3). This is equivalent to that of a very cloudy day but is above the photosynthesis limit.

Greenhouse global warming caused by CO$_2$ released from the vaporized carbonates at Chicxulub must also be considered [26]. The mass of CO$_2$ released is about an order of magnitude more than the sulfur mass because carbonates were possibly more abundant and they vaporize at relatively low (10–40 GPa) shock pressures [26]. The climate forcing represented by an instantaneous release of $10^{19}$ g of CO$_2$, the maximum indicated by our model, is about 8 Wm$^{-2}$, which is equivalent to a 4°C warming above pre-impact temperatures [27]. This temperature increase is a maximum and would be less if smaller amounts of CO$_2$ were released or if terminal Cretaceous CO$_2$ levels were much higher than today’s. This positive forcing, as well as the very slight greenhouse effect due to the SO$_2$ cloud [27] or water vapor [28], are insignificant compared to the $-300$ Wm$^{-2}$ predicted for the impact vaporization of sulfates at Chicxulub (Fig. 3). Nevertheless, the 50–200 yr residence time of CO$_2$ [29] is greater than that proposed for the cooling event; therefore, temperatures rapidly rebounded to a few degrees Celsius above pre-impact levels following the initial cooling.

The $-300$ Wm$^{-2}$ climate forcing proposed for the impact aerosols is equivalent to $-100$°C cooling if a new equilibrium temperature were reached and no other feedbacks occurred [27]. However, the actual temperature drop would be buffered by heat released from the oceans for several years. Modeling of short-term impact-induced ocean cooling [30] suggests that significant cooling can occur in <14 yr but precise estimates of temperature changes remain uncertain, due to poorly known Cretaceous circulation patterns, which were probably much different from today's [31].

Despite these uncertainties, significant global cooling must have occurred for a decade after the impact, followed by a more prolonged period of moderate warming. A brief episode of cooling of the oceans’ surface, followed by a much longer episode of warming, has been proposed independently from stable isotope studies of early Tertiary marine organisms [32]; however, it is difficult to resolve events on timescales of decades to centuries in the geological record. Spatial patterns are more readily examined. We hypothesize that biota in continental regions were severely stressed by the impact, due to freezing. Coastal and island areas probably became temperate
refugia for terrestrial biota and survivors may have been species with access to the refugia and the ability to survive a prolonged period of constricted habitat. Marine extinctions may have been related to an organism's ability to survive the initial photosynthesis blackout, perhaps by undergoing a dormant state for several months, and its tolerance of ocean cooling. These hypotheses can be tested by future palaeontological research.

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Chicxulub impact ejecta deposits in southern Quintana Roo, México, and central Belize

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ABSTRACT

Discoveries of Chicxulub impact ejecta of the Albion Formation in road cuts and quarries in southern Quintana Roo, México and Belize, broaden our understanding of ejecta depositional processes in large impacts. There are numerous new exposures of ejecta near the Río Hondo in Quintana Roo México, located at distances of 330–350 km from the center of the Chicxulub crater. A single ejecta exposure was discovered near Armenia in central Belize, 470 km from Chicxulub. The Albion Formation is composed of two lithostratigraphic units: the spheroid bed and diamicrite bed, originally identified at Albion Island, Belize. The new spheroid bed exposures range from

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2 to 5 m thick and are composed of altered glass fragments, accretionary lapilli, and pebble-sized carbonate clasts in a fine-grained calcite matrix. The base of the spheroid bed is exposed at Ramonal South in México and at Albion Island and Armenia in Belize, and at all three locations, the spheroid bed was deposited on a weathered karst land surface that had emerged in the Late Cretaceous. The new diamicomite bed exposures are composed of altered glass fragments and carbonate clasts up to 9.0 × 3.2 m in size. In all but one of the new exposures, the diamicomite bed extends to the surface with observed thicknesses up to 8 m. At Agua Dulce in México, the weathered top of the diamicomite bed is overlain by thin-bedded Tertiary carbonates. No diamicomite bed is found in Armenia, where the spheroid bed is overlain with a limestone conglomerate containing altered glass shards and shocked quartz. These discoveries indicate that ejecta are emplaced in large terrestrial impacts by at least two distinct flows: (1) an initial flow involving a volatile-rich cloud of fine debris similar to a volcanic pyroclastic flow, which extends >4.7 crater radii (the spheroid bed), and (2) a later flow of coarse debris that may not extend much beyond 3.6 crater radii (the diamicomite bed). The former deposit we attribute to material entrained in the impact vapor plume, and the latter to the turbulent collapse of the ejecta curtain.

Keywords: Chicxulub crater, impact ejecta, Cretaceous-Tertiary boundary, México; Belize.

INTRODUCTION

Out-of-crater ejecta deposits from the Chicxulub impact are the best preserved of any large crater on Earth, and they provide an ideal opportunity to study impact processes. The distal, global ejecta deposits from Chicxulub are well known through decades of research related to the Cretaceous-Tertiary (K-T) boundary and mass extinction of life apparently caused by the impact. Studies in northern Belize reveal that a portion of the ejecta blanket is exposed south of the crater (Ocampo et al., 1996; Pope et al., 1999; Smit, 1999; Fouke et al., 2002; King and Petrany, 2003).

In this paper we report on our ongoing study of Chicxulub impact ejecta surface exposures, including new outcrops in southern Quintana Roo, México and central Belize (Fig. 1). These outcrops provide the only known exposures of the outer portion (3.3–4.7 crater radii) of the ejecta blanket from a large impact crater. Impact ejecta deposits in this region comprise the Albion Formation, which is subdivided into two lithostratigraphic sub-units following previous work at Albion Island, Belize (Ocampo et al., 1996; Pope et al., 1999). These two sub-units are named the spheroid bed and diamicomite bed, following the common use of the term "bed" to designate small formation sub-units (e.g., Salvador, 1994).

SOUTHERN QUINTANA ROO

Geological maps of México indicate that the Cretaceous is not exposed in the Mexican portion of the Yucatán Peninsula (INEGI, 1987). Nevertheless, our 1997 and 2001 geological reconnaissance along the highway from Ucum to La Unión in southern Quintana Roo, México, discovered several outcrops of Chicxulub impact ejecta and exposures of the underlying Upper Cretaceous Barton Creek Formation (Fig. 2). These new

Figure 1. Map of northern Belize and southern Quintana Roo, México, showing Chicxulub impact ejecta outcrops. Square symbols mark location of Albion Formation ejecta outcrops (see Figure 2 for detailed locations of ejecta outcrops along the México-Belize border; not all can be shown at this scale). Diamonds mark other locations mentioned in text. AR1—Armenia 1, PH2—Pook’s Hill 2, SA1—San Antonio 1, and HH1—Hummingbird Highway 1. Lightly shaded region at bottom of map is area above 200 m elevation.
ejecta outcrops lie ~330–350 km southeast from the center of the Chicxulub crater. The ejecta deposits belong to the Albion Formation previously identified on Albion Island in nearby northern Belize (Ocampo et al., 1996; Pope et al., 1999). The Albion Formation exposures in Quintana Roo are found in a series of road cuts along the highway that parallels the Río Hondo and in nearby quarries between the towns of Ucum and Alvaro Obregón (Fig. 2). Reconnaissance of road cuts and quarries further south from Alvaro Obregón to La Unión produced no Albion Formation outcrops. Locations of 15 sites with confirmed impact ejecta in this region are given in Appendix 1. The closest site to Chicxulub is the Johnson quarry site (Fig. 2), which contains Albion Formation diamictite deposits 330 km from the center of Chicxulub. The combined Albion Formation exposures in Belize and Quintana Roo indicate that a surface or near-surface discontinuous sheet of impact debris is preserved for ~40 km along the Río Hondo, covering at least a 70 km².

We conducted detailed studies of four locations: Ramonal North, Ramonal South, Agua Dulce, and Alvaro Obregón (Figs. 3–6), which all lie 335–350 km from Chicxulub. The basal contact of the Albion Formation with the underlying Barton Creek Formation is well exposed at Ramonal South (Fig. 3). The only site with an exposed upper contact of the Albion Formation is Agua Dulce, where the weathered top of the ejecta deposit is overlain by Tertiary limestones (Fig. 6). The other two sites, Ramonal North and Alvaro Obregón, have good exposures of ejecta, but no upper or lower contact.

**Ramonal South**

**Field Observations**

The Barton Creek Formation at Ramonal South exhibits extensive karst weathering with local relief of 3–10 m in the surface of a heavily recrystallized limestone with iron-oxide staining, caliche deposits, abundant vugs and travertine deposits. Well-preserved fossils are rare due to the recrystallization, but several Late Cretaceous nerineid gastropods (Pope et al., 1999)
were found in Barton Creek outcrops between Ramonal South and the town of Allende. This confirms that the Cretaceous is exposed in southern Quintana Roo. Ongoing research in Quintana Roo has recovered a rather diverse Upper Cretaceous fauna in the Barton Creek Formation. Several species of bivalves and gastropods are being studied. A new species of the gastropod *Apollinaria* represents the first record for that genus in the Cretaceous of the Gulf Coast and Caribbean Provinces (Vega et al., 2001). Although the stratigraphic range for this genus extends from Lower Cretaceous to Recent, specimens from Quintana Roo show similarities to species from the Maastrichtian of Montana and Germany.

Overlying the Barton Creek Formation at Ramonal South is a 2-m-thick section of the Albion Formation spheroid bed, which is overlain by a 5-m-thick section of the diamictic bed that extends to the surface (Figs. 3 and 7). The upper and lower contacts of the spheroid bed are marked by 2–20-cm-thick layers of orange, purple, and green calcite clay with common slickensides. These clay layers appear to be shear planes. There is an abrupt appearance of large micticite dolomite clasts above the upper shear plane and one large dolomite boulder rests immediately on top (Fig. 7). Field tests with HCl indicate that the base of the spheroid bed is calcitic, and becomes progressively more dolomitic near the top. The diamictite bed matrix is dolomitic.

**Laboratory Analyses**

We examined 12 thin sections from the top of the Barton Creek Formation and from the spheroid and diamictite beds at Ramonal South. Here we describe the textures and key aspects of the mineralogy. Estimates of the percentages (area) of major constituents were made using photomicrographs and percentage charts. The top of the Barton Creek exhibits abundant iron oxide staining, secondary coarse calcite filling fractures and vugs,
and polycrystalline calcite replacement of dolomite rhombs (de-dolomitization) (Fig. 8), all consistent with a subaerially weathered surface. The main stratum of the spheroid bed (stratum II, Fig. 3) contains 20% yellowish-green clay with spherulitic devitrification features and relict vesicles typical of altered glass (Fig. 9). The spheroid bed contains 20% carbonate clasts of various types, including foraminifera fragments (Fig. 9), and 3% accretionary lapilli (core-type, Schumacher and Schmincke, 1991) composed of aggregates of detrital calcite grains 10–125 μm in size (Figs. 9). The matrix of the spheroid bed is composed of detrital calcite grains similar in size and character to that of the accretionary lapilli aggregates. Some portions of the matrix are altered to interlocking grains of dolomite, especially near the top of the bed. Thin section analysis of the diamictite bed reveals that it is pervasively dolomitized, but contains 10% clay and 20% dolomite clasts (>0.5 mm) of various types (smaller clasts are completely recrystallized) (Fig. 10).

**Ramonal North**

**Field Observations**

The Ramonal North road cut exposes a 3.6 m section of the spheroid bed in a dip in Ucum–La Unión highway ~200 m north of Ramonal South (Figs. 4 and 11). Neither the top nor the base of the spheroid bed is exposed in the road cut, but the Albion Formation diamictite bed crops out ~30 m behind the road cut, suggesting the top of this exposure may be near the upper contact with the diamictite bed. The base of the Ramonal section lies ~13 m below the base of the spheroid bed at Ramonal South. We interpret this elevation difference as a dip in the paleo-karst landscape, as the exposed surface of the Barton Creek Formation at Ramonal South is sloping toward Ramonal North and this surface is observed to undulate up and down in numerous road cuts along the Ucum–La Unión highway.

**Laboratory Analyses**

We analyzed 17 thin sections from the Ramonal North spheroid bed. Yellowish-green clay fragments comprise 20% of the bed and contain common relict vesicles and spherulitic devitrification features typical of altered glass (Figs. 12). No preserved glass was found. Calcite accretionary lapilli of diverse types comprise 10% of the bed, and range in size from 0.2 to 5.0 mm, and average ~1.0 mm (Figs. 13–15). There are many examples of what are sometimes classified as mantled lapilli—lithic cores coated with fine ash (Fig. 15), and both rim-type and core-type accretionary lapilli—aggregates of fine detrital grains, with or without a fine-grained rim (Schumacher and Schmincke, 1991). We refer to all types as accretionary lapilli, in part for simplicity, but also because it is not always apparent whether the core is an aggregate or lithic fragment when the latter is rounded and has a similar lithology to the aggregate. Rim-type accretionary lapilli are the most abundant type (Fig. 13), but core-type are also common (Fig. 14), as are ones with limestone (Fig. 15) and clay (altered glass) lithic cores (Fig. 14). The detrital calcite grains in the lapilli aggregates range

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**Figure 6.** Agua Dulce stratigraphic section. (I) 25% sub-angular to sub-rounded micritic dolomite and limestone pebbles, cobbles, and boulders up to 3.2 × 9.0 m in size; 5%–10% green clay clasts; fewer (5%) cobbles and boulders in the upper part. (II) 10% micritic dolomite clasts 1–15 cm in diameter; 1%–3% green and orange clay clasts 0.5–2 cm in diameter; 85% matrix of coarse calcite silt with orange and purple iron oxide staining (weathered version of stratum I); (III) calcite cemented caliche with large 2–3 mm calcite crystals; (IV) weathered white micritic dolomite overlying pink and tan, thin-bedded, micritic limestone.