Deccan volcanism, the KT mass extinction and dinosaurs

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Recent advances in Deccan volcanic studies indicate three volcanic phases with the phase-1 at 67.5 Ma followed by a 2 m.y. period of quiescence. Phase-2 marks the main Deccan volcanic eruptions in Chron 29r near the end of the Maastrichtian and accounts for ~80% of the entire 3500 m thick Deccan lava pile. At least four of the world's longest lava flows spanning 1000 km across India and out into the Gulf of Bengal mark phase-2. The final phase-3 was smaller, coincided with the early Danian Chron 29n and also witnessed several of the longest lava flows.

The KT boundary and mass extinction was first discovered based on planktic foraminifera from shallow marine intertrappean sediments exposed in Rajahmundry quarries between the longest lava flows of the main volcanic phase-2 and smaller phase-3. At this locality early Danian (zone P1a) planktic foraminiferal assemblages directly overlie the top of phase-2 eruptions and indicate that the masse extinction coincided with the end of this volcanic phase. Planktic foraminiferal assemblages also mark the KT boundary in intertrappean sediments at Jhilmili, Chhindwara, where freshwater to estuarine conditions prevailed during the early Danian and indicate the presence of a marine seaway across India at KT time.

Dinosaur bones, nesting sites with complete eggs and abundant eggshells are known from central India surrounding the hypothesized seaway through the Narmada-Tapti rift zone. A Maastrichtian age is generally assigned to these dinosaur remains. Age control may now be improved based on marine microfossils from sequences deposited in the seaway and correlating these strata to nearby terrestrial sequences with dinosaur remains.

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1. Introduction

About 65 milion years ago Deccan volcanic eruptions covered most of India (figure 1). Lava eruptions piled up flow after flow to several thousand meters thick, which today still form 3500 m high mountains (figure 2). The most massive eruptions reached over 1000 km across India and out to the Gulf of Bengal, forming the longest lava flows known on Earth (Self *et al.* 2008a). It is therefore no surprise that scientists advocated Deccan volcanism as the major contributor or cause of the KT mass extinction even before the impact theory was proposed (McLean 1978) and through the 1980-1990s (McLean 1985; Courtillot *et al.* 1986, 1988; Courtillot 1999). Over the past decade continental flood basalts (CFB) have been correlated with most major mass extinctions (Wignall 2001) leading Courtillot and Renne (2003) to suggest that this may be the general cause of mass extinctions. But acceptance of CFB volcanism as the likely catastrophe that led to or even significantly contributed to the extinction of the dinosaurs and many other groups has lagged for two main reasons: (1) the popularity of the Chicxulub impact theory and its general acceptance as the cause for the mass extinction, and (2) the absence of a direct link between the mass extinction and Deccan volcanism. Indeed, until very recently it was not possible to pinpoint the KTB within the Deccan lava pile (Keller *et al.* 2008a).

Recent studies on Deccan volcanism and the Chicxulub impact are leading the way to a reassessment of Deccan Trap volcanism and its role in the end-Cretaceous mass extinction. In particular, three developments have been instrumental: (1) Findings that the Chicxulub impact predates the KT boundary and could not have caused

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the mass extinction. (2) Comprehensive palaeomagnetic, K/Ar and Ar/Ar studies of the Deccan volcanic province revealing that volcanic eruptions occurred in three phases with the main phase in C29R. (3) Identification of the KT boundary in intertrappean sediments between Ambenali and Mahalabeshwar Formations in Rajahmundry and Jhilmili (Chhindwara District, Madhya Pradesh) based on marine microfossils.

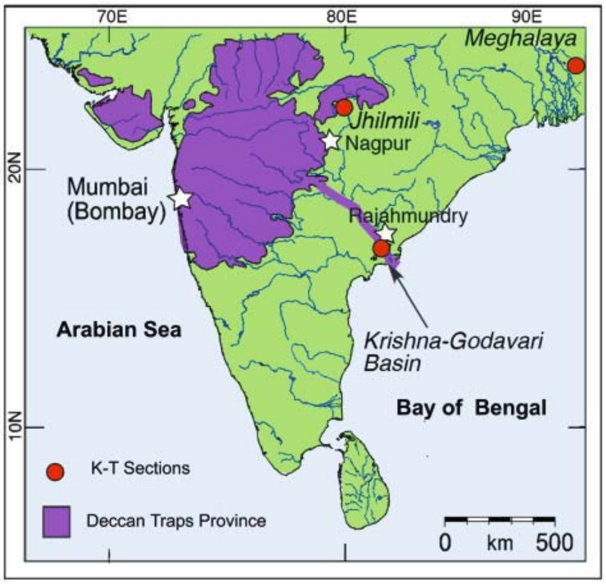

Figure 1. Map of India with main Deccan Volcanic Province. The longest lava flows ranged 800-1000 km across India and out to the Gulf of Bengal. The KT boundary was first identified in sections from Rajahmundry Jhilmili and Meghalaya.

These developments are briefly reviewed below. We will then explore future directions that may make it possible to further link Deccan volcanism to the KTB throughout the Deccan volcanic province, explore ways to obtain better age control for dinosaur remains, evaluate and reconstruct the palaeoenvironment at the time of Deccan eruptions and end with a scenario of the mass extinction caused by Deccan volcanism.

2. High resolution K-T biostratigraphy

One of the most important aspects of any stratigraphic studies is age control. For KT boundary studies this includes precisely locating the time of the mass extinction by incorporating unique short-term historical events, which leave signals in the sedimentary rocks, into a comprehensive scheme of relative age from oldest to youngest in any rock sequence. Although this seems like a straightforward application, it is in fact, complicated by the particular sedimentary environment and the completeness of the sedimentary record. For example, impact signals that are well separated in high sedimentation marginal

Figure 2. Deccan Traps of India form 3500 m high mountains of layered volcanic rocks. Volcanic eruptions occurred in three phases: an initial relatively small phase at 67.5 Ma, the main phase in C29R accounts for 80% of the total eruptions and led to the KT mass extinction. The last phase erupted in C29R. (Photo S Self.)

shelf environments are frequently juxtaposed in condensed sequences of the deep sea. Hiatuses may have removed sediments containing the impact signals, and erosion and redeposition of impact ejecta into younger sediments results in disparate age relationships (review in Keller 2008a). Stratigraphy and biostratigraphy are the primary tools that can unravel the complex post-depositional history of the sedimentary record. But to do so, high-resolution biostratigraphy is necessary.

Planktic foraminifera provide excellent biomarkers for the KT boundary transition because they suffered the most severe mass extinction of all microfossils groups. All tropical and subtropical specialized large species (2/3 of the assemblage) died out at or shortly before the KT boundary and all but one survivor (*Guembelitria cretacea*) died out during the early Danian zone P1a (MacLeod and Keller 1994). The mass extinction at the K-T boundary was followed by the rapid evolution and diversification of Danian species beginning within a few cm of the boundary clay and Ir anomaly in most sequences. The high-resolution planktic foraminiferal zonal scheme developed for the KT transition is based on the stratotype and co-stratotype sections at El Kef and Elles in Tunisia plus numerous KT sections worldwide (Keller *et al.* 1995, 2002; Li and Keller 1998a; Pardo *et al.* 1996) (figure 3). Ages for these biozones are estimated based on palaeomagnetic stratigraphy and extrapolation based on sediment accumulation rates. The zonal schemes of Berggren *et al.* (1995) and Caron (1985) are shown for comparison in figure 3.

The KT boundary is characterized by (1) the mass extinction of all tropical and subtropical species by KT time, though the decrease in diversity and abundance begins in zone CF1 coincident with the short global warming that appears to coincide with the main phase of Deccan volcanism. (2) The first appearance of Danian species *Parvularugoglobigerina extensa, Woodringina hornerstownensis* and *Globoconusa daubjergensis* in the KT boundary clay almost immediately after the KTB (Keller *et al.* 1995, 2002). Note that the presence of the boundary clay depends on the depositional environment and therefore may not always be present, particularly in high sedimentation nearshore areas such as Brazos River, Texas (Keller *et al.* 2007, 2009a). (3) A negative δ^{13}C excursion coincident with the KTB. This carbon isotope excursion is global and an excellent marker for the KTB. In condensed sections, including deep-sea sequences, the δ^{13}C excursion is abrupt, whereas in expanded high sedimentation sequences the δ^{13}C excursion is gradual beginning slightly below or at the KTB (e.g., Barrera and Keller 1990; Keller *et al.* 2009a). (4) An iridium anomaly is frequently concentrated in a thin (2–4 mm) red oxidized layer at the base of the boundary clay. However, an Ir anomaly by itself is not sufficient evidence to identify the KTB because multiple Ir enrichments are common in late Maastrichtian and early Danian sediments and may be due to a variety of factors, including multiple impacts, volcanism and redox conditions (Graup and Spettel 1989; Grachev *et al.* 2005; Stüben *et al.* 2005; Keller 2008a). Moreover, Ir anomalies typically occur in organic-rich shales or clays, which serve as low-permeability redox boundaries where Ir can move both upward and downward (Tredoux *et al.* 1988; Sawlowicz 1993; Wang *et al.* 1993).

Some workers proposed to redefine the KTB solely on the basis of impact evidence (e.g. Ir anomaly, impact spherules, impact breccia, shocked quartz minerals) and the mass extinction (Olsson *et al.* 1997; Norris *et al.* 1999; Gradstein and Ogg 2004; Molina *et al.* 2006; MacLeod *et al.* 2006; Schulte *et al.* 2006, 2008). The underlying assumption is that the Chicxulub impact caused the mass extinction and therefore impact evidence marks the KTB. This has led to the obvious circular reasoning – the Chicxulub impact is KT in age, therefore impact ejecta defines the KTB (*see* Schulte *et al.* 2008 and reply by Keller *et al.* 2008b). But there are also many other problems. For example, (a) Chicxulub impact spherule evidence is restricted to Central America, Caribbean and USA, (b) the primary impact spherule deposits are in the lower part of zone CF1 and predate the KTB by about 300,000 years (Keller *et al.* 2003a, 2007), (c) the Ir anomaly has never been found in sediments with Chicxulub impact ejecta (review in Keller 2008a, b) and (d) multiple Ir anomalies are common (Keller *et al.* 2003a, b; Stüeben *et al.* 2005). A more prudent approach to identifying the KTB is to use the independent and unique global criteria of the mass extinction, first appearances of Danian species and the δ^{13}C excursion. Evidence of impact(s) and volcanism can be dated relative to these criteria and within the global biostratigraphic and chemostratigraphic correlation scheme.

3. Age of Chicxulub impact

The Chicxulub impact on Yucatan is commonly believed to have caused the KT mass extinction based on the proximity of impact glass spherules at or near the KT boundary in Haiti, Mexico and Texas (e.g. Izett 1991; Smit *et al.* 1992, 1996; Arrenillas *et al.* 2006; Schulte *et al.* 2006, 2008). However, impact spherules are commonly found at various stratigraphic levels, including interbedded in Maastrichtian sediments well below the KTB in NE Mexico and Texas, at the KTB in condensed or incomplete sections, and frequently reworked into Danian sediments in Belize, Guatemala, Haiti and Cuba (Keller *et al.* 2003a, b, 2007, 2009a). Only the stratigraphically oldest impact spherule layer marks the time of the impact, all other spherule layers are reworked.

Chicxulub Impact spherules were first discovered at the base of a sandstone complex that infills submarine channels in Texas and NE Mexico, as illustrated for the El Peñon section in NE Mexico (figure 4). In both regions the KTB

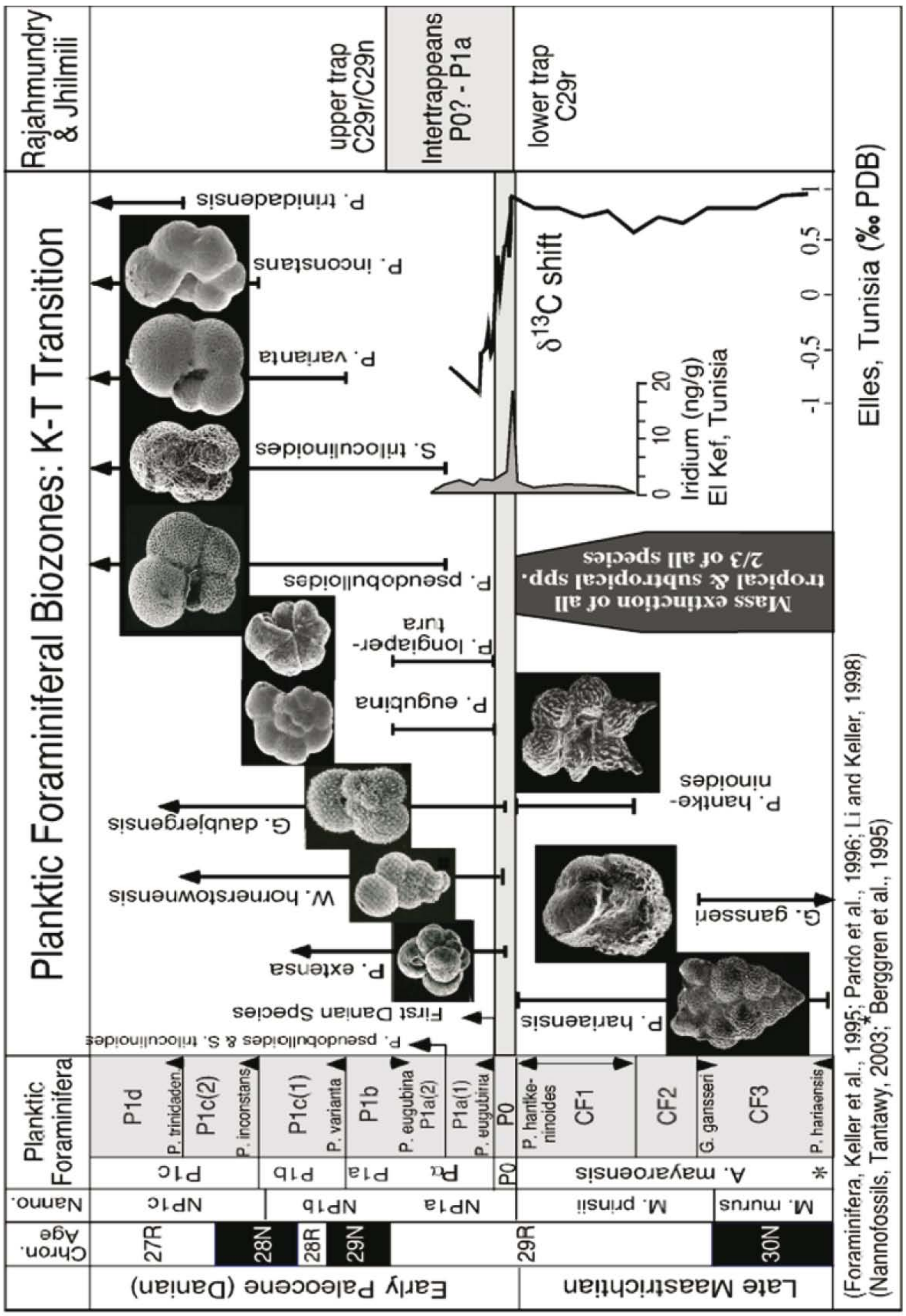

Figure 3. The high-resolution planktic foraminiferal zonal scheme based on the KT stratotype at El Kef, Tunisia, identifies the KT boundary in India as well as worldwide.

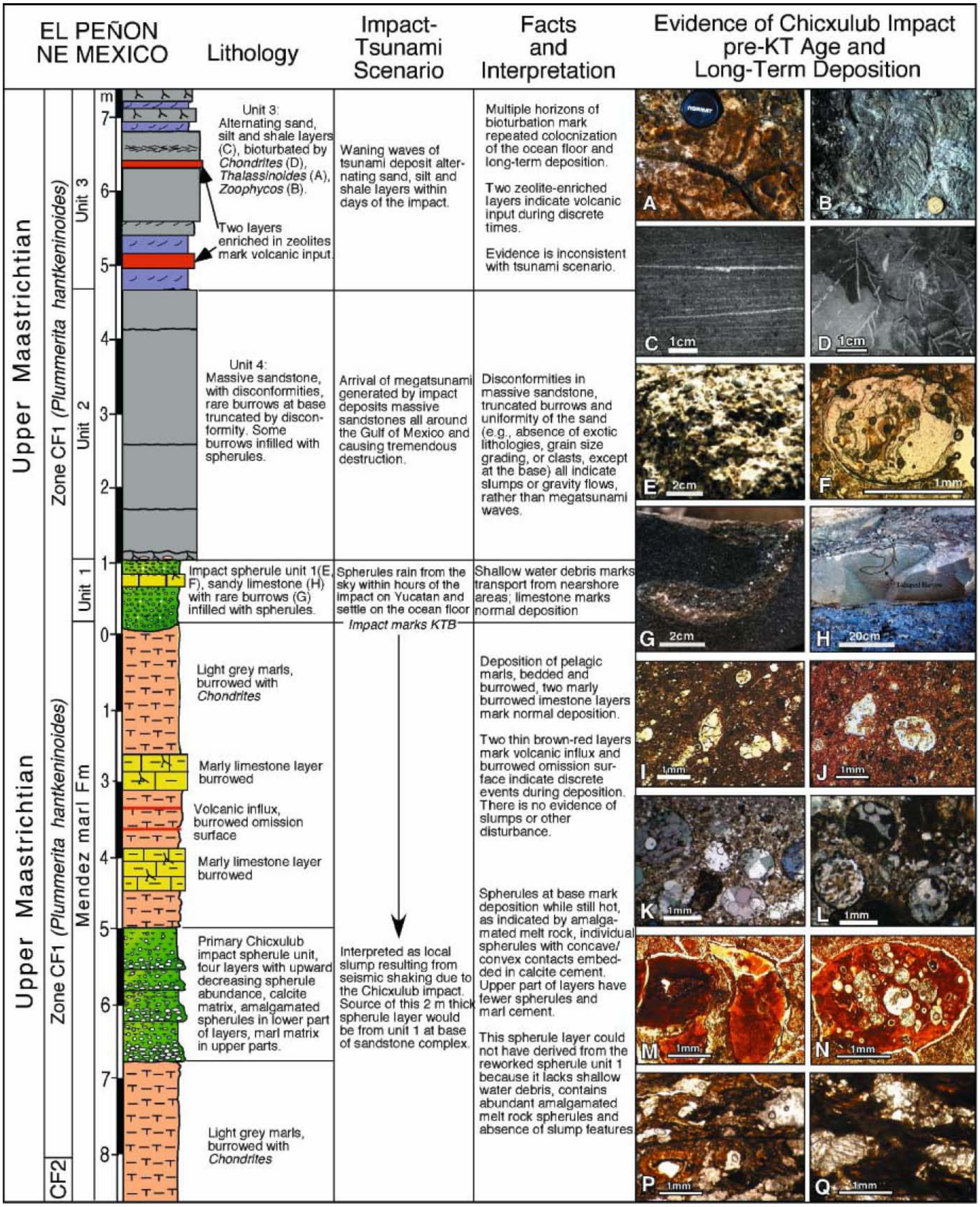

Figure 4. Upper Maastrichtian sequence at El Penon, NE Mexico, shows the primary (original) impact glass spherule deposit in Maastrichtian marls near the base of zone CF1, or about 300 ky prior to the KT boundary. Two reworked spherule layers separated by a limestone layer mark the base of a sandstone complex that was deposited during a sea level lowstand, but has been erroneously interpreted as impact generated tsunami deposit.

and Ir anomaly are invariably above the sandstone complex. This presented a problem because the Chicxulub impact was assumed to be KTB in age, which meant that the impact spherules, Ir anomaly and KTB mass extinction had to be coincident. The solution was to interpret the sandstone complex between the KTB and the spherule layer as impact-generated tsunami deposits, which called for deposition within hours to days and therefore would be consistent with the presumed KTB age (figure 4) (e.g. Bourgeois *et al.* 1988; Smit *et al.* 1992, 1996; Smit 1999; Schulte *et al.* 2006; Arenillas *et al.* 2006; Kring 2007).

Closer study of the sandstone complex in NE Mexico revealed a spherule layer with abundant shallow water debris reworked and transported from near shore areas and re-deposited in the channel system of the continental slope (figure 4 E, F) (Keller *et al.* 1997, 2003a; Alegret *et al.* 2001). In some sections a 20–25 cm thick sandy limestone layer with rare J-shaped burrows infilled with spherules and truncated at the top separates two reworked spherule layers (figure 4, G, H) (Keller *et al.* 1997; Ekdale and Stinnesbeck 1998). This indicates that deposition of spherules occurred in two events separated by the considerable amount of time it took for the limestone layer to form. Moreover, the upper fine sand, silt and shale layers of the sandstone complex contain several discrete, highly bioturbated and truncated intervals burrowed by *Chondrites, Thalassinoides* and *Zoophycos,* (figure 4A–D) which indicates repeated colonization of the ocean floor during deposition (Keller *et al.* 1997, 2007; Ekdale and Stinnesbeck 1998; Gale 2006). In addition, two zeolite-enriched layers mark discrete volcanic influx (Adatte *et al.* 1996). All of these characteristics are inconsistent with the impact-tsunami interpretation, but suggest deposition over an extended time period during a sea level fall.

The presence of clasts with impact spherules at the base of the sandstone complex in the Brazos sections of Texas and shallow water reworked debris in NE Mexico sections suggested the presence of an older primary impact spherule layer (Keller *et al.* 2003a, 2007). A regional study of late Maastrichtian sediments discovered the primary impact spherule layer interbedded in marls and claystones 4 m below the sandstone complex at El Penon (figure 4) (Keller *et al.* 2003a, 2009b). This spherule layer contains abundant amalgamated impact melt rock and spherules with convex/concave contacts and calcite cement in the lower part, decreasing abundance of spherules and increasing marl matrix in the upper part followed by normal marl sedimentation with common planktic foraminifera (figure 4I-Q). No shallow water debris is present. Deposition of this stratigraphically oldest (primary) impact spherule layer occurred near the base of *Plummerita hantkeninoides* zone CF1, which spans the last 300,000 years of the Maastrichtian (Pardo *et al.* 1996). This is the basis for the estimated ~300 ky pre-KT age for the Chicxulub impact (Keller *et al.* 2003a).

Biotic and environmental effects of the Chicxulub impact have been evaluated across the primary impact spherule layer, the sandstone complex in Texas and Mexico (Keller *et al.* 2009a, b). At El Peñon, as elsewhere in NE Mexico, no species went extinct across the primary impact spherule layer and no significant species abundance changes occurred. All species range up to the sandstone complex. Similarly, in Texas no species extinctions occurred across the primary impact spherule layer. Although some species disappeared before and after the Chicxulub impact ejecta layer, these species are known to range up to the KTB and their local disappearance in Texas is the result of the shallowing shelf environment. These data indicate that no species extinctions can be attributed to the Chicxulub impact in either deep-water slope (>500 m) or shallow shelf (<80 m) environments even within distances of 600 km to 1000 km from the impact crater on Yucatan.

The absence of any recognizable biotic effects as a result of the Chicxulub impact comes as a surprise mainly because we have *assumed* that this impact caused the K-T mass extinction. In fact, none of the large impact craters over the past 500 m.y. is associated with a mass extinction (Courtillot 1999; Wignall 2001; White and Saunders 2005; Keller 2005). Apart from the Chicxulub crater, with a diameter of about 170 km, other well studied large impacts that show no extinctions or significant other biotic effects include the 90-100 km in diameter late Eocene Chesapeake Bay and Popigai craters, the 100-120 km in diameter late Triassic Manicouagan and late Devonian Alamo and Woodleigh craters (Montanari and Koeberl 2000; Wignall 2001; Keller 2005). This suggests that the biotic effects of large impacts have been vastly overestimated and that the real cause for the KT mass extinction must be found elsewhere.

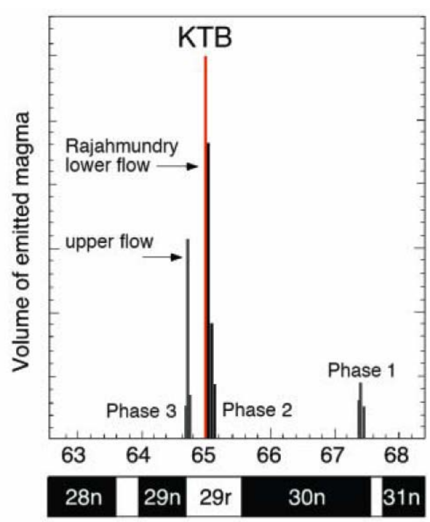

Figure 5. Deccan eruptions occurred in three phases, with the phase-2 encompassing 80% of the total eruptions and ending at the KT boundary (modified from Chenet *et al.* 2008).

4. Deccan Volcanic Province: Age of main eruption phases

The Deccan Traps (named for the stepwise sequence of successive lava flows) and its correlation with the KTB mass extinction are the most extensively studied continental flood basalt (CFB) volcanism. However, a direct correlation has been difficult to establish because the estimated duration of Deccan volcanism varied from less than one million to several million years based on palaeomagnetic studies and $^{40}Ar/^{39}Ar$ dating of the main Deccan Vocanic Province (DVP) and Rajahmundry Traps (Courtillot *et al.* 1986, 1988, 2000; Duncan and Pyle 1988; Vandamme *et al.* 1991; Vandamme and Courtillot 1992; Baksi 1994; Raju *et al.* 1995; Venkatesan *et al.* 1993, 1996; Hoffmann *et al.* 2000; Widdowson *et al.* 2000; Sheth *et al.* 2001). In the past few years, significant advancements have been made with respect to the age of volcanic eruptions based on $^{40}K/^{40}Ar$ and $^{40}Ar/^{39}Ar$ dating (e.g. Knight *et al.* 2003, 2005; Pande *et al.* 2004; Baksi 2005; Chenet *et al.* 2007, 2008) and geochemical characterization of different eruptions (Jerram and Widdowson 2005; Jay and Widdowson 2008; Jay *et al.* 2009).

Based on comprehensive studies, Chenet *et al.* (2007, 2008) proposed that Deccan volcanism occurred in three short phases. The initial phase 1 was relatively small, occurred around 67.4 to 67.5 Ma (time scale of Cande and Kent (1995) near the C30R/C30N transition and may have lasted less than 10 ky (figure 5). A period of quiescence followed for at least 1.6 m.y. Phase 2 marks the largest eruptions in C29R encompassing a total of ~80% of the total Deccan Traps volume (Chenet *et al.* 2007, 2008). This mega-phase consists of several major eruptive events, each with volumes ranging from 20,000 km^3 to 120,000 km^3, attaining a thickness up to 200 m and emplaced over hundreds of km (Chenet *et al.* 2008; Jay and Wioddowson 2008; Jay *et al.* 2009) with the longest lava flows spanning over 1000 km into the Gulf of Bengal (Self *et al.* 2008a). These eruptions mark the Ambenali Formation. The duration of phase 2 within C29r remains speculative. Chenet *et al.* (2007, 2008) suggested that phase 2 eruptions occurred over a very short time on the order of one thousand to tens of thousands of years based on assumptions of how red bole layers formed and the frequent absence of intertrappean sediments in the main DVP. Recent studies of the Rajahmundry intertrappean sediments indicate that phase 2 ended at or very near the KT mass extinction (Keller *et al.* 2008a). Further studies are needed to refine age control for the onset of phase 2.

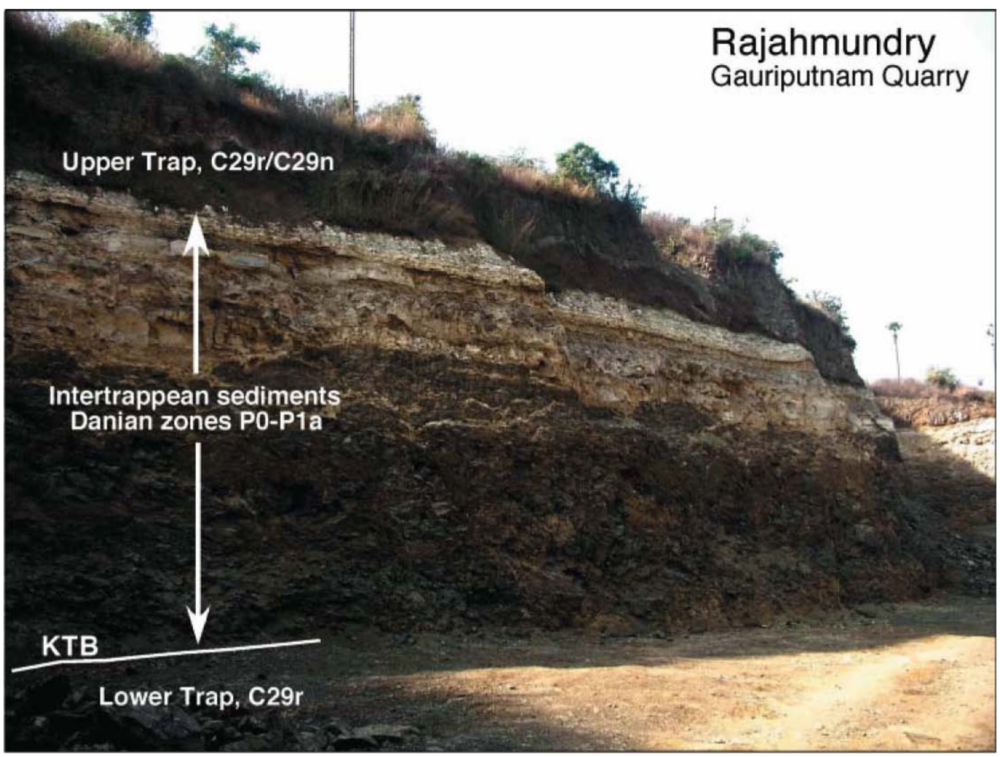

Figure 6. Intertrappean sediments between lower (C29R) and upper (C29R/C29N) lava flows in the Gauriputnam Quarry of Rajahmundry. These intertrappean sediments were deposited in shallow estuarine to marine sediments that contain planktic foraminifera of the earliest Danian (zones P0-P1a). Four of the longest lava flows mark the end of the main phase of the Deccan eruptions in C29R. The KT mass extinction coincides with the end of the main eruption phase in the Rajahmundry area and Krishna-Godavari Basin.

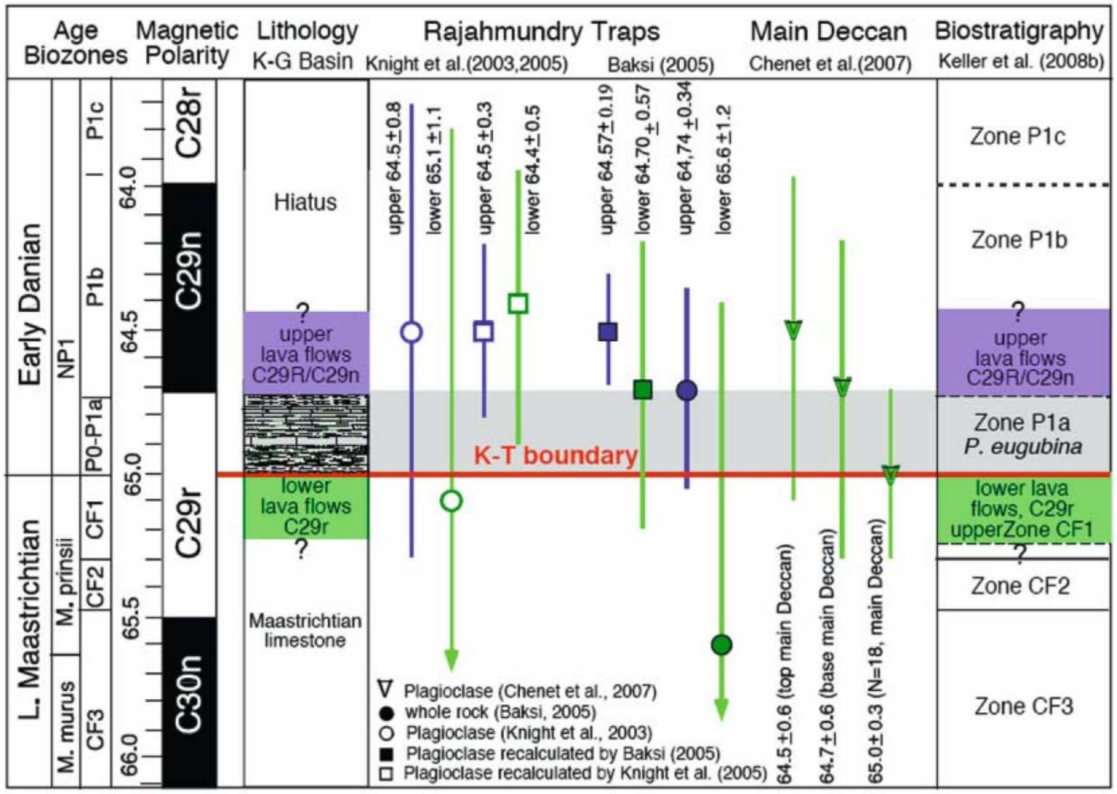

Figure 7. $^{40}K/^{40}Ar$ and $^{40}Ar/^{39}Ar$ ages of the lower and upper Rajahmundry Deccan traps yield ages with an accuracy of 1% or ± 0.6 m.y., which is too imprecise to locate the KT boundary. Planktic foraminiferal biostratigraphy places the lower trap in the latest Maastrichtian with the uppermost of four lava flows at the KT boundary and mass extinction. (Modified from Keller *et al.* 2008b).

Volcanic phase 3 occurred in the early Danian magnetochron C29n, or about 270 ky after the KTB (time scale of Cande and Kent 1995) (figure 5). The volume of eruptions was relatively small compared with phase 3 (<20% of the entire Deccan volume). Phase 3 marks the Mahabaleshwar Formation, which in Rajahmundry is represented by the upper trap flows (Jay and Widdowson 2008, Jay *et al.* 2009). Volcanic phase 3 may have been responsible for the long delay in biotic recovery that has remained an enigma for so long. However, this remains to be investigated, particularly in marine sediments of offshore drill cores.

5. Deccan volcanism linked to KTB

5.1 *Palaeomagnetic and radiometric ages*

For decades the major stumbling block in linking Deccan volcanism to the KT mass extinction and successfully advocate a cause-effect scenario, has been the lack of high-resolution age control to pinpoint the KT boundary. The mainstay of Deccan Trap age control has been the palaeomagnetic reversal history that indicates that the bulk of eruptions (phase 2) occurred in C29r (e.g. Courtillot *et al.* 1988; Duncan and Pyle 1988; Chenet *et al.* 2007, 2008). Additional key information was achieved from Deccan trap exposures in quarries near Rajahmundry and subsurface wells in the Krishna-Godavari Basin (figures 1, 6). In these quarries and subsurface wells a thick intertrappean sequence separates what is known as lower and upper Rajahmundry traps of C29R and C29N, respectively (Subbarao and Pathak 1993; Jaiprakash *et al.* 1993; Raju *et al.* 1995). Age determinations based on $^{40}K/^{40}Ar$ (absolute) and $^{40}Ar/^{39}Ar$ (relative) dates are in general agreement with palaeomagnetic ages, but the large error bars (1% or 0.6 m.y.) permit no determination of the KTB position (figure 7) (Knight *et al.* 2003, 2005; Baksi 2005; Chenet *et al.* 2007).

The Rajahmundry traps have been historically considered as part of the original Deccan volcanic province with lava flows traveling along existing river valleys and extending about 70 km offshore into the Bay of Bengal (Venkaya 1949). This has been confirmed by magnetostratigraphy and geochemical similarities with the main Deccan volcanic province to the west (Lightfoot *et al.* 1990; Subbarao and Pathak 1993; Banerjee *et al.* 1996; Baksi 2001; Jay and Widdowson 2008; Jay *et al.* 2009). The Rajahmundry traps,

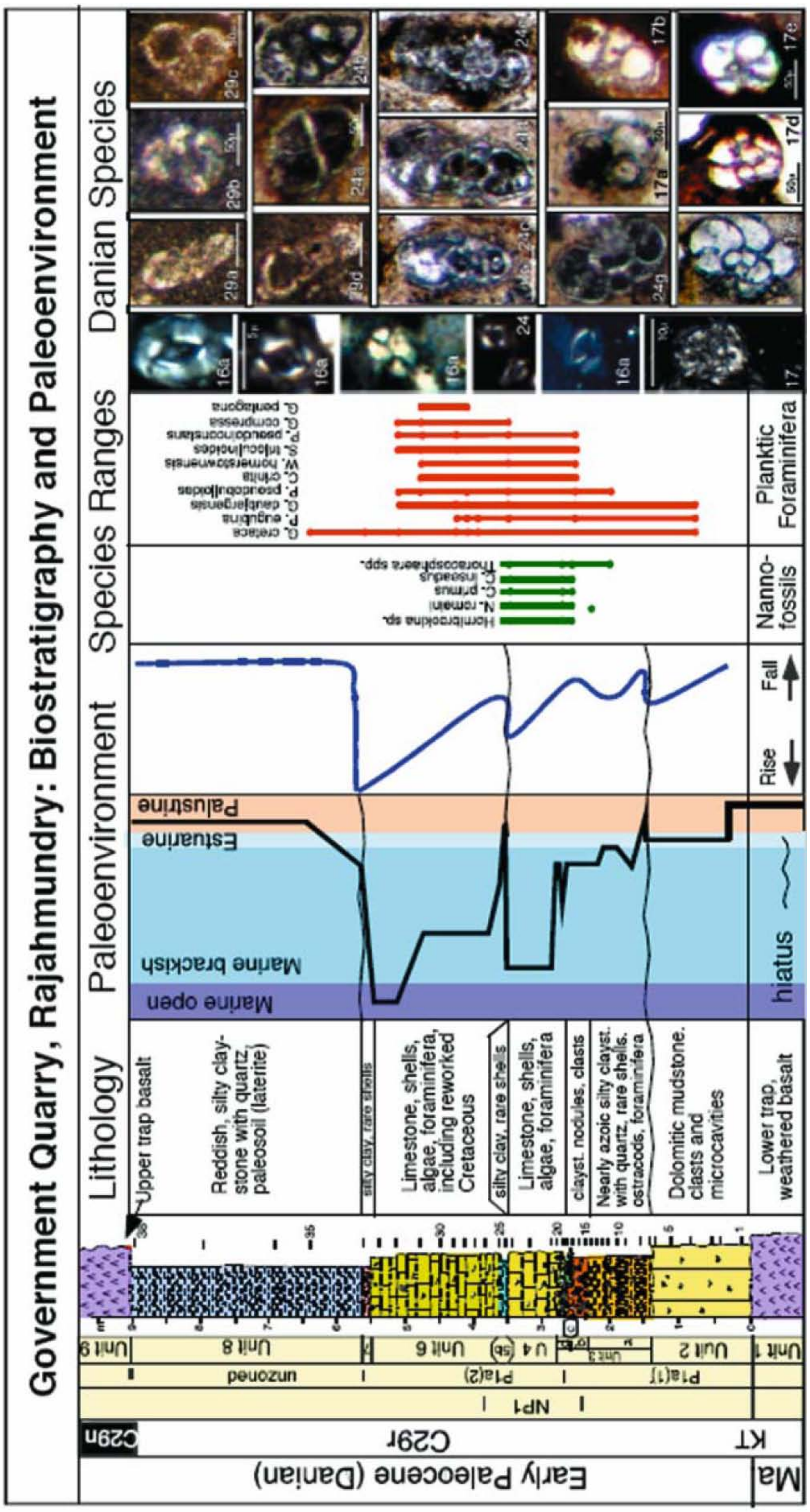

Figure 8. Lithology, biostratigraphy and sea level changes of intertrappean sediments between lower and upper traps at the Government Quarry, Rajahmundry. Sediment deposition after the main phase of volcanic eruptions occurred in a shallow estuarine to marine environments with repeated emersions. Planktic foraminifera and calcareous nannofossils mark this time as earliest Danian zones P0-P1a, immediately following the mass extinction. (Modified from Keller *et al.* 2008b).

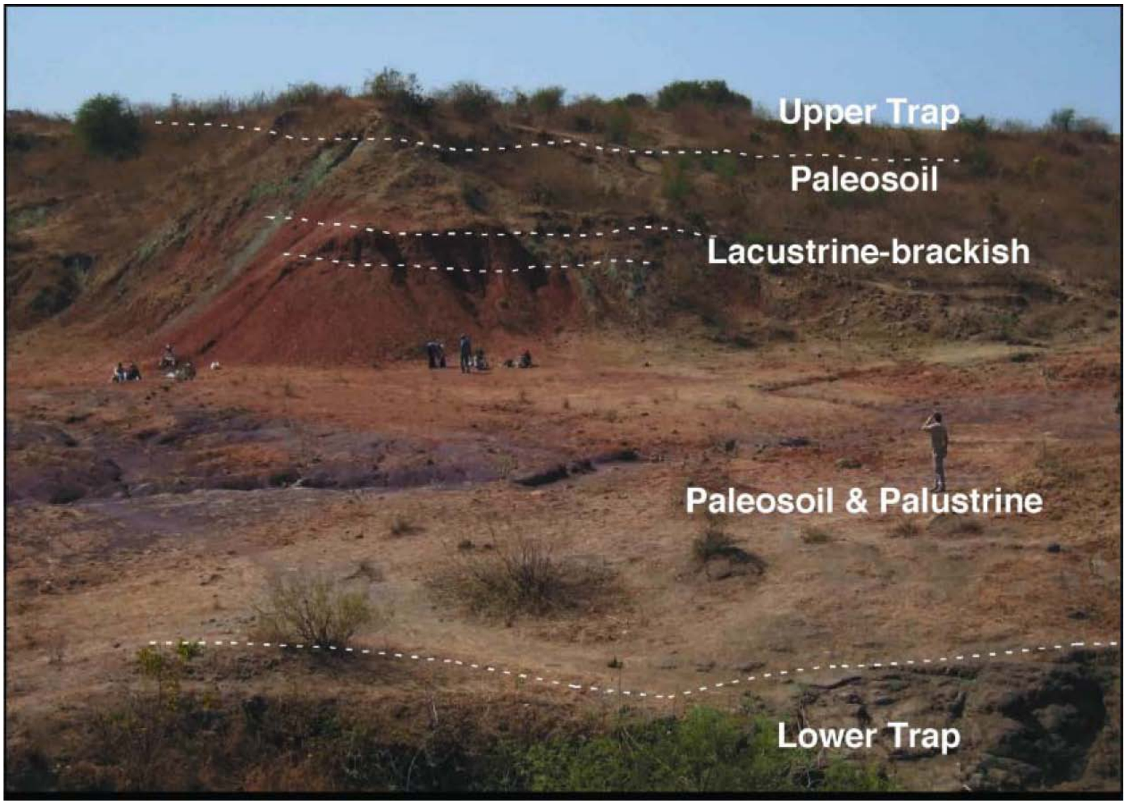

Figure 9. Panoramic view of Jhilmili intertrappean sequence (District Chhindwara, MP) showing intertrappean sediments and the upper and lower basalt trap flows. Planktic foraminifers in these sediments reveals a major trans-India seaway at the Cretaceous-Tertiary transition.

which reach 1000 km across India, are thus the longest lava flows known in Earth history (Self *et al.* 2008a) and may represent the volcanic acme of phase 2 ending at or near the KT mass extinction (Keller *et al.* 2008a).

5.2 *Palaeontologic age control – Krishna-Godavari Basin*

Since Deccan eruptions generally occurred upon terrestrial sequences, palaeontologic age control is largely restricted to terrestrial and fresh water fossils, (e.g. Khosla and Sahni 2003) have long-ranging histories. The intertrappean biota includes ostracods (e.g. Bajpai and Whatley 2001; Whatley *et al*. 2002; Whatley and Bajpai 2005, 2006; Khosla and Nagori 2007), palynomorphs (e.g. Kummaran *et al.* 1997; Cripps *et al.* 2005; Samant and Mohabey 2005; Samant *et al.* 2008), fishes (Prasad and Cappetta 1993) and dinosaur remains (e.g. Sahni and Bajpai 1988; Ghevariya 1988; Srinivasan 1996; Bajpai and Prasad 2000; Prasad *et al.* 2007). The presence of dinosaur remains in intertrappean and infratrappean sediments has led to the general acceptance of a Maastrichtian age for the main Deccan volcanic province (e.g., phase 2). However, locating the KTB based on these fossils has remained elusive.

Better age control was achieved based on marine microfossils in sequences from subsurface wells of the Krishna-Godavari Basin. For example, planktic foraminifera from the ONGC (Oil and Natural Gas Corporation) Palakollu-A well show a limestone of latest Maastrichtian age below the lower trap and a Danian (P1b to P2) age for the intertrappean beds (Raju *et al.* 1994, 1995; Jaiprakash *et al.* 1993), interrupted by frequent hiatuses (Raju *et al.* 1994; Raju 2008). Similarly, the Narasapur well yielded an early Palaeocene (Danian) age based on planktic foraminifera (Govindan 1981), calcareous nannoplankton (Saxena and Misra 1994), dinoflagellates (Mehrotra and Sargeant 1987) and palynology (Prasad and Pundeer 2002). These observations were confirmed in the shallow water intertrappean sediments of the Rajahmundry quarries where ostracod faunas also yielded a Danian age (Bhandari 1995; Khosla and Nagori 2002).

Although the precise location of the KTB remained elusive in these studies, they indicated that the KTB had to be at or within the lower trap and overlying intertrappean sediments (figures 6, 7). A restudy of the intertrappean sediments in the Rajahmundry quarries based on planktic foraminifera, calcareous nannofossils, sedimentology and mineralogy yielded improved age control (Keller *et al.* 2008a). This study revealed the first direct link between the KT mass extinction and Deccan volcanism based on planktic foraminifera. Foraminiferal studies were conducted mainly on thin sections because the mostly tiny and fragile early Danian specimens are obliterated in the standard laboratory processing.

Intertrappean sediments in Rajahmundry quarries show similar biostratigraphy and depositional environments as shown for the Government Quarry (figure 8). Sediment deposition above the lower trap basalt begins with dolomitic mudstone with clasts containing the small earliest Danian planktic foraminifera indicative of Zone P0, or base of zone P1a. In the 4 m above, sediments vary from silty claystone with rare shells and foraminifera to limestones with common shells, calcareous nannofossils (early Danian NP1) and foraminifera indicative of zone P1a. The upper 3.4 m consist of palaeosoil followed by the upper trap basalt. Microfossils and microfacies analyses thus indicate a sea level transgression at the base of the Danian followed by fluctuating estuarine to inner neritic environments and a return to terrestrial deposition well prior to the arrival of the upper trap basalt (figure 8, Keller *et al.* 2008a).

Biostratigraphic data thus indicate that the lower Rajahmundry trap directly underlies earliest Danian sediments. This indicates that the mass extinction coincides with the end of the main phase of Deccan volcanism, as represented by the last of at least four of the longest (1000 km) lava flows that are observed in the Krishna-Godavari Basin (Jaiprakash *et al.* 1993; Keller *et al.* 2008a).

5.3 *Palaeontologic age control – Jhilmili, Chhindwara, Madhya Pradesh*

A surprising discovery of early Danian planktic foraminifera was made in intertrappean sediments near the village of Jhilmili, Chhindwara District, Madhya Pradesh (figure 1) during routine ostracod analyses by different laboratories (e.g. S Bajpai at IIT Roorkee, A Khosla at Panjab University, S C Khosla at Mohanlal Sukhadia University, Keller *et al.* 2009c). The Jhilmili intertrappean sequence is about 14 m thick and sandwiched between lower and upper trap basalts (figure 9). These intertrappeans were considered to be of terrestrial origin and late Maastrichtian age. In 2008 the section was revisited for systematic high-resolution sampling for sedimentologic mineralogic and palaeontologic analyses.

The lower part (unit 2, 0–6.0 m) and upper parts (unit 4, 6.6–11.0 m) of the Jhilmili intertrappean sequence consist of monotonous red claystone and clayey siltstone. The top 2.7 m (unit 5, 11–13.7 m) consist of green-grey siltstone, a layer of white calcite nodules (12.8 m) and volcanic glass and spherules below the upper trap basalt. These intervals represent palaeosoils deposited in terrestrial and palustrine environments (figure 10). Of particular interest is the 0.6 m thick interval of unit 3 (between 6.0–6.6 m), which consists of yellow limestone, nodular coarse limestone, pink and tan laminated clays and volcanic glass. This interval is topped by a tempestite. Microfacies and clay mineral analyses indicate deposition in palustrine to flood plain environments in the lower part of unit 3 and fresh water to marine brackish conditions in the upper part (figure 10, Keller *et al.* 2009c).

Palaeontologic analyses revealed an abundance of predominantly fresh water ostracods in unit 3 and only rare brackish water species (Keller *et al.* 2009c, d). Planktic foraminifera analysed in washed sample residues and thin sections revealed a diverse early Danian zone P1a assemblage. Only the larger more robust specimens could be recovered in washed residues, including *Parasubbotina pseudobulloides, Subbotina triloculionoides, Globigerna (E) pentagona, Globanomalina compressa* and Cretaceous survivors *Hedbergella holmdelensis, Gobigerinelloides aspera* (figure 10). The smaller, fragile species were analyzed in thin sections. Some species show signs of high-stress conditions. For example, *P. pseudobulloides* has slightly compressed chambers, nearly planispiral coil, smoother perforate wall and an umbilical-extraumbilical aperture covered by a broad rim. This may reflect adaptation to local environmental conditions. The presence of assemblages with *Parvularugoglobigerina eugubina, P. pseudobulloides* and *S. triloculinoides* indicates the upper half of zone P1a, or subzone P1a(2) (figure 10).

6. Palaeoenvironment – Marine seaway

In the Krishna-Godavari (K-G) Basin deposition of the lower trap basalt occurred in a marine shelf setting. Further inland in the Rajahnundry area, deposition occurred primarily in terrestrial settings punctuated by short marine incursions. The presence of pillow lavas indicates that some lava flows erupted under water (Keller *et al.* 2008a). During the early Danian, intertrappean deposition occurred in fluctuating brackish marine to estuarine environments. Microfossil and microfacies analyses indicate an overall deepening, which briefly reached open marine conditions (top of unit 6, figure 8) prior to a sea level regressions and return to a terrestrial (palustrine) environment (Keller *et al.* 2008a). Upper trap lavas in the Rajahmundry area and K-G basin to the east were deposited in terrestrial and shallow shelf environments, respectively.

In central India, the Jhilmili lower traps were deposited in a terrestrial environment, although the presence of pillow lavas suggests the existence of sizable lakes (Keller *et al.* 2009c). Deposition of intertrappean sediments occurred predominantly in arid terrestrial and palustrine environments with lakes and ponds, except for a short interval marked by repeated incursions from offshore marine

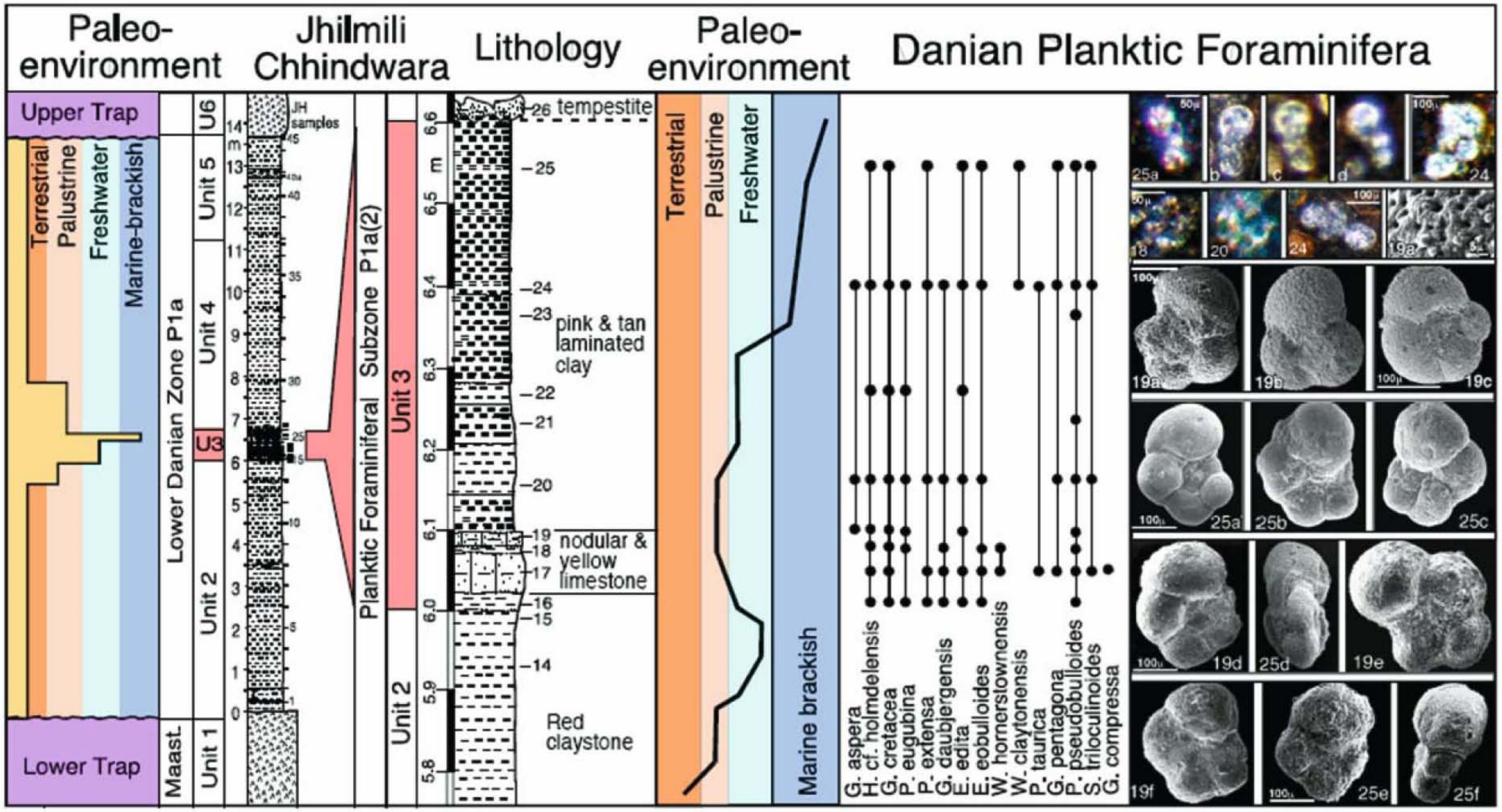

Figure 10. Lithology, biostratigraphy and paleoenvironmental changes of intertrappean sediments between lower and upper traps at Jhilmili, Chhindwara. Sediment deposition is predominantly terrestrial to palustrine, except for a short interval (unit 3) of freshwater to brackish marine environments. Planktic foraminifera mark this time as earliest Danian zone P1a (Modified from Keller *et al.* 2009d).

currents transporting planktic foraminifera. Influx of marine waters established brackish to estuarine conditions in which planktic foraminifera survived, but experienced high stress, as suggested by their varied morphologies. The end of this marine transgressive phase is marked by a storm deposit (tempestite, figure 10), which is followed by palaeosoils indicating a return to terrestrial deposition. Upper trap lavas were deposited in a terrestrial environment.

The presence of planktic foraminifera in central India indicates a source of marine waters. The nearest ocean from Jhilmili is the Arabian sea about 800 km to the west, or the Gulf of Bengal about 800 km to the east (figure 11). Jhilmili is located near the easternmost extension of the Tapti rift valley, which forms an arm of the Narmada rift valley that meets the northern extension of the Godavari rift zone. A seaway may have existed through the Narmada and Tapti

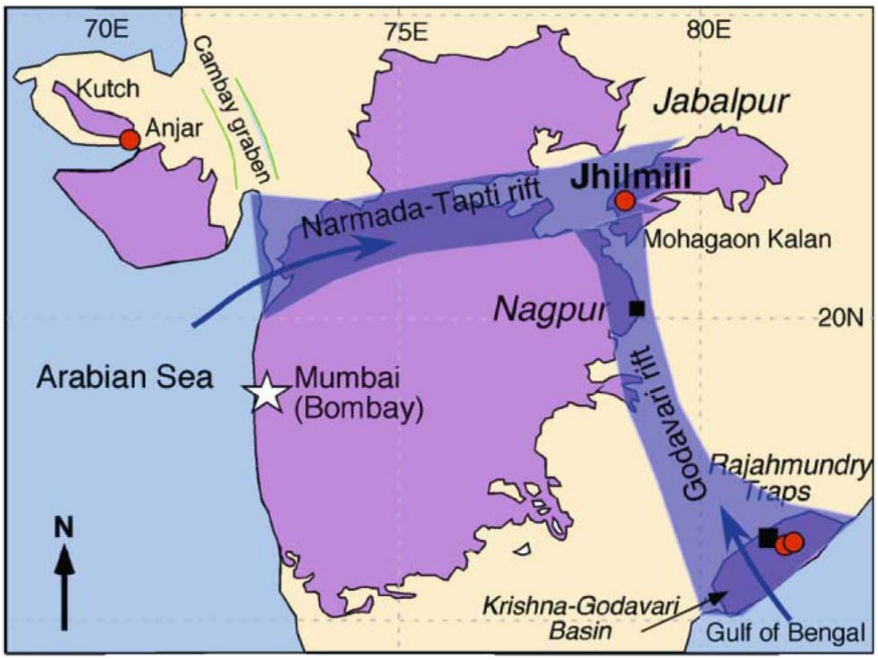

Figure 11. Map of India with exposures of the main Deccan volcanic province superimposed by the proposed India seaways along the Narmada-Tapti rift valleys and a possible seaway that may have existed along the Godavari rift zone.

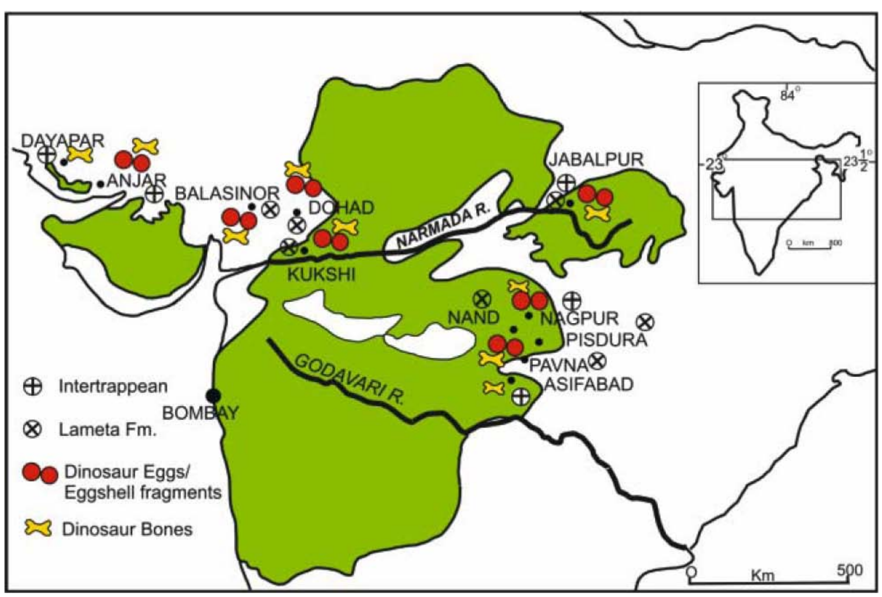

Figure 12. Distribution of Dinosaur remains in the Lameta and intertrappean deposits of the Deccan volcanic province.

rift valleys into central India. Likewise, a seaway could also have extended from Rajahmundry north into central India along the Godavari rift valley.

Marine incursions along the Godavari and Narmada rift zones are known from the lower Cretaceous and late Cenomanian to early Turonian Bagh Formation based on marine invertebrates, including ostracods, planktic foraminifera and algae (Chiplonkar and Badve 1968; Badve and Ghare 1977). Planktic foraminiferal assemblages from the Chirakhan marl of the Bagh Formation indicate a late Cenomanian to early Turonian age, a time of maximum sea level transgression (Sharma, 1976; Rajshekhar, 1996). However, evidence for a seaway during the late Cretaceous is highly controversial and based largely on sedimentological data (e.g. Singh 1981, but see Tandon *et al.* 1995), though lagoonal deposits have been reported from the Maastrichtian Lameta beds of the Jabalpur area (Shukla and Srivastava 2008).

Based on prevailing fossil evidence (e.g., marine algae, Bande *et al.* 1981), Sahni (1983) suggested that marine incursions formed a connecting narrow seaway along the two major structural rift zones of the present day Godavari and Narmada Rivers (figure 11). He surmised that this 'Trans Deccan Strait' would have been temporary and subject to marine transgressions, which would not have fostered the establishment of stable marine benthic communities, but served as conduit and dispersal for marine biota. Evidence from Jhilmili supports this hypothesis. Early Danian planktic foraminiferal assemblages are as diverse as in open marine environments. But unusual morphologic variations of species (e.g. broad lips covering aperture, Keller *et al.* 2009c) reveal high stress conditions. The absence of benthic species reveals unstable marine conditions where the presence of planktic species is the result of current transport (e.g. storms, high tides).

Jhilmili represents the first fossil evidence of a marine seaway into central India during the KT transition. Similar evidence must abound in intertrappean sediments along the Narmada, Tapti and Godavari rift zones. The challenge is to find these marine sediments in the intertrapean and infratrappean sediments along these rift zones. Marine microfossils can provide the necessary age control for the volcanic eruptions. Correlation of these strata to dinosaur fossil-bearing continental strata can identify the K-T boundary within the Deccan Traps and yield age control for the dinosaur remains tied to the marine record. The resultant age control can provide crucial information regarding the biotic, climatic and environmental effects of the Deccan eruptions and their role in the K-T mass extinction.

7. Dinosaur fossils

Dinosaur egg shells, nests and bone fragments are abundant and ubiquitous through central India along the projected seaways of the Narmada-Tapti rift valleys and Godavari rift zone (figure 12). This suggests that the primary dinosaur breeding habitats surrounded interior seaways, which were likely more fertile than the dry inland areas. This setting may have been similar to the late Cretaceous dinosaur habitats that surrounded the Western Interior Seaway of North America (e.g. Kauffman 1977; Lehman 1987).

7.1 *Dinosaur fossil distribution in the Deccan province*

Dinosaur fossils are found in two distinct stratigraphic settings in the Deccan volcanic province, and a large majority of these occurrences are along the Narmada valley in central and western India (figure 12). The main dinosaur-bearing horizons occur in the sandy limestones, clays and conglomerates of the Lameta Formation, locally below the Deccan Trap flows (i.e. infratrappean in position). Dinosaur fossils from the Lameta Formation include egg clutches (e.g. Srivastava *et al.* 1986; Sahni *et al.* 1994; Mohabey 2001), numerous disarticulated skeletal remains (Huene and Matley 1933; Chatterjee 1978; Berman and Jain 1982; Mathur and Srivastava 1987; Wilson and Mohabey 2006) and coprolites (e.g. Matley 1939). Although rare, articulated and associated dinosaur remains are also known (Mohabey 1987; Wilson *et al.* 2003) Among the important dinosaur-yielding Lameta localities are Bara Simla at Jabalpur, Pisdura and Dongargaon near Nagpur in central India, and Kheda and Panchmahal areas of Gujarat, western India.

In contrast to the Lameta Formation, dinosaur fossils occur rarely in the Deccan intertrappean deposits. The latter consist mostly of clays and marls deposited in small ponds and lakes. Intertrappean dinosaur fossils include eggshell fragments, but not complete eggs (e.g. Bajpai *et al.* 1993; Srinivasan 1996), isolated teeth (e.g. Sahni and Bajpai 1988; Bajpai and Prasad 2000) and rare bones (Rao and Yadagiri 1981; Ghevariya 1988). Among the important dinosaur-yielding intertrappean localities are Anjar in the District Kutch, Gujarat; Mohagaonkalan in the District Chhindwara, Madhya Pradesh; Ranipur in the District Jabalpur, Madhya Pradesh and Asifabad in the District Adilabad, Andhra Pradesh.

Reworking of dinosaur remains from the infratrappean Lameta Formation is unlikely for several reasons, the most compelling of which is the complete absence of Lameta outcrops in some of the localities where dinosaur-bearing intertrappeans are known, such as Anjar. Also, it has been argued (e.g. Bajpai and Prasad 2000) that the serrated dinosaur teeth and eggshell fragments from the intertrappeans show delicately preserved features and are not worn as one would expect in the event of their reworking. It should be noted, however, that no complete eggs have been found in the intertrappeans until now; such eggs, if found, would constitute a much stronger evidence against reworking for the simple reason that complete eggs cannot be reworked without being fragmented. Another evidence that possibly rules out reworking of dinosaur remains is the absence of any exclusively Palaeocene taxa in the dinosaur-bearing intertrappean levels, even in sections with reported Ir-enrichment, such as Anjar (Bhandari *et al.* 1996; Bajpai and Prasad 2000)

7.2 *Current age control of dinosaur remains*

The age of the Lameta dionosaurs is widely considered to be latest Cretaceous (Maastrichtian) (e.g. Sahni and Bajpai 1988). Initially, the Lameta dinosaurs were considered to be Turonian in age based on their comparison with taxa from the similarly-aged deposits of South America (Huene and Matley 1933). However, a re-assessement of these dinosaurs suggested a much younger, Maastrichtian age (Chatterjee 1978; Buffetaut 1987), a determination that has been followed by most subsequent workers. Additional evidence cited for a Maastrichtian age include the ray fish *Igdabatis* (Courtillot *et al.* 1986) and the palynomorph *Aquilapollenties* (Dogra *et al.* 1994) from the Lameta beds at Jabalpur.

The age of dinosaur-bearing Deccan intertrappean deposits clearly lies within the terminal Maastrichtian since the volcanism itself is well constrained between 67 and 64 Ma. So far, no dinosaur fossils have been found in any Palaeocene-aged intertrappeans, such as those at Jhilmili, District of Chhindwara in central India (Keller *et al.* 2009c, d). In this area, there are multiple intertrappean levels and the one that yields dinosaur fossils (eggshell fragments) occurs stratigraphically below the intertrappean level dated as early Palaeocene (P1a) based on planktic foraminifera. The discovery of foraminifera in the Jhilmili section provides, for the first time, a reliable biostratigraphic framework for assigning a more precise age to the intertrappean/infratrappean dinosaurs. Such age control is important for ascertaining whether dinosaurs in India persisted up to the K-T boundary or whether they died prior to the K-T boundary. For this, however, the lava flows bounding the dinosaur-yielding interrappean levels, as well as those capping the infratrappean Lametas, need to be studied for magneto- and chemostratigraphic controls, and the data integrated with the biostratigraphic (including palynological) age constraints from the intertrappeans. Such an integrated approach, involving bio-, magneto- and chemostratigraphy, has already been attempted successfully in the Rajahmundry area (Keller *et al.* 2008a), but is of special interest in the context of the Chhindwara outcrops because this area has known dinosaur fossils remains and offers a chance to age date these within the context of the K-T mass extinction.

8. Discussion

The critical link between Deccan volcanism and the KT mass extinction has now been established in intertrappean sediments in Rajahmundry quarries of southeastern India and subsequently confirmed in intertrappean sediments at Jhilmili in central India (Keller *et al.* 2008a, 2009c, d). Palaeontologic, palaeomagnetic, radiometric and geochemical studies have linked the KT mass extinction to the longest lava flows on Earth, spanning over 1000 km across India (e.g. Knight *et al.* 2003, 2005; Chenet *et al.* 2007, 2008; Jay and Widdowson 2008; Keller *et al.* 2008a; Self *et al.* 2008a, b). The main phase of Deccan volcanism, which encompasses 80% of the Deccan lava pile, can now be positively linked to the KT mass extinction. In the Rajahmundry area at least four closely spaced lava flows reached across India and out to the Gulf of Bengal.

Environmental consequences of these massive eruptions were likely devastating not just because of the dust cloud obscuring sunlight and causing short-term global cooling, but because of gas emission, particularly SO_2 and CO_2. Sulfur dioxide gas released by volcanism and injected into the stratosphere forms sulfate aerosol particulates, which act to reflect incoming solar radiation and causes global cooling. Since sulfate aerosol has a short lifespan in the atmosphere, the cooling would be short-term (years to decades), unless repeated injections from volcanic eruptions replenish atmospheric sulfate aerosols and lead to a run-away effect.

Based on rare gas bubbles preserved in Deccan volcanic rocks, Self *et al.* (2008a) estimate annual gas rates released by Deccan lavas at many times anthropomorphic emissions of SO_2 and more than an order of magnitude grater than the current global background volcanic emission rate. Chenet *et al.* (2007, 2008) estimate gas emissions based on volume of Deccan lavas. Concentrating on the largest 30 eruption pulses, they estimated that each pulse injected up to 150 GT of SO_2 gas, the equivalent of the Chicxulub impact (e.g. 50-500 GT), over a very short time (decades). By this estimate the total Deccan eruptions injected 30 to 100 times the amount of SO_2 released by the Chicxulub impact. It is not just the sheer volume of SO_2 injection, but also the rapid succession of volcanic eruptions with repeated SO_2 injections that would have compounded the adverse effects of SO_2 leading to severe environmental consequences (e.g., cooling, acid rain, extinctions), preventing recovery and likely causing a run-away effect.

In contrast to SO_2, it is believed that CO_2 emissions (greenhouse gases) would have been small compared with the mass already in the atmosphere during the Cretaceous, and therefore would have had more limited effects. This view is countered by global oxygen isotope evidence of rapid short warming of 3–4ºC in ocean temperatures in zone

CF1 of C29r (e.g. Li and Keller 1998b; Wilf *et al.* 2003; MacLeod *et al.* 2005) that appears to be related to enhanced CO_2 emissions from Deccan volcanism at that time. A rapid shift in $^{187}Os/^{188}Os$ ratios coincides with this warming and is interpreted to mark the onset of the main Deccan pulse in C29r (Robinson *et al.* 2009). Given current data it appears that both SO_2 and CO_2 emissions from Deccan volcanism may have had detrimental environmental effects.

How Deccan volcanism affected the environment and how it may have led to the mass extinction of dinosaurs and other organisms in India and globally is still speculative. Documentation of the biotic and environmental effects of Deccan volcanism is still in the early stages. Age correlation between terrestrial sequences with dinosaur fossils and the KTB remains problematic without marine microfossils, but may now be possible as outlined in this paper. Age control for the onset of the main phase of Deccan volcanism that ended at the KTB still remains to be determined along with the immediate biotic and environmental effects leading up to the KT mass extinction. Despite the many unanswered questions, Deccan volcanism is closely linked to the KT mass extinction, whereas the Chicxulub impact is not.

9. Conclusions

(1) Evidence from Texas, NE Mexico and the Chicxulub impact crater on Yucatan demonstrates that the Chicxulub impact and KT mass extinction are two separate and unrelated events with the Chicxulub impact predating the KTB (Keller *et al.* 2003, 2004, 2007).

(2) Planktic foraminifera, which suffered the most severe mass extinction at the KT boundary, show that not a single species went extinct as a result of the Chicxulub impact in either Mexico or Texas. The biotic and environmental effects of this large impact have been vastly overestimated (Keller *et al.* 2009a, b).

(3) The cause for the KT mass extinction must lie with the other end-Cretaceous catastrophe – the massive continental flood basalt eruptions of India. Recent studies indicate three main volcanic phases with the main phase encompassing ~80% of the Deccan eruptions and coinciding with the end of the Maastrichtian (Chenet *et al.* 2007; Keller *et al.* 2008, 2009c, d).

(4) All indications thus point to the main pase of Deccan volcanism as the cause for the KT mass extinction. How and why this volcanic phase caused such devastation globally remains to be explored, including the demise of the dinosaurs and its correlation to the KT mass extinction.

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References

Adatte T, Stinnesbeck W and Keller G 1996 Lithostratigraphic and mineralogical correlations of near-K/T boundary clastic sediments in northeastern Mexico: Implications for mega-tsunami or sea level changes; *Geol. Soc. Am. Special Paper* **307** 197–210

Alegret L, Molina E and Thomas E 2001 Benthic foraminifera at the Cretaceous-Tertiary boundary around the Gulf of Mexico; *Geology* **29** 891–894

Arenillas I, Arz J A, Grajales-Nishimura J M, Murillo-Muneton G, Alvarez W, Camargo-Zanguera A, Molina E and Rosales-Dominguez C 2006 Chicxulub impact event is Cretaceous/Paleogene boundary in age: New micropaleontological evidence; *Earth Planet. Sci. Lett.* **249** 241–257

Badve R M and Ghare M A 1977 Palaeoecological aspects of the Bagh Beds, India; *Rec. Res. Geol.* **4** 388–402

Bajpai S and Prasad G V R 2000 Cretaceous age for Ir-rich Deccan intertrappean deposits: palaeontological evidence from Anjar, western India; *J. Geol. Soc. London* **157** 257–260

Bajpai S and Whatley R 2001 Late Cretaceous non-marine ostracods from the Deccan intertappean beds, Kora (western Kachchh, India); *Rev. Esp. Micropaleontol.* **33** 91–111

Bajpai S, Sahni A. and Srinivasan S 1993 Ornithoid egshells from Deccan intertrappean beds near Anjar (Kachchh), western India; *Curr. Sci.* **64** 42–45

Baksi A K, Byerly G R, Chan L H and Farrar E 1994 Intracanyon flows in the Deccan province, India: Case history of the Rajahmundry Traps; *Geology* **22** 605–608

Baksi A K 2001 The Rajahmundry Traps, Andhra Pradesh: evaluation of their petrogenesis relative to the Deccan Traps; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **110** 397–407

Baksi A K 2005 Comment on "$^{40}Ar/^{39}Ar$ dating of the Rajahmundry Traps, eastern India and their relations to the Deccan Traps" by Knight *et al.* [*Earth Planet Sci. Lett.* **208** (2003) 85–99]; *Earth Planet. Sci. Lett.* **239** 368–373

Bande M B, Prakash U and Bonde S D 1981 Occurrence of *Peysonnelia* and *Distichoplax* in the Deccan Intertrappeans with remarks on the age of Chhindwara traps and paleogeography of the region; *Geophytology* **11** 182–188

Banerjee P K, Ghose N C, Ravikumar V and Chacko S 1996 Petrography, geomagnetism, and rare-earth element abundances of the Rajahmundry lavas, eastern India; *J. Southeast Asian Earth Sci.* **13** 139–143

Barrera E and Keller G 1990 Stable isotope evidence for gradual environmental changes and species survivorship across the Cretaceous/Tertiary boundary; *Paleoceanography* **5** 867–890

Berggren W A, Kent D V, Swisher C C and Aubry M P 1995 A revised Cenozoic geochronology and chronostratigraphy; in *Geochronology, time scales and Global stratigraphic correlation* (eds) W A Berggren, D V Kent, M P Aubry and J Hardenbol (Society for Sedimentary Geology, Special Publication) vol. 54, pp 129–212

Berman D S and Jain S L 1982 The braincase of a small sauropod dinosaur (Reptilia: Saurischia) from the Upper Cretaceous Lameta Group, Central India, with review of Lameta Group localities; *Ann. Carnegie Mus.* **51** 405–422

Bhandari N, Shukla P N, Ghevariya Z G and Sundaram S 1996 K/T boundary layer in Deccan intertrappeans at Anjar, Kutch; *Geol. Soc. Am. Special Paper* **307** 417–424

Bhandari A 1995 Ostracodes from the inter-trappean beds near Duddukuru, Andhra Pradesh and a note on their age and paleoecological significance; *Indian J. Petrol. Geol.* **4** 89–107

Bourgeois I, Hansen T A, Wiberg P L and Kauffman E G 1988 A tsunami deposit at the Cretaceous-Tertiary boundary in Texas; *Science* **241** 567–570

Buffetaut E 1987 On the age of the dinosaur fauna from the Lameta Formation (Upper Cretaceous of Central India); *Newlett. Strat.* **18** 1–6

Cande S and Kent D V 1991 Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic; *J. Geophys. Res.* **100** 159–190

Caron M 1985 Cretaceous planktonic foraminifera; in *Plankton stratigraphy* (eds) H M Bolli, J B Saunders and K Perch-Nielsen (Cambridge: Cambridge University Press) pp 17–86

Chatterjee S 1978 *Indosuchus* and *Indosaurus*, Cretaceous carnosaurs from India; *J. Paleontol.* **52** 570–580

Chenet A-L, Quidelleur X, Fluteau F, Courtillot V and Bajpai S 2007 ^{40}K/^{40}Ar dating of the main Deccan Large Igneous Province: Further Evidence of KTB Age and short duration; *Earth Planet. Sci. Lett.* **263** 1–15

Chenet A-L, Fluteau F, Courtillot V, Gerard M and Subbarao K V 2008 Determination of rapid Deccan eruptions across the KTB using paleomagnetic secular variation: (I) Results from 1200 m thick section in the Mahabaleshwar escarpment; *J. Geophys. Res.* **113** B04101

Chiplonkar G W and Badve R M 1968 Age and affinities of the Bagh fauna–A Reassessment; in *Symposium Deccan Trap Country Special Issue, Bulletin* (Indian National Science Academy) vol. 45, pp 19–29

Courtillot V 1999 *Evolutionary catastrophes: The science of mass extinctions* (Cambridge: Cambridge University Press) pp 171

Courtillot V E and Renne P R 2003 On the ages of flood basalt events; *C. R. Geosci.* **335** 113–140

Courtillot V, Besse J, Vandamme D, Montigny R, Jaeger J J and Capetta H 1986 Deccan flood basalts at the Cretaceous/Tertiray boundary; *Earth Planet. Sci. Lett.* **80** 361–374

Courtillot V, Feraud G, Maluski H, Vandamme D, Moreau M G and Besse J 1988 Deccan flood basalts and the Cretaceous/Tertiary boundary; *Nature (London)* **333** 843–846

Courtillot V, Gallet Y, Rocchia R, Féraud G, Robin E, Hofmann C, Bhandari N and Ghevariya Z G 2000 Cosmic markers, ^{40}Ar/^{39}Ar dating and Paleomagnetism of the KT sections in the Anjar area of the Deccan large igneous province; *Earth Planet. Sci. Lett.* **182** 137–156

Cripps J A, Widdowson M, Spicer R A and Jolley D W 2005 Coastal ecosystem response to late stage Deccan Trap volcanism: the post-K-T boundary (Danian) palynofacies of Mumbai (Bombay), west India; *Paleogeogr. Paleoclimatol. Palaeoecol.* **216** 303–332

Dogra N N, Singh R Y and Kulshrestha S K 1994 Pynostratigraphy of infra-trappeanJabalpur and Lameta Formations (Lower and Upper Cretaceous) in Madhya Pradesh, India; *Cret. Res.* **15** 205–215

Duncan R A and Pyle D G 1988 Rapid eruption of the Deccan flood basalt at the Cretaceous/Tertiary boundary; *Nature (London)* **333** 841–8443

Ekdale A A, Stinnesbeck W 1998 Ichnology of Cretaceous-Tertiary (K/T) boundary beds in northeastern Mexico; *Palaios* **13** 593–602

Gale A S 2006 The Cretaceous-Palaeogene boundary on the Brazos River, Falls County, Texas: Is there evidence for impact-induced tsunami sedimentation?; *Proc. Geol. Assoc.* **117** 173–185

Ghevariya Z G 1988 Inter-trappean dinosaurian fossils from Anjar area, Kachchh District, Gujarat; *Curr. Sci.* **57** 248–251

Govindan A 1981 Foraminifera from the infra- and intertrappean subsurface sediments of Narsapur Well-1 and age of the Deccan Trap flows; in *Proceedings of IXthe Indian Colloquium on Micropaleontology and Stratigraphy* (eds) S C Khosla and R P Kachhara (Udaipur) pp 81–93

Grachev A F, Korchagin O A, Kollmann H A, Pechersky D M and Tsel'movich V A 2005 A new look at the nature of the transitional layer at the K/T boundary near Gams, Eastern Alps, Austria, and the problem of the mass extinction of the biota; *Russ. J. Earth Sci.* **7** ES600 1–45

Gradstein F M and Ogg J G 2004 Geologic time scale 2004 – why, how, and where next; *Lethaia* **37** 175–181

Graup G and Spettel B 1989 Mineralogy and phase-chemistry of an ir-enriched pre-K/T layer from the Lattengebirge, Bavarian Alps, and significance for the KTB problem; *Earth Planet. Sci. Lett.* **95** 271–290

Hofmann C, Féraud G and Courtillot V 2000 ^{40}Ar/^{39}Ar dating of mineral separates and whole rocks from the Western Ghats lava pile: further constraints on duration and age of the Deccan traps; *Earth Planet. Sci. Lett.* **180** 13–27

Huene F V and Matley C A 1933 Cretaceous Saurischia and Ornithischia of the central provinces of India; *Palaeontol. Indica* **21** 1–74

Izett G, Dalrymple G B and Snee L W 1991 40Ar/39Ar age of K-T boundary tektites from Haiti; *Science* **252** l59–1543

Jaiprakash B C, Singh J and Raju D S N 1993 Foraminiferal events across the K/T boundary and age of Deccan volcanism in Palakollu area, Krishna-Godavari Basin, India; *J. Geol. Soc. India* **41** 105–117

Jay A E and Widdowson M 2008 Stratigraphy, structure and volcanology of the south-easts Deccan continental flood basalt province: implications for eruptive extent and volumes; *J. Geol. Soc.* **165** 177–188

Jay A E, MacNiocaill C, Widdowson M, Self S and Turner W 2009 New Palaeomagnetic data from the Mahabaleshwar Plateau, Deccan Flood Basalt Province, India: Implications fro the volcanostratigraphic architecture of Continental Flood Basalt Provinces; *J. Geophys. Res.* **166** 1–12, doi: 10.1144/0016-76492007-150

Jerram D A and Widdowson M 2005 The anatomy of Continental Flood Basalt Provinces: geological constraints on the processes and products of flood Volcanism; *Lithos* **79** 385–405

Kauffman E G 1977 Geological and biological overview: western interior Cretaceous basin; *Mountain Geol*. **14** 75–99

Keller G 2005 Impacts, volcanism and mass extinctions: random coincidence or cause and effect?; *Aust. J. Earth Sci.* **52** 725–757

Keller G 2008 Impact Stratigraphy: Old principle, new reality; *Geol. Soc. Am. Special Paper* **437** 147–178

Keller G, Stinnesbeck W and Lopez-Oliva J G 1994 Age, deposition and biotic effects of the Cretaceous/Tertiary boundary event at Mimbral, NE Mexico; *Palaios* **9** 144–157

Keller G, Li L and MacLeod N 1995 The Cretaceous/Tertiary boundary section at El Kef, Tunisia: How catastrophic was the mass extinction?; *Palaeogeogr. Paleoclimatol. Palaeoecol*. **119** 221–254

Keller G, Lopez-Oliva J G, Stinnesbeck W and Adatte T 1997 Age, stratigraphy and deposition of near K/T siliciclastic deposits in Mexico: Relation to bolide impact?; *Geol. Soc. Am. Bull.* **109** 410–428

Keller G, Adatte T, Stinnesbeck W, Affolter M, Schilli L and Lopez-Oliva J G 2002 Multiple spherule layers in the late Maastrichtian of northeastern Mexico; *Geol. Soc. Am. Special Paper* **356** 145–161

Keller G, Stinnesbeck W, Adatte T and Stüben D 2003a Multiple impacts across the Cretaceous-Tertiary boundary; *Earth Sci. Rev*. **62** 327–363

Keller G, Stinnesbeck W, Adatte T, Holland B, Stueben D, Harting M, De Leon C and de la Cruz J 2003b Spherule deposits in Cretaceous-Tertiary boundary sediments in Belize and Guatemala; *J. Geol. Soc. London* **160** 783–795

Keller G, Adatte T, Stinnesbeck W, Rebolledo-Vieyra M, Urrutia Fucugauchi J, Kramar U and Stueben D 2004 Chicxulub crater predates K-T boundary mass extinction; *Proc. Natl. Acad. Sci. USA* **101** 3721–3992

Keller G, Adatte T, Harting M, Berner Z, Baum G, Prauss M, Tantawy A A and Stueben D 2007 Chicxulub impact predates the K-T boundary: new evidence from Texas; *Earth Planet. Sci. Lett*. **255** 339–356

Keller G, Adatte T, Gardin S, Bartolini A and Bajpai S 2008a Main Deccan volcanism phase ends near the K-T boundary: Evidence from the Krishna-Godavari Basin, SE India; *Earth Planet. Sci. Lett*. **268** 293-311, doi: 101016/j.epsl.2008.01.015.

Keller G, Adatte T, Baum G and Berner Z 2008b Reply to 'Chicxulub impact predates K-T boundary: New evidence from Brazos, Texas' Comment by Schulte *et al.*; *Earth Planet. Sci. Lett*. **269** 620–628, doi:10.1016/j.epsl.2007.12.025

Keller G, Abramovich S, Berner Z and Adatte T 2009a Biotic effects of the Chicxulub impact, K-T catastrophe and sea-level change in Texas; *Palaeogeogr. Palaeoclimatol. Palaeoecol*. **271** 52–68, doi:10.1016/j.palaeo.2008.09.007

Keller G, Adatte, T, Pardo Juez A and Lopez-Oliva J G 2009b New Evidence concerning the Age and biotic effects of the Chicxulub impact in NE Mexico; *J. Geol. Soc. London* **166** 393–411 doi: 10.1144/0016-76492008-116

Keller G, Khosla S C, Sharma R, Khosla A, Bajpai S and Adatte T 2009c Early Danian Planktic foraminifera from Intertrappean beds at Jhilmili, Chhindwara District, Madhya Pradesh, India; *J. Foram. Res*. **39** 40–55

Keller G, Adatte T, Bajpai S, Mohabey D M, Widdowson M, Khosla A, Sharma R, Khosla S C, Gertsch B, Fleitman D and Sahni A 2009d K-T transition in Deccan Traps of Central India marks major marine seaway acroos India; *Earth Planet. Sci. Lett*. **282** 10–23

Khosla S C and Nagori M L 2002 Ostracodes from the intertrappean beds (Early Paleocene) of the east coast India; *Paleontol. Res. (Jpn.)* **6** 191–210

Khosla S C and Nagori M L 2007 Ostracoda from the Inter-Trappean Beds of Mohgaon-Haveli, Chhindwara District, Madhya Pradesh; *J. Geol. Soc. India* **69** 209–221

Khosla A and Sahni A 2003 Biodiversity during the Deccan volcanic eruptive Episode; *J. Asian Earth Sci.* **21** 895–908

Knight K B, Renne P R, Halkett A and White N 2003 $^{40}Ar/^{39}Ar$ dating of the Rajahmundry traps, Eastern India and their relationship to the Deccan Traps; *Earth Planet. Sci. Lett*. **208** 85–99

Knight K B, Renne P R, Baker J, Waight T and White N 2005 Reply to $^{40}Ar/^{39}Ar$ dating of the Rajahmundry Traps, Eastern India and their relationship to the Deccan Traps: Discussion by A.K. Baksi; *Earth Planet. Sci. Lett*. **239** 374–382

Kring D A 2007 The Chicxulub impact event and its environmental consequences at the Cretaceous-Tertiary boundary; *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **255** 4–21

Kumaran K P N, Bonde S D and Kanitkar M D 1997 An Aquilapollenites associated palynoflora from Mohgaon Kalan and its stratigraphic implications for age and stratigraphic correlation of Deccan intertrappean beds; *Curr. Sci*. **72** 590–592

Lehman T M 1987 Late Maastrichtian paleoenvironments and dinosaur biogeography in the western interior of North America; *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **60** 189–217

Li L and Keller G 1998a Maastrichtian climate, productivity and faunal turnovers in planktic foraminifera in South Atlantic DSDP Sites 525A and 21; *Marine Micropaleontol*. **33** 55–86

Li L and Keller G 1998b Abrupt deep-sea warming at the end of the Cretaceous; *Geology* **26** 995–998

Lightfoot P C, Hawkesworth C J, Devey C W, Rogers N W and van Calsteren PWC 1990 Source and differentiation of Deccan Trap lavas: implications of geochemical and mineral chemical variations; *J. Petrol*. **31** 1165–1200

MacLeod N and Keller G 1994 Comparative biogeographic analysis of planktic foraminiferal survivorship across the Cretaceous/Tertiary (K/T) boundary; *Paleobiology* **20** 143–177

MacLeod K G Huber B T Isaza-Londono C 2005 North Atlantic warming during global cooling at the end of the Cretaceous. *Geology* **33** 437–440

MacLeod K G, Whitney D L, Huber B T and Koeberl C 2006 Impact and extinction in remarkably complete Cretaceous-Tertiary boundary sections from Demerara Rise, tropical western North Atlantic; *Geol. Soc. Am. Bull.* Nov. 28 doi: 10.1130/B25955.1

Matley C A 1939 The coprolites of Pijdura, Central Province; *Rec. Geol. Surv. India* **74** 535–547

Mathur U B and Srivastava S 1987 Dinosaur teeth from Lameta Group (Upper Cretaceous) of Kheda district, Gujarat; *J. Geol. Soc. India* **29** 554–566

McLean D M 1978 A terminal Mesozoic "Greenhouse": lessons from the past; *Science* **201** 401–406

McLean D M 1985 Deccan Traps mantle degassing in the terminal Cretaceous marine Extinctions; *Cret. Res.* **6** 235–259

Mohabey D M 1987 Juvenile sauropod dinosaurs from Upper Cretaceous Lameta Formation of Panchmahals District, Gujarat, India; *J. Geol. Soc. India* **30** 210–216

Mohabey D M 2001 Indian dinosaur eggs; A review; *J. Geol. Soc. India* **58** 479–508

Mehrotra N C and Sargeant W A S 1987 Late Cretaceous to Early Tertiary dinoflagellate cysts from Narsapur Well-1, Godavari–Krishna Basin, south-India; *Geobios* **20** 149–191

Molina E, Alegret L, Arenillas I, Arz J A, Gallala N, Hardenbol J, von Salis K, Steurbraut E, Vandenberghe N and Zaghbib-Turki D 2006 The global stratotype boundary section and point for the base of the Danian Stage (Paleocene, Paleogene "Tertiary", Cenozoic) at El Kef, Tunisia – Original definition and revision; *Episodes* **29** 263–273

Montanari A and Koeberl C 2000 Impact stratigraphy; in *Lecture Notes in Earth Sciences* (Springer and Heidelberg, Germany) vol. 93, pp 364

Norris R D, Huber B T and Self-Trail J 1999 Synchroneity of the K-T oceanic mass extinction and meteorite impact: Blake Nose, western North Atlantic; *Geology* **27** 419–422

Olsson R K, Miller K G, Browning J V, Habib D and Sugarmann P J 1997 Ejecta layer at the Cretaceous-Tertiary boundary, Bass River, New Jersey (Ocean Drilling Program Leg 174AX); *Geology* **25** 759–762

Pande K, Pattanayak S K, Subbarao K V, Navaneethakrishna P and Venkatesan T R 2004 40Ar/39Ar age of a lava flow from the Bhimashankar Formation, Giravali Ghat, Deccan Traps; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **113** 755–758

Pardo A, Ortiz N and Keller G 1996 Latest Maastrichtian and K/T boundary foraminiferal turnover and environmental changes at Agost, Spain; in *The Cretaceous-Tertiary mass extinction: Biotic and environmental effects* (eds) N MacLeod and G Keller (New York: Norton Press) pp 157–191

Prasad B and Pundeer B S 2002 Palynological events and zones in Cretaceous-Tertiary Boundary sediments of Krishna-Godavari and Cauvery basins, India; *Palaeontogr. Abt. B* **262** 39–70

Prasad G V R and Cappetta H 1993 Late Creraceous Selachians from India and the age of the Deccan Traps; *Palaeontology* **36** 231–248

Prasad G V R, Verma O, Sahni A, Parmar V and Khosla A 2007 A Cretaceous Hoofed Mammal from India; *Science* **318** 937

Rajshekhar C 1996 Micropaleontology of the Bagh Group, Narmada Basin, India; *Proc. XV Indian Colloquium on Micropalaeontology and Stratigraphy, Dehra Dun* pp 1–6

Raju D S N 2008 Stratigraphy of India; *ONGC Bull*. (*Special Issue*) **43** 44

Raju D S N, Jaiprakash B C, Kumar A, Saxena R K, Dave A, Chatterjee T K and Mishra C M 1994 The magnitude of hiatus and sea-level changes across K/T boundary in Cauvery and Krishna-Godavari basins; *J. Geol. Soc. India* **44** 301–315

Raju D S N, Jaiprakash B C, Kumar A, Saxena R K, Dave A, Chatterjee T K and Mishra C M 1995 Age of Deccan volcanism across KTB in Krishna-Godavari Basin: new evidences; *J. Geol. Soc. India* **45** 229–233

Rao B R and Yadagiri P 1981 Cretaceous intertrappean beds from Andhra Pradesh and their stratigraphic significance; *Mem. Geol. Soc. India* **3** 287–291

Robinson N, Ravizza G, Coccioni R, Peucker-Ehrenbrink B and Norris R 2009 A high-resolution marine 187Os/188Os record for the late Maasrichtian: Distinguising the chemical fingerprints of Deccan volcanism and the KP impact event; *Earth Planet. Sci. Lett*. **281** 159–168, doi:10.1016/j.epsl.2009.02.019

Sahni A 1983 Upper Cretaceous Palaeobiogeography of Peninsular India and the Cretaceous-Paleocene transition: the vertebrate evidence; in *Cretaceous of India. Indian Assoc. Palynostratigraphers* (ed.) H K Maheshwari (Lucknow) pp 128–140

Sahni A and Bajpai S 1988 Cretaceous-Tertiary boundary events: the fossil vertebrate, paleomagnetic and radiometric evidence from peninsular India; *J. Geol. Soc. India* **32** 382–396

Samant B and Mohabey D M 2005 Response of flora to Deccan volcanism: A case study from Nand-Dongargaon basin of Maharashtra, implications to environment and climate; *Gondwana Geol. Mag.* **8** 151–164

Samant B, Mohabey D M and Kapgate D K 2008 Palyno-floral record from Singpur Intertrappean, Chhindwara district, Madhya Pradesh: Implication for Late Cretaceous stratigraphic correlation and resolution; *J. Geol. Soc. India* **71** 851–858

Saxena R K and Misra C N 1994 Time and duration of Deccan volcanism in the Rezole area, Krishna-Godavari Basin, India; *Curr. Sci.* **66** 74–76

Sawlowicz Z 1993 Iridium and other platinum-group elements as geochemical markers in sedimentary environments; *Paleogeogr. Paleoclimatol. Paleoecol*. **104** 253–270

Schulte P, Speijer R P, Mai H and Kontny A 2006 The Cretaceous-Paleogene (K-P) boundary at Brazos, Texas: Sequence stratigraphy, depositional events and the Chicxulub impact; *Sediment. Geol.* **184** 77–109

Schulte P, Speijer R P, Brinkhuis H, Kontny A, Caleys P, Galeotti S and Smit J 2008 Comment on the paper; 'Chicxulub impact predates K-T boundary: New evidence from Brazos, Texas' by Keller et al. (2007); *Earth Planet. Sci. Lett*. **269** 613–619 doi: 10.1016/j.epsl.2007.11.066

Self S, Jay A E, Widdowson M and Keszthelyi L P 2008a Correlation of the Deccan and Rajahmundry Trap lavas: Are these the longest and largest lava flows on Earth?; *J. Volcanol. Geother. Res*. **172** 3–19

Self S, Blake S, Sharma K, Widdowson M and Sephton S 2008b Sulfur and Chlorine in Late Cretaceous Deccan Magmas and Eruptive gas release; *Science* **319** 1654–1657

Sharma V 1976 Planktonic Foraminifera from the Begh Beds, Madhya Pradesh; *Proc. VI Indian Colloquium on Micropalaeontology and Stratigraphy* (Varanasi) pp 235–244

Sheth H C, Pande K and Bhutani R 2001 ^{40}Ar/^{39}Ar age of a national geological monument: The gilbert Hill basalt, Deccan Traps, Bombay; *Curr. Sci*. **80** 1437–1440

Shukla U K and Srivastava R 2008 Lizard eggs from Upper Cretaceous Lameta Formation of Jabalpur, central India, with interpretation of depositional environments of the nest-bearing horizon; *Cret*. *Res*. **29** 674–686

Singh I B 1981 Palaeoenvironment and palaeogeography of Lameta Group sediments (Late Cretaceous) in Jabalpur area, India; *J*. *Paleontol*. *Soc*. *India* **26** 38–53

Smit J 1999 The global stratigraphy of the Cretaceous-Tertiary boundary impact ejecta; *Annu. Rev. Earth Planet*. *Sci*. **27** 75–113

Smit J, Montanari A, Swinburne N H M, Alvarez W, Hildebrand A, Margolis S V, Claeys P, Lowerie W and Asaro F 1992 Tektite-bearing deep-water clastic unit at the Cretaceous-Tertiary boundary in northeastern Mexico; *Geology* **20** 99–104

Smit J, Roep T B, Alvarez W, Montanari A, Claeys P, Grajales-Nishimura J M and Bermudez J 1996 Coarse-grained clastic sandstone complex at the K/T boundary around the Gulf of Mexico: Deposition by tsunami waves induced by the Chicxulub impact; *Geol*. *Soc*. *Am. Special Paper* **307** 151–182

Srinivasan S 1996 Late Cretaceous egg shells from the Deccan volcano-sedimentary sequence of Central India; in *Cretaceous stratigraphy and Environment* (ed.) A Sahni (Rama Rao Volume, *Mem. Geol. Soc. of India)* vol.37, pp 321–336

Srivastava S, Mohabey D M, Sahni A and Pant S C 1986 Upper Cretaceous dinosaur egg clutches from Kheda district (Gujarat, India); *Palaeontogr. Abt. A* **193** 219–233

Stüben D, Kramar U, Harting M, Stinnesbeck W and Keller G 2005 High-resolution geochemical record of Cretaceous-Tertiary boundary sections in Mexico: New constraints on the K/T and Chicxulub events; *Geochem*. *Cosmochim. Acta* **69** 2559–2579

Subbarao K V and Pathak S 1993 Reversely magnetized flows, Rajahmundry, Andhra Pradesh; *J. Geol*. *Soc*. *India* **41** 71–72

Tandon S K, Sood A, Andrews JE and Dennis P F 1995 Palaeoenvironment of Dinosaur-bearing Lameta Beds (Maastrichtian), Narmada valley, Central India; *Palaogeogr*. *Palaeoclimatol*. *Palaeoecol*. **117** 153–184

Tantawy A A A 2003 Calcareous nannofossil biostratigraphy and Paleoecology of the Cretaceous-Paleogene transition in the central eastern Desert of Egypt; *Marine Micropaleontol*. **47** 323–356

Tredoux M, de Wit M J, Hart R J, Linsay N M, Verhagen B and Sellschop J P F 1988 Chemostratigraphy across the Cretaceous-Teriary boundary and a critical assessment of the iridium anomaly; *J*. *Geol*. **97** 585–605

Vandamme D and Courtillot V 1992 Paleomagnetic constraints on the structure of the Deccan Traps; *Phys*. *Earth Planet*. *Int*. **74** 241–261

Vandamme D, Courtillot V, Besse J and Montigny R 1991 Paleomagnetism and age determinations of the Deccan traps (India): results of a Nagpur–Bombay traverse and review of earlier work; *Rev. Geophys. Space Phys*. **29** 159–190

Venkatesan T R, Pande K and Ghevariya Z G 1996 ^{40}Ar-^{39}Ar ages of lava flows from Anjar, western Deccan Province, India and its relation to the Cretaceous-Tertiary Boundary events; *Curr. Sci.* **70** 990–996

Venkatesan T R, Pande K and Gopalan K 1993 Did Deccan volcanism pre-date the Cretaceous/Tertiary transition?; *Earth Planet*. *Sci*. *Lett*. **119** 181–189

Venkaya E 1949 Deccan Trap outliers of the Godavari districts; *Proc. Indian Acad*. *Sci*. **A29** 431–441

Wang K, Attrep M Jr and Orth C J 1993 Global iridium anomaly, mass extinction and redox change at the Devonian-Carboniferous boundary; *Geology* **21** 1071–1074

Whatley R C and Bajpai S 2005 Some aspects of the paleo-ecology and distribution on non-marine ostracoda from Upper Cretaceous Intertrappean deposits and the Lameta Formation of Peninsular India; *J*. *Palaeontol*. *Soc*. *India, Golden Jubilee* **50** 61–76

Whatley R and Bajpai S 2006 Extensive endemism among the Maastrichtian non-marine Ostracoda of India with implications for palaeobiogeography and "Out of India" dispersal; *Rev*. *Esp. Micropaleontol.* **38** 229–244

Whatley R C, Bajpai S and Srinivasan S 2002 Upper Cretaceous intertrappean non-marine Ostracoda from Mohagaonkala (Mohgaon-Kalan), Chhindwara District, Madhya Pradesh State, Central India; *J*. *Micropaleontol*. **21** 105–114

White R V and Sauders A D 2005 Volcanism, impact and mass extinctions: incredible or credible coincidences?; *Lithos* **79** 299–316

Widdowson M, Pringle M S and Fernandez O A 2000 A post K-T boundary (Early Paleocene) age for Deccan-type feeder dykes, Goa, India; *J*. *Petrol*. **41** 1177–1194

Wignall P B 2001 Large igneous provinces and mass extinctions; *Earth Sci*. *Rev*. **53** 1–33

Wilf P, Johnson K R and Huber B T 2003 Correlated terrestrial and marine evidence for global climate changes before mass extinction at the Cretaceous-Paleogene boundary. *Proc*. *Natl*. *Acad. Sci*. *USA* **100** 599–604

Wilson J A and Mohabey D M 2006 A titanosauriform (Dinosauria: Sauropoda) axis from the Lameta Formation (Upper Cretaceous: Maastrichtian) of Nand, central India; *J*. *Vertebr*. *Paleontol*. **26** 471–479

Wilson J A, Sereno P C, Srivastava S, Bhatt D K, Khosla A and Sahni A 2003 *A new Abelisaurid (Dinosauria, Theropoda) from the Lameta Formation (Cretaceous, Maastrichtian) of India* (Museum of Paleontology, University of Michigan, USA) vol. 31, pp 1–42

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