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The Chicxulub-Shiva extraterrestrial one-two killer punches to Earth 65 million years ago

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ABSTRACT

Two large asteroids struck Earth at almost the same time, 65 million years ago, causing the major extinctions recognized as ending the Mesozoic Era. Although occurring close together in time, the Earth's magnetic pole had moved from the South Pole to the North Pole in between, allowing a time difference between the impacts to be calculated. The first strike produced a ~180 km diameter crater named Chicxulub on the Yucatan shelf of southern Mexico. The second hit the shelf of the northward drifting Indian continent in the southern Indian Ocean, producing a crater ~450 × 600 km named Shiva. Hitherto, the main obstacle to verifying this scenario has been the paucity of geological sections containing evidence of both impacts. Here, we present such evidence, and conclude that the two impacts were separated by about 40,000 years.

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1. Introduction

Evidence for two large extraterrestrial impacts on Earth at the time of the Cretaceous–Tertiary (K–T) boundary extinctions has come from opposite sides of the globe. A probable impact crater of approximate K–T boundary (KTB) age was pointed out by Hartnady (1986) in the Seychelles Islands area of the Arabian Sea. This possibility was further investigated and expanded upon in the next several years by investigators (Alt et al., 1988; Chatterjee, 1992) who re-assembled a now divided large (450 × 600 km) impact structure named Shiva. The impact occurred in the southern Indian Ocean on the western shelf of the India–Seychelles continent, which was drifting northward from the breakup of the super-continent Gondwanaland. Subsequently, another crater-like structure 150–180 km in diameter on the Yucatan Peninsula of southern Mexico was also interpreted to be an impact structure of KTB age named Chicxulub (Hildebrand et al., 1991).

The KTB is well established in recent Geomagnetic Polarity Time Scales (GPTS) as occurring near the middle of 0.6 myr-long reversed polarity magnetochron 29r (Gradstein et al., 2004). In western Canada, however, the boundary impact marker, the "K–T boundary clay" (KTBC), was found to occur near the middle of a relatively thin (~3 m) interval of normal polarity within magnetozone 29r (Lerbekmo et al., 1996). To date, this magnetosubzone represents the only identified magnetosubchron in 29r and is therefore labelled 29r•1n.

Because meltrock in the Chicxulub crater has reversed magnetic polarity (Urrutia-Fucugauchi et al., 1994), the polarity data indicate that the KTBC in western Canada was not produced by the Chicxulub impact. Thus, there are two candidate KTBs, of different age, attributable to two major impacts. It was the purpose of this study to differentiate between the two impacts stratigraphically, and to determine the difference in time between them.

2. North American evidence for two impacts

In northeastern Montana, in the dinosaur-rich badlands of the Hell Creek drainage, one of the KTBs occurs at the base of the Z coal, which separates the Upper Cretaceous Hell Creek Formation from the overlying lower Tertiary Tullock Formation. The coal is well preserved about 25 km north of Jordan, 50 m east of the Hell Creek State Park access road (HCPR). The coal is 130 cm thick and contains a ~10 cm bentonite 60 cm below the top. Diagnostic latest Cretaceous palynomorph species disappear 10 cm below the coal, at the base of a carbonaceous mudstone. An Ir peak of 0.646 ± 0.025 ppb is present 2 cm above the base of the coal. Shocked quartz with multiple planar dislocations (mpd) occurs within the 10 cm carbonaceous mudstone below the coal. An erosion surface at the top of the coal cuts down to the west to the extent that at the next

[1] Jack Lerbekmo passed away on November 29th 2012, a few days before his 88th birthday. At the time of his death, the manuscript of this paper was in its final form, ready for submission. The formal submission was therefore made by Jack's colleague, Ted Evans, with contributions from Art Sweet and John Duke.

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exposure, 0.8 km to the west (HCPRW), the 60 cm of coal above the bentonite is missing. The magnetostratigraphy of this section (Fig. 1) shows normal polarity for 1.1 m below the base of the coal. This is the Cretaceous portion of magnetosubzone 29r•1n. Shocked quartz with mpd associated with the Z coal first appears in a sample 8–12 cm below the base of the coal. A 5 cm concretionary layer occurs 3.5 m below the base of the coal, overlying a few centimetres of grey shale. The upper 1 cm of the shale contains an Ir anomaly of 0.290 ppb over a background of 0.03–0.05 ppb, and shocked quartz with mpd (Fig. 1). This is in magnetosubzone 29r•2r, corresponding to the Chicxulub impact. Scattered dinosaur bones occur 0.5 m below the concretions.

Roughly 5 km west of HCPR is Brownie Butte. About 0.8 km to the east, a KTBC is preserved for a few metres laterally at the base of a slope below an 8 cm coal, at a locality known as Rick's Place (Hotton, 2002). Four magnetostratigraphic samples taken 15 and 30 cm above, at the base, and 25 cm below the boundary clay have reversed polarity and are assigned to 29r•2r, embracing the Chicxulub impact. There is also a record of the Chicxulub impact ~600 m south of Rick's Place at what is herein called "Jack's Place". This was a sandier environment and the impact level is represented by 1 cm of poorly-sorted siltstone carrying abundant very fine sand-sized shocked quartz with mpd.

Approximately 1 km south of Brownie Butte is a smaller butte, herein called "Baby Brownie". It exposes a Z coal-equivalent interval, including the bentonite, rarely preserved west of HCPR. Only 16 cm is continuous coal, the remainder being carbonaceous shale, including a 30 cm unit below the coal. The pervasive disconformity is present at the top of the Z coal interval, cutting off the top of 29r•1n, which continues downward for 1 m below the base of the coal (Fig. 2). The basal 2 cm of the lower carbonaceous shale unit contains shocked quartz with mpd. At 1.45 m below the base of the Z coal carbonaceous shale is another 5 cm carbonaceous shale. This is in reversed polarity subzone 29r•2r, 75 cm below the base of 29r•1n. It carries shocked quartz with mpd, is equivalent to the Rick's Place coal, and represents the Chicxulub impact.

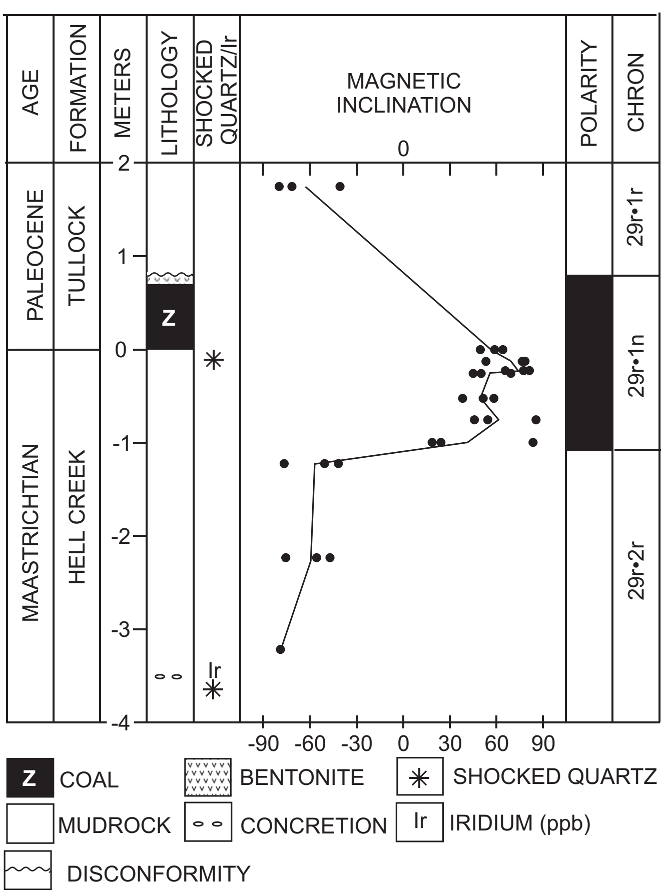

Figure 1. Stratigraphy of the HCPRW K–T interval. Lithostratigraphy, magnetostratigraphy and mineralogy of the Hell Creek Park Road West (HCPRW) section K–T boundary (KTB) interval. Solid inclination line is drawn between the means of 3 independently oriented percussion core samples perpendicular to bedding, if available, otherwise to inclination of a single sample.

In the Raton Basin of Colorado–New Mexico, a continental KTB has been studied in detail in at least 17 sections by Izett (1990). During the present study, 3 magnetostratigraphic samples were taken straddling the boundary coal at the Starkville South locality. All have the reversed polarity of Chicxulub time and 29r•2r.

A KTB is also present in a 14 m coal seam on the MacKenzie River in the Northwest Territories of Canada, known as the Police Island section (Sweet and Braman, 2001). Twenty mid- to late Maastrichtian palynomorphic taxa disappear at the KTB within 5 cm of the appearance of shocked quartz. An Ir anomaly peaks at 0.364 ± 0.008 ppb in the 5 cm interval above the shocked quartz. Normal polarity (29r•1n) was found in two available samples 4 m above and 1 m below the KTB. There is no KTBC.

Two different KTBCs have been identified in western North America. The first was deposited during magnetosubchron 29r•2r; the second was deposited during magnetosubchron 29r•1n. The time interval between them can be calculated approximately if the average rock accumulation rate (ARAR) can be determined in sections where both impacts are represented. Cyclostratigraphic studies have resulted in a relatively small range for the duration of 29r of 603–608 kyr, and a proportioning of ~335 kyr to the Maastrichtian and ~270 kyr to the Paleocene (Preisinger et al., 2002; D'Hondt et al., 1996). In the HCPRW section (Fig. 3), the preserved Paleocene portion of 29r is ~23 m thick, yielding an

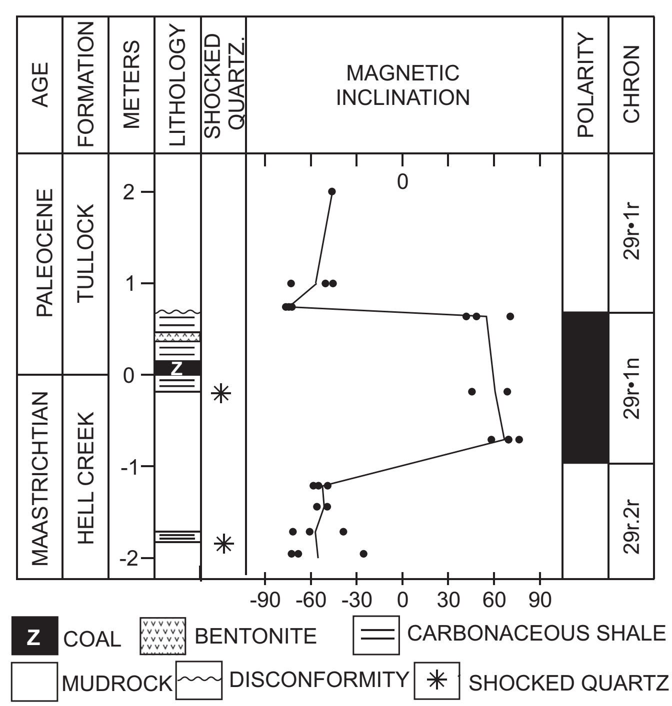

Figure 2. Stratigraphy of the Baby Brownie K–T interval. Lithostratigraphy, magnetostratigraphy and mineralogy of the Baby Brownie section KTB interval. See Figure 1 for additional explanation.

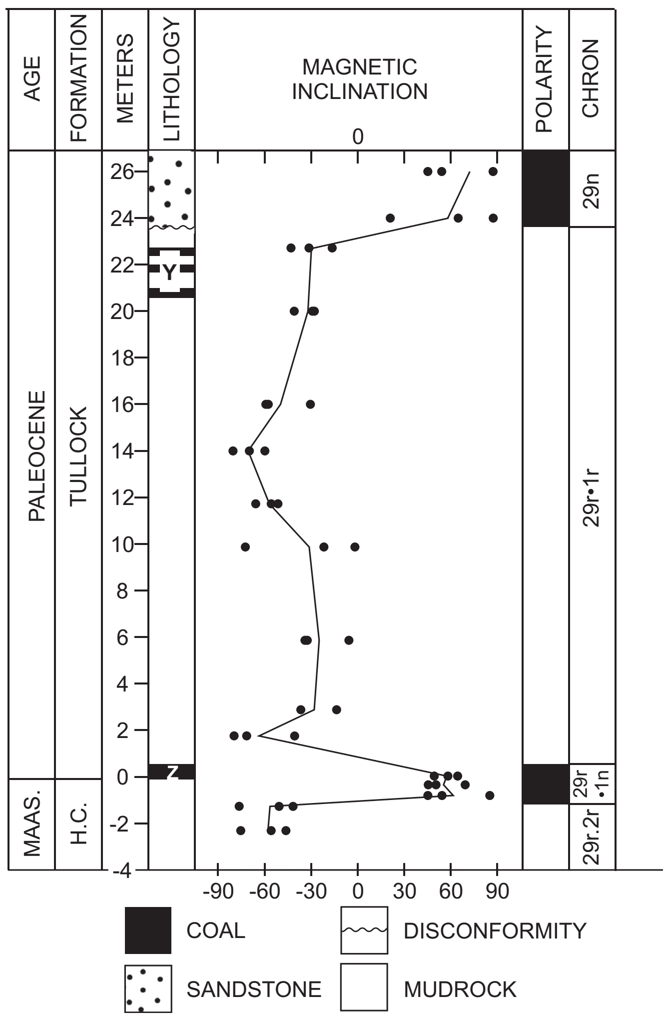

Figure 3. Stratigraphy of the upper HPCRW section. Lithostratigraphy and magnetostratigraphy of the upper part of the HCPRW section.

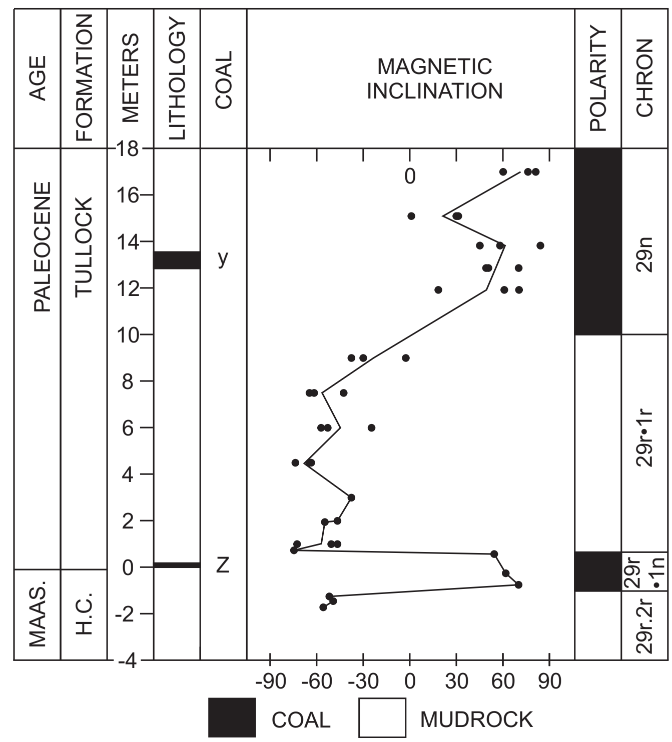

Figure 4. Stratigraphy of the upper Baby Brownie section. Lithostratigraphy and magnetostratigraphy of the upper part of the Baby Brownie section.

ARAR of ~1 m/11,700 years. When applied to the 3.5 m between the Z coal and the lower Ir anomaly representing the Chicxulub impact, the time separation is ~41,000 years. In the Baby Brownie section the Paleocene part of 29r is ~9.5 m thick (Fig. 4), giving an ARAR of ~1 m/28,400 years. The 1.45 m of separation between the impacts is thus also calculated to be ~41,000 years.

3. Types and distribution of KTB impact ejecta

The KTB continental deposits of North America show that they have been produced by two different impacts separated in time by ~40,000 years. The first was Chicxulub, the second was Shiva. Thus, KTB deposits outside of North America must be assignable to one or the other.

Identifiable ejecta from large impacts are of 4 types. Three are relatively coarse particulate material which travel on ballistic trajectories from impact site to depositional area.

1) Molten glass mixtures of meteorite and target material, splashed or driven out of the impact crater (Type 1 spherules) (Bohor and Betterton, 1990).
2) Spherules crystallizing out of the hot vapour cloud as the ejecta reenter the atmosphere on descent (Type 2 spherules) (Bohor and Betterton, 1990).
3) Shocked quartz and other minerals from the target rock.
4) Ir from the impactor, identifiable only by its radioactive behaviour and too fine to travel ballistically.

1) Type 1 spherules splashed from the Chicxulub crater (Koeberl, 1994) are widespread in northeast Mexico and in Haiti, which was nearby at 65 Ma, but do not occur as far as the Raton Basin (~2000 km away) (Izett, 1990). Alvarez (1996) showed the reentry loci of Chicxulub ejecta launched at 45°. His 5 km/s loci includes the U.S. midwest where Bohor and Foord (1987) recorded the reentry-crystallizing spinel magnesioferrite. Type 1 spherules which are "driven", rather than "splashed" out of the crater, are considered to be the equivalent of the tektites of more recent "strewnfields" (Koeberl, 1994). However, the four known strewnfields are all the product of low-angle impacts. The low-angle Shiva impact directed ~N70°E (Chatterjee and Rudra, 1996; Chatterjee, 1997) is a candidate to reproduce a strewnfield tektite distribution. Type 1 spherules (altered tektites) occur in at least 4 of the Pacific KTB cores, including the southernmost (596) and the northernmost (886) where the largest (1.5 mm) have been found (Kyte et al., 1996).

In addition, Hole 596 also has a very large Ir fluence and an exceptionally large concentration of shocked quartz. In this regard, it is very similar to K–T sections 15° to the south in New Zealand. Two KTB's 15° apart in the extreme South Pacific, with near-identical ejecta records indicates a comparable fallout over a large area of the southern Pacific. At the other extreme in the North Pacific, Hole 886 (7600 km away) has by far the largest concentration of shocked quartz (~13,800 grains/cm^2) (Kyte et al., 1996) found anywhere. In between these southernmost and northernmost locations are coreholes 576 and 577. Spheroidal debris of meteoritic composition was found in Hole 577 by Robin et al. (1993), and Kyte (1998) found a 2.5 mm meteorite fragment in Hole 576, ~600 km to the east. Again, two random locations in the central Pacific, with identifiable K–T impact fallout, indicates that a concentration of K–T ejecta covers the entire Pacific Basin.

Alvarez (1996) showed that the reentry loci of ejecta launched eastward from a near equatorial latitude at angles of 15° and 30° would be 150°–180° east of the impact site. For a launch from 60° E, the location of the Shiva impact at 65 Ma, the reentry would be at 150°W–120°W. The meteorite fragment found by Kyte is here considered to be a beheaded fragment of the Shiva meteorite because low-angle impacts can produce ricochets of unshocked projectiles with velocities >0.5 of that of the impactor (Schultz and Gault, 1990).

2) Type 2 spherules in the Pacific Basin contain magnesioferrite that differs from that in other parts of the world except the Indian Ocean. It is texturally different and has a higher Mg content. Kyte and Bostwick (1995) concluded that the only likely mechanism to produce this asymmetry is a low-angle impact (less than 45°). Type 2 spherules investigated at ~20 sites in Europe by Montanari et al. (1983) were considered to have originally been of basaltic composition derived from an impact into an ocean basin. A similar source was concluded by Shaw and Wasserburg (1982) on the basis of Sm–Nd results. Sharpton et al. (1990) wrestled with the conflicting evidence for both an oceanic (basaltic) and a continental margin target, and concluded that if post-depositional alteration was not to blame, multiple "simultaneous" impacts would be required. However, the Shiva impact on a continental margin penetrating lower Deccan basalts provided an "oceanic" source.

3) Shocked quartz from Chicxulub is found from Mexico to Montana. The modal grain size decreases northward from 0.2 mm in the Raton Basin to 0.15 mm at Brownie Butte, Montana. The modal grain size of shocked quartz from Shiva is 0.25 mm at the KTB in the Red Deer Valley (RDV) of Alberta (Izett, 1990).

In the northwest Pacific, the Japanese island of Hokkaido has a marine KTB showing severe palynomorphic perturbations, leading Saito et al. (1986) to favour wildfires as a cause. Ivany and Salawitch (1993) believed that the only likely source of the large amount of light isotope C in marine KTB surface waters was the burning of perhaps 25% of the terrestrial biomass. If so, this burning would have been in east Asia.

Thus the North American and Pacific data lead to the conclusion that most, and probably all, of the KTB trajectory material found in Pacific cores and the western Pacific is a product of the Shiva impact. A well-preserved KTB is present in the western South Atlantic on the Demerara Rise (DR) at ODP site 1259. Impact ejecta here have been attributed to Chicxulub, ~4500 km away (Erbacher et al., 2004; Schulte et al. 2009; Vickery and Melosh, 1990). The presence of carbonate clasts in the DR ejecta deposit was taken to indicate a Chicxulub carbonate-evaporite target, but these lithologies were also target rocks in the Shiva area (Chatterjee and Rudra, 1996). Most of the ~2 cm DR deposit consists of Type 1 spherules up to 1 mm in size. Chicxulub Type 1 spherules, however, did not reach the Raton Basin KTBs, 2500 km away (Izett, 1990). The Nd results at DR indicate a basement target age of ~1.9 Ga, older than any rocks known from Chicxulub, but well within the age range of Precambrian lithologies on the west coast of India (Reddy et al., 1999). The upper <1 mm of the DR spherules are more Fe and Mg rich than the targets at Chicxulub and are therefore attributed to the impactor, but might also have come from the targeted lower Deccan basalts at Shiva. It seems unlikely that Chicxulub ballistic ejecta reached the South Atlantic, and, if not, it did not reach Europe or the stratotype KTB at El Kef, Tunisia.

4. Sizes of the impactors

The sizes of the two impactors are poorly constrained. The total size cannot be determined by the quantity of Ir retained on Earth, because in the case of large impacts some will be lost to space (Vickery and Melosh, 1990). The relative sizes can be semi-quantitatively judged by the sizes of their craters (≤180 km for Chicxulub, and ~450 × 600 km for Shiva). The thickness of the crust at the location of the Shiva impact had been thinned because of heating by early Deccan volcanism to ~24 km (Reddy et al., 1999). The now-separated Seychelles half of the Shiva central uplift consists of highly fractured Precambrian basement (Chatterjee, 1997), showing that the impactor did not go through the crust. Grieve (1987) calculated that an asteroid should penetrate to a depth at least equal to its diameter. If so, the diameter of the Shiva meteorite was less than 24 km.

5. Dinosaur extinctions

Dinosaur footprints have been found as close as 37 cm below the Chicxulub KTB in the Raton Basin of Colorado (Pillmore et al., 1994), indicating that dinosaurs in the southwestern U.S. lived up until the Chicxulub impact, but not afterwards. Late Maastrichtian dinosaurs were widely present in India at KTB time (Chatterjee and Rudra, 1996). They disappeared abruptly at the Shiva impact. The last known dinosaurs to succumb to the KTB event are represented by bones just beneath the Ir anomaly in a section at Anjar Kutch in northwest India (Chatterjee and Rudra, 1996; Bhandari et al., 1994).

6. Summary

About 65 million years ago, a meteorite struck the Yucatan Peninsula of Mexico producing a crater 150–180 km in diameter named Chicxulub. It produced acid rain and ejecta which fell in the western USA. A record of this event was called the Cretaceous–Tertiary Boundary Clay (KTBC). It was fortuitously preserved where it fell on the margins of advancing and overriding peat swamps later to be changed to coal.

Roughly 40,000 years later, a much larger meteorite struck the shelf of the India–Seychelles continent drifting northward in the southern Indian Ocean, producing a crater 450 × 600 km named Shiva. This low-angle impact spread ejecta worldwide and produced a similar KTBC in western North America. In addition, a large amount of acid rain acidified the surface of the world ocean, killing the calcareous microscopic floating animals and plants, the extinctions of which mark the end of the Cretaceous Period and Mesozoic Era. Shiva was aptly named after the Hindu deity of "Destruction and Rebirth".

References

Alt, D., Sears, J.M., Hyndman, D.W., 1988. Terrestrial Maria: the origins of large basalt plateaus, hotspot tracks and spreading ridges. J. Geol. 96, 647–662.

Alvarez, W., 1996. Trajectories of ballistic ejecta from the Chicxulub crater. Geol. Soc. Am. Spec. Pap. 307, 141–150.

Bhandari, N., Shukla, P.N., Ghevaria, Z.G., Sundaram, S.M., 1994. KT boundary in Deccan intertrappean: chemical anomalies and their implications. Lunar Planet. Inst. Contrib. 825, 10–11.

Bohor, B.F., Betterton, W.J., 1990. K/T Boundary Spherules: Clarifying the Concept. In: Lunar Planet. Sci., vol. 21. Lunar and Planetary Institute, Houston, Texas, pp. 108–109.

Bohor, B.F., Foord, E.E., 1987. Magnesioferrite from a Nonmarine K–T Boundary Clay in Wyoming. In: Lunar Planet. Sci., vol. 18. Lunar and Planetary Institute, Houston, Texas, pp. 101–102.

Chatterjee, S., 1992. A kinematic model for the evolution of the Indian plate since the Late Jurassic. In: Chatterjee, S., Hotton III, N. (Eds.), New Concepts in Global Tectonics. Texas Tech. University Press, pp. 33–62.

Chatterjee, S., 1997. Multiple impacts at the KT boundary and the death of the dinosaurs. In: Proc. 30th Int. Geol. Cong., vol. 26, pp. 31–54.

Chatterjee, S., Rudra, D.K., 1996. KT events in India: impact, rifting, volcanism and dinosaur extinction. Mem. Qld. Mus. 39, 489–532.

D'Hondt, S., Herbert, T.D., King, J., Gibson, C., 1996. Planktic foraminifera, asteroids, and marine production: death and recovery at the Cretaceous–Tertiary boundary. Geol. Soc. Am. Spec. Pap. 307, 303–317.

Erbacher, J., Mosher, D.C., Malone, M.J., et al., 2004. Leg 207 summary. In: Proc. Ocean Drill. Prog., Init. Rep., vol. 207, pp. 1–89.

Gradstein, F., Ogg, J., Smith, A., 2004. A Geologic Time Scale. Cambridge University Press, p. 610.

Grieve, R.A.F., 1987. Terrestrial impact structures. Ann. Rev. Earth Planet. Sci. 15, 245–270.

Hartnady, C.H., 1986. Amirante Basin, western Indian Ocean: possible impact site of the Cretaceous/Tertiary extinction bolide? Geology 14, 423–426.

Hildebrand, A.R., et al., 1991. Chicxulub crater: a possible Cretaceous/Tertiary boundary impact crater on the Yucatan Peninsula, Mexico. Geology 19, 867–871.

Hotton, C.L., 2002. Palynology of the Cretaceous–Tertiary boundary in central Montana: evidence for extraterrestrial impact as a cause of the terminal Cretaceous extinctions. Geol. Soc. Am. Spec. Pap. 361, 473–501.

Ivany, L.C., Salawitch, R.J., 1993. Carbon isotopic evidence for biomass burning at the K–T boundary. Geology 21, 487–490.

Izett, G., 1990. The Cretaceous/Tertiary boundary interval, Raton Basin, Colorado and New Mexico, and its content of shock-metamorphosed minerals; evidence relevant to the K/T boundary impact-extinction theory. Geol. Soc. Am. Spec. Pap. 249, 100.

Koeberl, C., 1994. Tektite origin by hypervelocity asteroidal or cometary impact: target rocks, source craters, and mechanisms. Geol. Soc. Am. Spec. Pap. 293, 133–151.

Kyte, F.T., 1998. A meteorite from the Cretaceous/Tertiary boundary. Nature 396, 237–239.

Kyte, F.T., Bostwick, J.A., 1995. Magnesioferrite spinel in Cretaceous/Tertiary boundary sediments of the Pacific basin: remnants of hot, early ejecta from the Chicxulub impact? Earth Planet. Sci. Lett. 132, 113–127.

Kyte, F.T., Bostwick, J.A., Zhou, L., 1996. The Cretaceous–Tertiary boundary on the Pacific plate: composition and distribution of impact debris. Geol. Soc. Am. Spec. Pap. 307, 389–401.

Lerbekmo, J.F., Sweet, A.R., Duke, M.J.M., 1996. A normal polarity subchron that embraces the K/T boundary: a measure of sedimentary continuity across the boundary and synchroneity of boundary events. Geol. Soc. Am. Spec. Pap. 307, 465–476.

Montanari, A., et al., 1983. Spheroids at the Cretaceous–Tertiary boundary are altered impact droplets of basaltic composition. Geology 11, 668–671.

Pillmore, C.L., Lockley, M.G., Fleming, R.F., Johnson, K.R., 1994. Footprints in the rocks—new evidence from the Raton Basin that dinosaurs flourished on land until the terminal Cretaceous impact event. Lunar Planet. Inst. Contrib. 825, 89–90.

Preisinger, A., et al., 2002. Cretaceous–Tertiary profile, rhythmic deposition, and geomagnetic polarity reversals of marine sediments near Bjala, Bulgaria. Geol. Soc. Am. Spec. Pap. 356, 213–229.

Reddy, P.R., Venkateswarlu, N., Rao, P.K., Prasad, A.S.S.S.R.S., 1999. Crustal structure of Peninsular Shield, India from DSS studies. Curr. Sci. 77, 1606–1611.

Robin, E., Froget, L., Jehanno, C., Rocchia, R., 1993. Evidence for a K/T impact event in the Pacific Ocean. Nature 363, 615–617.

Saito, T., Yamanoi, T., Kaiho, K., 1986. End-Cretaceous devastation of terrestrial flora in the boreal Far East. Nature 323, 253–255.

Schulte, P., et al., 2009. A dual-layer Chicxulub ejecta sequence with shocked carbonates from the Cretaceous–Paleogene (K–Pg) boundary, Demerara Rise, western Atlantic. Geochim. Cosmochim. Acta 73, 1180–1204.

Schultz, P.H., Gault, D.E., 1990. Prolonged global catastrophes from oblique impacts. Geol. Soc. Am. Spec. Pap. 247, 239–261.

Sharpton, V.L., Schuraytz, B.C., Burke, K., Murali, A.V., Ryder, G., 1990. Detritus in K/T boundary clays of western North America; evidence against a single oceanic impact. Geol. Soc. Am. Spec. Pap. 247, 349–357.

Shaw, H.F., Wasserburg, G.J., 1982. Age and provenance of the target materials for tektites and possible impactites as inferred from Sm–Nd and Rb–Sr systematics. Earth Planet. Sci. Lett. 60, 155–177.

Sweet, A.R., Braman, D.R., 2001. Cretaceous–Tertiary palynofloral perturbations and extinctions within the *Aquilapollenites* Phytogeographic Province. Can. J. Earth Sci. 38, 249–269.

Urrutia-Fucugauchi, J., Marin, L., Sharpton, V.L., 1994. Reverse polarity magnetized melt rocks from the Cretaceous/Tertiary Chicxulub structure, Yucatan peninsula, Mexico. Tectonophysics 237, 105–112.

Vickery, A.M., Melosh, H.J., 1990. Atmospheric erosion and impactor retention in large impacts, with application to mass extinctions. Geol. Soc. Am. Spec. Pap. 247, 289–300.