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Shiva impact event and its implications for Deccan Volcanism and Dinosaur Extinction

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ABSTRACT

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We have identified a buried 500 km diameter Shiva structure on the western shelf of India as a possible impact crater that formed at the Cretaceous-Tertiary (KT) boundary time. The location of the Shiva crater was initially suggested between India-Seychelles block, when Seychelles was part of the Indian Plate at its western margin around 65 Ma. This work refines previous interpretations of the structure, morphology and the extent of the Shiva crater, which now appears to be located entirely on the Mumbai Offshore Basin encircling the Bombay High area. The Shiva crater is largely submerged on the passive western continental shelf and is buried by 7 km thick strata of post-impact Cenozoic sediments. It is the largest impact crater known on Earth, about 500 km diameter and is a rich source of oil and gas. It has the morphology of a complex peak ring structure with a multiring basin configuration, thus providing an ideal structural trap for petroleum entrapment. Four different ring structures have been identified, where the inner peak ring represents the central uplift of the Bombay High area with a core of Neoproterozoic granite basement. Inside the peak ring, a series of rugged mountainous peaks tower more than 7 km above the basin floor. We speculate that the Shiva bolide (~40 km diameter) crashed obliquely on the western continental shelf of India around 65 Ma, excavating the crater, shattering the lithosphere, initiated the rifting between India and the Seychelles and triggered the acceleration of the Indian Plate northward. The Cretaceous-Tertiary boundary sections of India have yielded several proximal ejecta components linked to the Shiva event such as shocked quartz, spherules and glass shards and iridium-rich alkaline melt rocks. Other cosmic signatures at the KT boundary of India from the vapourized meteorite include iridium anomaly, natural fullerenes, nickel-rich spinels and magnetic nanoparticles. Although the Reunion hotspot responsible for Deccan eruption was close to the Shiva crater in time and space, impact did not trigger the hotspot because the first phase of the Deccan volcanism preceded the Shiva impact by 400,000 years or more. Two large impacts such as Shiva and Chicxulub in quick succession on the antipodal position, in concert with Deccan eruption, would have devastating effects globally leading to climatic and environmental calamity that wiped out the dinosaurs and many other organisms at the KT boundary.

Key-words—Cretaceous-Tertiary (KT) boundary, Shiva crater, Impact cratering process, Bombay High, Deccan volcanism, Dinosaur extinction.

शिव संघट्ट घटना एवं दक्कन ज्वालामुखी व डायनोसॉर विलोपन हेतु इसकी युगपत अंतर्वृद्धि

शंकर चटर्जी तथा धीरज कुमार रुद्र

सारांश

हमने भारत के पश्चिमी उपतट पर एक 500 किमी अंतर्हित शिव संरचना की संभावित संघट्ट विवर के रूप में पहचान की है जो क्रिटेशस-टर्शियरी (के-टी) सीमा काल में बनी। शिव विवर का स्थान प्रारंभिक रुप से भारत-सेशेल्स खंड के मध्य प्रस्तावित किया गया था, जब सेशेल्स इसके पश्चिमी उपांत में 650 लाख वर्ष के लगभग भारतीय आधार पट्टिका का भाग था। वर्तमान शोध, शिव विवर, जोकि वर्तमान में मुंबई अप तट द्रोणी में बंबई हाई क्षेत्र को घेरे हुए हैं की संरचना, फैलाव के संबंध में पूर्व व्याख्याओं को परिष्कृत करता है। शिव विवर निष्क्रिय पश्चिमी समुद्री उपतट पर बृहत् रुप से निमग्न हो गया है तथा

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पश्च-संघट्ट आदिनूतन अवसादों के 7 किमी मोटी पट्टीदार से अंतर्हित है। यह लगभग 500 किमी व्यास का पृथ्वी पर पाए जाने वाला विशालतम संघट्ट विवर है तथा तेल एवं गैस का प्रचुर स्रोत है। यह बहुवलय द्रोणी विन्यास सहित एक जटिल शिखर वलय संरचना है, इस तरह पेट्रोलियम पाशबद्धता हेतु एक आदर्श संरचनात्मक ट्रैप प्रदान कर रहा है। चार विविध वलय संरचनाएं पहचानी गई हैं जहाँ अंतः शिखर वलय बंबई उच्च क्षेत्र का मध्य उत्थान नियोप्रोटेरोज़ोइक ग्रेनाइट आधार निरूपित करती है। शिखर वलय के अन्दर द्रोणी तल से सात किलोमीटर उपर एक अ-सम पर्वतीय शिखरों की श्रेणी है। हम परिकल्पना करते हैं कि 650 लाख वर्ष के लगभग भारत के पश्चिमी महाद्वीपीय उपतट पर शिव बोलाइड (40 किमी व्यास) तिरछे रूप से टकराया, जिसने विवर को उत्खनित, स्थल मंडल विशरण, भारत एवं सेशेल्स के मध्य अनुपाट की पहल की तथा भारतीय प्लेट के त्वरण को उत्तर की ओर विमोचित किया। भारत के क्रिटेशस-टर्शियरी सीमा खंडों से शिव घटना से संबद्ध विविध समीपस्थ निष्कासित पदार्थ घटक प्राप्त हुए हैं। जैसे प्रघाती क्वार्ट्ज़, निगोलक तथा काँच लावा, और इरीडियम प्रचुर क्षारीय पिघली चट्टाने। भारत के के-टी सीमा काल की चट्टानों में वाष्पित उल्कापिंड के अन्य अंतरिक्ष चिह्नकों में इरीडियम असंगति, प्राकृतिक फुलरेंस, निकिल प्रचुर स्पीनेल तथा चुंबकीय नेनौपार्टिकल्स सम्मिलित हैं। यद्यपि दक्कन विस्फोट हेतु उत्तरदायी रियुनियन हॉटस्पाट समय एवं स्थान में शिव ज्वालामुखी-विवर के समीप था, संघट्ट ने रियुनियन हॉटस्पाट विमोचित नहीं किया क्यों कि दक्कन ज्वालामुखी की प्रथम प्रावस्था शिव संघट्ट के 400,000 वर्ष पूर्व घटित हो गई थी। दो विशाल संघट्टों जैसे शिव एवं चिक्सलब ने प्रतिव्यासांत स्थिति में त्वरित अनुक्रम में दक्कन विस्फोटन के सामंजस्य से, जलवायवी एवं पर्यावरणीय आपदा के लिए विश्वव्यापी रुप से विनाशक प्रभाव के रहे होंगे जिससे के-टी सीमा-पट्टी पर डायनोसॉर एवं अन्य जीवों का अस्तित्व मिट गया।

संकेत-शब्द—क्रिटेशस-टर्शियरी सीमा-पट्टी, शिव विवर, संघट्ट विवर प्रक्रम, बंबई उच्च, दक्कन ज्वालामुखी, डायनोसॉर विलोपन।

INTRODUCTION

LARGE bolide impacts are catastrophic geologic events, especially because they exert stupendous energy bursts in extremely short time periods—virtually a geological blink of an eye. Massive impact cratering is a dominant destructive and constructive process on the Earth like cosmic dance of the Shiva that has affected both the geologic and biologic evolution of the Earth. For example, impacts have created enormous scars on the surface of nearly all solar system bodies and large-scale impact events may have been responsible for such phenomena as the formation of the Earth's moon and certain mass extinctions in the biologic record. The role of impact in Earth evolution is beginning to emerge in recent study.

To date, about 150 impact craters have been identified on the Earth; most of them are highly eroded, poorly preserved and only exposed on land (Grieve, 1998) and their global effects are poorly known. Only two larger submerged craters at the Cretaceous-Tertiary (KT) boundary event, the Chicxulub crater at the Yucatan peninsula of Mexico and the Shiva crater on the western shelf of India have had enough evidence to suggest a cause-and-effect relation between impact and mass extinction. Alvarez *et al.* (1980) first linked the KT extinction that brought the age of dinosaurs with a large asteroid impact 65 Ma. Numerous field studies have traced the KT impact site to the Chicxulub structure, the 'crater of doom' for the biotic crisis (Hilderbrand *et al.*, 1991, 1995; Sharpton *et al.*, 1993; Swisher *et al.*, 1992). Impact ejecta layers have been now widely recognized in numerous localities around the Gulf of Mexico and linked to the Chicxulub impact based on their geographic distribution (Smit, 1999).

We have assembled a suite of geophysical and stratigraphic evidence implying another impact event on the passive western shelf India that created the Shiva crater almost synchronously with the Chicxulub crater on the antipodal position at the KT boundary (Chatterjee & Rudra, 1996). Like the Chicxulub, the Shiva crater is largely submerged and is buried by 7-km thick strata of post-impact Cenozoic sediments and its presence is inferred from geophysical evidence, deep drill core data and emplaced ejecta components that have uncovered the principal structural and stratigraphic features of the impact crater. We initially suggested the location of the Shiva crater between India-Seychelles block at the KT boundary time, when the Seychelles was part of the Indian Plate at its western margin (Alt *et al.*, 1988; Hartnady, 1986; Chatterjee & Scotese, 1999). We hypothesized that with the spreading of the Carlsberg Ridge, the Shiva crater split into two halves when the Seychelles rifted and drifted away from the India. In this model, one part of the crater marked by the Amirante Basin is believed to be attached today to the Seychelles Plate and the other part to the western shelf of India.

Subsequent study by Chatterjee *et al.* (2006) has refined the location and structure of the Shiva crater on the basis of additional geophysical and mineralogical evidence and concluded that the Shiva crater is preserved entirely within the Mumbai Offshore Basin. These authors argued that if the Amirante Basin was indeed the western rim of the Shiva crater, the Mahe Granite on the Seychelles should bear some sign of an impact such as shock metamorphism. Detailed mineralogical study of the Mahe Granite fails to detect any evidence of shock metamorphism (A. Glikson, pers. comm.). Moreover, both palaeontologic (Johnson *et al.*, 1982) and radiometric (Fisher *et al.*, 1968) ages from the drill core samples of the Amirante Basin provided an Upper Cretaceous age (~80 Ma) that predates the KT boundary event. Thus the Amirante Basin can no longer be considered as the southern half of the Shiva crater as proposed earlier (Chatterjee & Rudra, 1996). On the other hand, the drill core sample of Neoproterozoic granite from the Bombay High, the central peak of the Shiva crater, shows evidence of impact-induced melt rocks in the form of pseudotachylite vein (Chatterjee *et al.*, 2006). In this paper we discuss the morphology of the Shiva crater, the trajectory of the bolide, the amount of energy released from the impact and the distribution of ejecta material at the KT

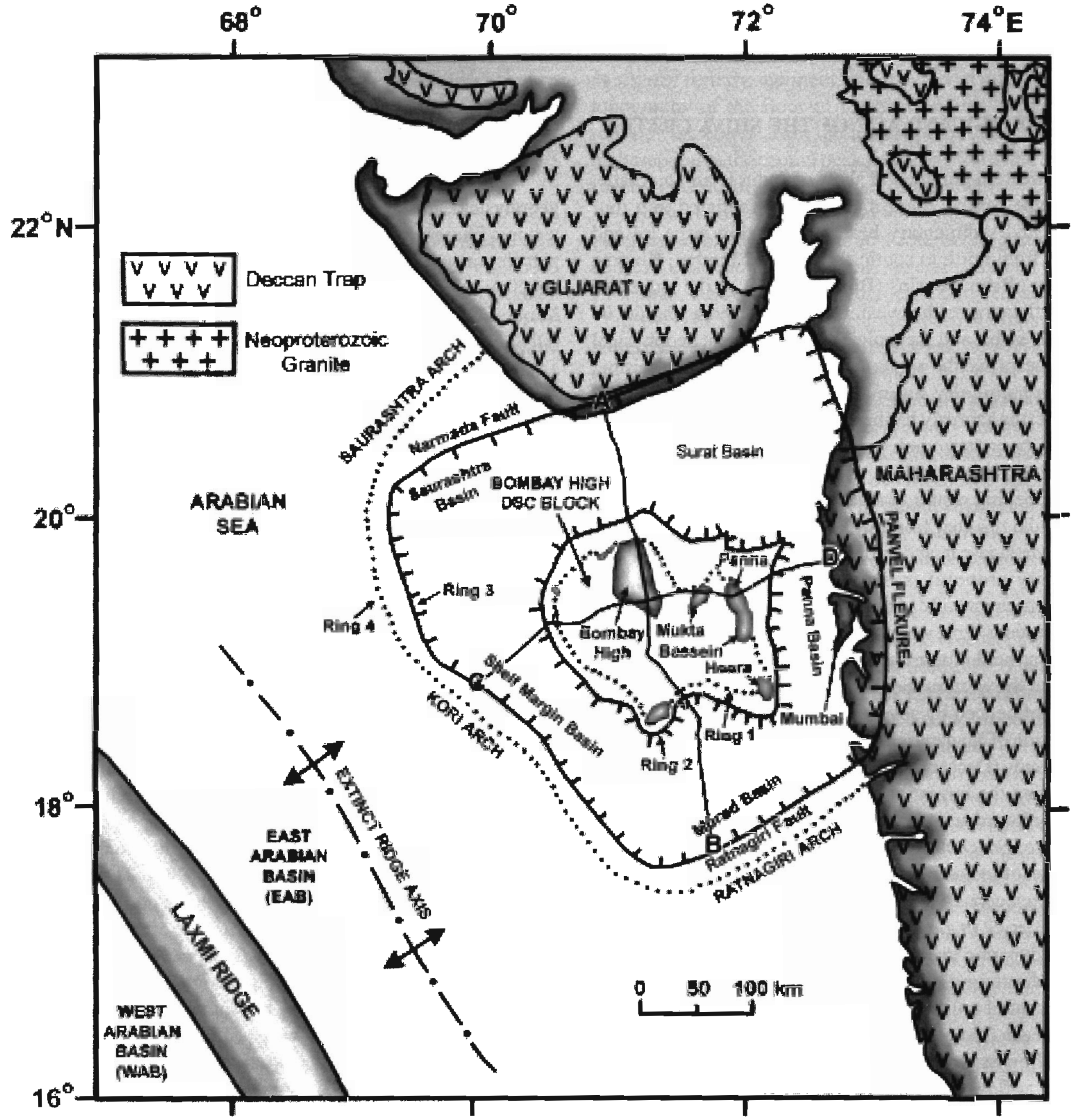

Fig. 1—Present day location of the Shiva crater at the Mumbai Offshore Basin, western shelf of India. The Shiva structure is a complex peak ring crater and a multiring basin, about 500 km across, which is buried by 7 km thick Cenozoic sediments. The crater is defined by a peak ring, annular trough and the faulted outer rim. A small segment of the eastern part of the crater lies near the Mumbai Coast, which is bordered by the Panvel Flexure; here the crater floor is overlain by 2 km thick Deccan lava pile. Four different ring structures have been identified. The inner peak ring (Ring 1) is about 200 km diameter and consists of several structural highs including the Bombay High, Mukta High, Panna-Bassein High, Heera High and several unnamed peaks. The peak ring is the structural trap for oil and gas. The peak ring is followed by a circular faulted rim (Ring 2), with a diameter of 250 km and is bordered by the annual depression consisting of several basins such as the Panna Basin, Surat Basin, Saurashtra Basin, Shelf Margin Basin and Murad Basin, where the crater fill Cenozoic sediments exceed 7 km in thickness. The annular basin is bordered by the faulted crater rim (Ring 3), about 500 km, consisting of the Panvel Flexure, Narmada Fault, Shelf Margin Fault and Ratnagiri Fault. Finally, the faulted rim is probably bordered by the raised rim of the crater (Ring 4), about 550 km in diameter, represented by the Saurashtra Arch, Kori Arch and the Ratnagiri Arch in the Arabian Sea. A-B and C-D show the regional cross-section lines across the crater, which are shown in Fig. 2. The enigmatic Laxmi Ridge, a continental silver about 700 km long and 100 km across in the Arabian Sea, lies west of the Shiva crater (modified from Mathur & Nair, 1993; Chatterjee & Rudra, 1996; Zutshi *et al.*, 1993; Talwani & Reif, 1998).

boundary. We also speculate the killing mechanisms linked to twin impacts, Shiva and Chicxulub, along with Deccan volcanisms.

MORPHOLOGY AND AGE OF THE SHIVA CRATER

The western continental shelf of India is an enigmatic, Atlantic-type passive margin and is differentiated into four structural and sedimentary basins containing large oil and gas fields from north to south: the Kutch, Mumbai, Konkan and Kerala offshore basins (Biswas, 1987). Like any other passive rift margin, the western shelf of India should be tectonically stable and aseismic. Yet, from recent geophysical work it appears that the western shelf of India is highly seismic and geodynamically anomalous with highly deformed lithosphere; the anomaly has been linked to major impact event at the KT boundary such as the Shiva crater (Pandey & Agarwal, 2001).

The opening of the Arabian Sea bordering the western shelf of India resulted from the breakup and dispersal of the African, Madagascar and Indian plates. A common broad evolutionary proposal is that seafloor spreading initiated between Africa and a Madagascar-Seychelles-India block in Early Cretaceous time, when the Indian Plate drifted northward entering warmer latitudes (Chatterjee & Scotese, 1999). The evolution of the western shelf of India in the Cretaceous Period has been influenced by several unusual geodynamic events: (1) separation of Madagascar from India (88 Ma); (2) Reunion hotspot activity (Deccan Trap) (64.5-65.5 Ma); (3) Shiva impact event leading the formation of the Shiva crater (65 Ma); (4) 500-km northward jump of the Carlsberg Ridge and concomitant separation of Seychelles from India (65 Ma); and (5) sudden acceleration of Indian Plate at the rate of 15-20 cm/year during the Late Cretaceous-Palaeocene time (Chatterjee & Scotese, 1999; Chatterjee *et al.*, 2006). Because of the effect of these major geodynamic events, the tectonic fabric of the western shelf of India around Bombay High is highly complex.

The central uplift of the Bombay High more than 7 km from the ocean floor, the upwarpping of the mantle more than 50 km on the passive margin of the western shelf, accompanied by high heat flow and seismicity and the destruction of the lithosphere is difficult to interpret by any known geologic processes (such as tectonism or volcanism) other than impact cratering process (Pandey & Agarwal, 2001, Chatterjee *et al.*, 2006). Apparently, the central peak region of the crater was uplifted considerably because of isostatic rebound caused by the impact. The Shiva impact had substantially altered the structural framework, created an enormous depocenter for accumulation of shallow marine shelf sediments and produced an ideal petroleum trap on the western self of India. Because of its gigantic size, the Shiva crater is the natural laboratory to study the interactions between large-scale impacts and other geodynamic and biotic effects such as shattering and destruction of lithosphere, initiation of spreading ridge, onset of flood basalt volcanism, major global environmental changes and mass extinctions.

The Shiva crater is located on the Mumbai Offshore Basin, which was discovered in 1974 using seismic data and is bounded by several fault and rift systems. It is largely submerged on the western continental shelf of India, buried by 7 km thick sediments and is reconstructed from the geophysical and drilling data. The stratigraphy, structure, tectonic framework, geophysical signature, facies distribution, petroleum geology and depositional history of the Shiva structure are known primarily from the exploration work in the Mumbai Offshore Basin by the Oil and Natural Gas Corporation (ONGC) of India and described by various authors (Rao & Talukdar, 1980; Basu *et al.*, 1982; Bhandari & Jain, 1984; Biswas, 1987; Mathur & Nair, 1993; Mehrotra *et al.*, 2001; Zutshi *et al.*, 1993). Our interpretation of the Shiva crater is largely based on the published material by the ONGC. Much research, collaboration and synthesis remain to be done before we reach a full understanding of the structure, morphology and cratering process of the Shiva impact that took place around 65 Ma.

Morphology of the Shiva crater

The Shiva crater is buried, so it is inaccessible but uncommonly well preserved as revealed from the geophysical evidence. The structural and morphologic features of the Shiva crater indicate that it is a complex peak ring crater and a multiring basin as evident from the concentric patterns in gravity, magnetic and seismic data (Srivastava, 1996; Rao & Talukdar, 1980; Subba Raju *et al.*, 1990) (Fig. 1). Gravity data of the Shiva crater show a major gravity low anomaly over the central peaks of the Bombay High region similar to the pattern of the Chicxulub crater (Hildebrand *et al.*, 1995). The peak ring has a clear gravitational signal. The Bouguer anomaly values reach extreme lows of -15 mgal at the centre of the crater and -5 mgal over the central peak ring, which gradually rise toward the crater rim about +40 mgal and become highs as much as +50 mgal at the Mumbai Coast, but show lower values in the western rim of the crater (Srivastava, 1996).

The crater has a distinct central peak ring, followed by an annular trough, which is bounded by two external rings (Chatterjee *et al.*, 2006). Such multiring craters have been recognized on the Moon, Mars and Mercury, with similar morphology and similar ratio between the diameters of the inner and outer rings from the remotely senses images (Melosh, 1989). However, these images of extraterrestrial craters do not typically provide information on the subsurface structure and lithological characteristics associated with craters. This is why the multiring craters on Earth may shed crucial information about their genesis, which is still poorly understood. Among terrestrial craters, both Chicxulub (Hildebrand *et al.*, 1991; Morgan & Warner, 1999) and Chesapeake Bay (Poag *et al.*, 1999) craters show peak ring structure associated with a multiring basin. Other multi-ring basins on Earth (>250-km diameter) include Sudbury crater in Canada and Vredefort crater in South Africa (Grieve, 1990).

Four concentric ring structures have been identified in the Shiva crater from the gravity, seismic and well log data, which are designated here as rings 4 to 1, as we move inward (Fig. 1).

Outer rim

The morphology of the Shiva crater is interpreted as a complex multiringed basin and is defined by the collapsed outer rim in the form of faulted margin (ring 3) with an elevated rim (ring 4) around the perimeter. The outer rim (ring 3) of the crater is about 500 km diameter and is marked on seismic profiles by a steep fault scarp. The eastern border of the outer rim rises to the continent and is bordered by the Panvel Flexure around the Mumbai Coast, whereas the northern border is limited by the Narmada Fault in the Arabian Sea (Chatterjee & Rudra, 1996); the Kori Arch bounds the western border and the Ratnagiri fault delineates its southern border (Fig. 1). The faulted outer rim is surrounded by another elevated rim that may represent the outermost ring (ring 4) and is represented by the Saurashtra Arch, Kori Arch and the Ratnagiri Arch in the Arabian Basin. If the faulted outer rim defines the final crater rim, the Shiva has a crater diameter of 500 km, the larger crater known on Earth.

Annular trough

The faulted crater rim (ring 3) is followed inward by the annular trough, which was largely filled with thick Cenozoic sediments. The annular trough is preserved in the form of the Surat Depression, Saurashtra Depression, Shelf Margin Depression, Murad Depression and Panna Depression and is filled with 7 km thick Cenozoic sediments. The annular trough is separated from the central peak by a faulted rim (ring, 2) of 250 km diameter.

Peak ring

Further inward from the faulted second ring lies an inner peak ring (ring 1) of high-relief crystalline rocks, about 200 km diameter, which is roughly half the rim-to-rim diameter of the crater. It encircles the Bombay High Deep Continental Shelf (DCS) block containing several subsurface mountainous peaks including the Bombay High, Mukta High, Panna-Bassein High, Heera High and several other unnamed peaks that stand more than 7 km above the surrounding basement. Based on seismic data and well data, each peak consists of a core of Neoproterozoic granite that was rebounded through the Deccan Trap and is overlain by thick Cenozoic sediments (Fig. 1). Inside the peak ring, the inner basin approximates the location of the transient crater.

Stratigraphic cross-section

Mathur and Nair (1993) provided a series of stratigraphic cross-sections of the Mumbai Offshore Basin across the Bombay High field. Two of their cross-sections, N-S and E-W across the Bombay High are shown in Fig. 2, where the overlying Tertiary sediments were removed just to expose the topography of the floor of the Shiva crater. The structural relief of the crater, from the lowest point of the basin to the highest point of the central peak, exceeds 7 km at the Saurashtra Basin in the northwestern corner of the crater.

Seismic stratigraphy and well drilling have identified the basement rock as the fractured Proterozoic granites, about 600 million years old, showing several peak and basin like structures. Above the basement rock, a thin veneer of Deccan Trap overlies the undulating crater basin. Apparently, the target rocks were both Neoproterozoic granite with a thin cover of Deccan Trap. Above the basement, the lower most crater-fill unit is composed of megablocks, mainly nonmarine Deccan Trap breccia. The megablocks probably formed by inward collapse of the crater's outer walls. The breccia unit is covered by the thick Panna Formation of Palaeocene age, overlying the KT boundary sequence. The Panna Formation is overlain by 7 km thick Eocene-Miocene sedimentary sequence represented by shallow marine shales, sandstones and carbonates (Wandrey, 2004).

The thickness of the Neoproterozoic basement rock, the Deccan lava floor and the Deccan Trap breccia unit within the crater, is unknown from published accounts. Thus, the total vertical rebound of the central peak cannot be estimated at the moment. The uplift in the centre of a complex crater amounts to about one tenth of the crater's final diameter (Grieve, 1990). The uplift associated with 500 km wide Shiva crater is estimated to be 50 km. A geophysical anomaly indicates that the lithosphere mantle in this region has been considerably sheared and deformed around Shiva crater, whereas the crust-mantle boundary has been uplifted more than 50 km with unusual high heat flow (Pandey & Agarwal, 2001). These authors have implicated this unusual rise of the Moho boundary and the geothermal anomaly (heat flow > 80m W/m^2) on the western shelf to an impact event that may indicate the amplitude of the uplift.

The crystalline rocks beneath the Shiva crater are shattered and broken to a great depth, inferred from seismic velocity beneath the crater and low gravity anomaly (Rao & Talukdar, 1980; Srivastava, 1996). Cores of Neoproterozoic granite (target rock) derived from petroleum exploration drilling under the Bombay High area contain evidence for cataclasis (rock pulverization) and pseudotachylite veins of impact origin (Chatterjee *et al.*, 2006). Petrographic studies of two samples display discordant veins 400-1000 microns thick of aphanitic, micro- to cryptocrystalline material that intrude into feldpsar phenocrysts within a mylonitized feldspathic gneiss. Inclusions of feldspar aggregates are observed within the aphanitic groundmass. These textures and intrusive relationships are consistent with experiments that have produced shock-melted glass during impact (Fiske *et al.*, 1995) and field/petrographic studies of pseudotachylite (e.g., McNulty, 1995). SEM images and Energy-dispersive X-ray spectra (EDXS) indicate that the composition of the pseudotachylite is pure silica glass melt rocks, the result of shock pressure induced by the Shiva impact.

Age of the Shiva crater

The Shiva crater was presumably formed at the KT boundary time during the rifting of India with the Seychelles, as the oldest sequence represent the Palaeocene Panna Formation (Chatterjee & Rudra, 1996). The available stratigraphic information provides the upper and lower bounds of the age of the Shiva crater represented by the Panna Formation and the Deccan Traps respectively. The subsurface stratigraphy of the Shiva crater is known primarily from petroleum exploration of drill holes and geophysical anomalies (Rao & Talukdar, 1980; Basu *et al.*, 1982; Bhandari & Jain, 1984; Mathur & Nair, 1993; Zutshi *et al.*, 1993; Wandrey, 2004). The post-impact sedimentary fill in the crater consists of nearly horizontal strata of Cenozoic sediments of typical shallow marine shelf sequence exceeding 7 km in thickness that ranges in age from Palaeocene to Holocene (Fig. 2C). The Panna Formation, the lowest unit of Tertiary sediments, which formed soon after the crater formation, lies unconformably on a thick layer of breccia unit embedded in reddish claystone and siltstone, referred to as the 'Deccan Trap Breccia' (Chatterjee *et al.*, 2006)—a sedimentary-clast impact breccia, dominated by fragments of Deccan Traps and their weathered products in the form of clay matrix. The middle part of the Panna Formation has yielded foraminifera (Basu *et al.*, 1982) and nummulites (Rao & Talukdar, 1980) of the Late Palaeocene but recent biostratigraphic analysis suggests that the lower part of the Panna Formation may extend to the Early Palaeocene (Zutshi *et al.*, 1993). Since the age estimates for the Deccan lavas in western India cluster around 65 Ma (Duncan & Pyle, 1988; Courtillot, 1990), it is speculated that the Deccan Trap Breccia unit, sandwiched between the Early Palaeocene Panna Formation and the Deccan Trap, thus indicating that the crater formed at the KT boundary. A radiometric age (~65 Ma) of the crater formation is provided by the impact melt rocks such as alkali igneous complexes, which are interpreted as proximal fluid ejecta within the Deccan Traps (Chatterjee & Rudra, 1996; Basu *et al.*, 1993).

Petroleum trap

More than 35 of the 150 impact craters known on Earth today contain mineral-enriched deposits. The deposits range from common building materials, such as limestone to oil and gas reserves and strategic metals like uranium, gold, copper, nickel and platinum (Poag, 1999). The economic potential of some impacts comes in totally unexpected forms. For example, KT boundary impact craters such as Shiva, Chicxulub and the Boltysh Depression are among the most productive hydrocarbon sites on Earth. Donofrio (1981, 1998) recorded 17 confirmed impact structures/events occurring in petroliferous areas of North America, 9 of which are being exploited for commercial hydrocarbons. The large impact craters (> 4 km diameter) exhibit the features characteristic of complex craters with distinctive uplifted central structures surrounded by an annular trough and a fractured rim (Grieve, 1990). Thus the central peak of a complex crater forms an antiformal structure and extensive fracturing and brecciation of the target rock, which, when covered by porous and permeable rocks such as sandstones and limestones can be conducive to hydrocarbon accumulations. In the Shiva crater, the most prolific traps are those located on persistent palaeo-highs of the peak ring area, where oil and gas is produced from fractured basement through middle Miocene reservoirs, with the most prolific being the platform carbonates such as the Lower Miocene Ratnagiri Formation (Rao & Talukdar, 1980). The most likely seals are an extensive series of thick middle to Upper Miocene shales. Ranked 38th worldwide, Shiva has reserves exceeding 8.4 billion barrels of oil, 24.2 trillion cubic feet of gas and 0.3 billion barrels of natural gas liquids (Wandrey, 2004). The total 12.7 billion barrels of oil equivalent including natural gas liquids, is from 165 fields of which 126 are I million of barrels of oil equivalent or greater in size.

IMPACT EJECTA LAYER AT THE KT BOUNDARY OF INDIA

If Shiva is indeed a very large impact crater dating from the KT boundary time, extensive deposits of impact ejecta should surround it. However, during the KT boundary time extensive eruption of Deccan lava covered most of western and central India and must have engulfed thick deposits of ejecta components proximate to the crater. Only rarely, ejecta layer would be preserved outside the Deccan volcanic province. This is indeed the case and the expected deposits have been located in many outcrops from India outside the Deccan province. Geological fieldwork and laboratory analyses of rocks from the surface outcrops at several KT boundary sections in India, particularly in and around the Deccan volcanic province reveal the existence of proximal (non-

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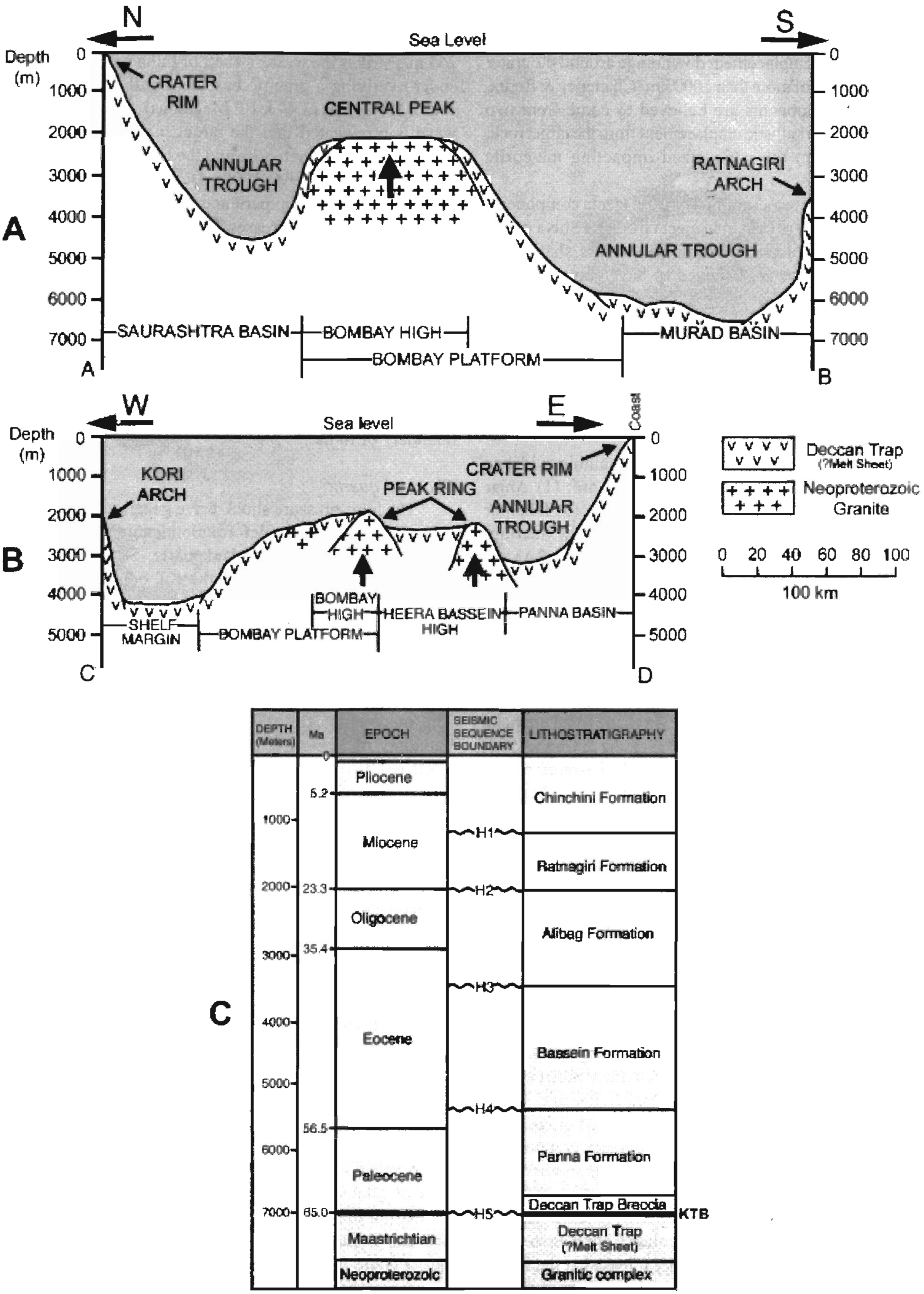
Fig. 2—Cross-sections across the Shiva crater to show relief the crater basin; the overlying Cenozoic sediments were removed (see Fig. 3 for reference). A, north-south cross section (A-B line) from Saurashtra Coast to Ratnagiri Arch; B, west-east cross section (C-D line) from the Kori Arch to Mumbai Coast (modified from Mathur & Nair, 1993). C, Generalized stratigraphy of the Shiva crater (modified from Rao & Talukdar, 1980; Basu *et al.*, 1982; Bhandari & Jain, 1984; Mathur & Nair, 1993; Zutshi *et al.*, 1993; Wandrey, 2004). The oldest sedimentary units in the crater basin, the Deccan Trap breccia, the early Palaeocene Panna Formation and the Deccan Trap floor bracket the age of crater at the KT boundary time.


A
N
S
Sea Level
Depth (m)
0
1000
2000
3000
4000
5000
6000
7000
CRATER RIM
CENTRAL PEAK
ANNULAR TROUGH
RATNAGIRI ARCH
ANNULAR TROUGH
SAURASHTRA BASIN
BOMBAY HIGH
BOMBAY PLATFORM
MURAD BASIN
A
B
B
W
E
Coast
Sea level
KORI ARCH
PEAK RING
CRATER RIM
ANNULAR TROUGH
SHELF MARGIN
BOMBAY PLATFORM
BOMBAY HIGH
HEERA BASSEIN HIGH
PANNA BASIN
C
D
Deccan Trap (?Melt Sheet)
Neoproterozoic Granite
0 20 40 60 80 100
100 km
C
DEPTH (Meters)
Ma
EPOCH
SEISMIC SEQUENCE BOUNDARY
LITHOSTRATIGRAPHY
0
5.2
23.3
35.4
56.5
65.0
1000
2000
3000
4000
5000
6000
7000
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Maastrichtian
Neoproterozoic
H1
H2
H3
H4
H5
Chinchini Formation
Ratnagiri Formation
Alibag Formation
Bassein Formation
Panna Formation
Deccan Trap Breccia
KTB
Deccan Trap (?Melt Sheet)
Granitic complex

global) and distal (global airfall) ejecta from the Shiva impact. The oblique impact of Shiva in a SW-NE trajectory caused multi-staged ejecta emplacement downrange around the crater up to radial distance of more than 1000 km (Chatterjee & Rudra, 1996). Ejecta components are believed to come from two different sources: (1) ballistic emplacement from the target rock; and (2) airfall from the vapourized impacting meteorite respectively.

Three types of coarse-grained or fluid ejecta components have been interpreted as proximal ejecta from the Shiva crater. They include fluid ejecta, spherules and glass shards and shocked quartz, which are believed to have come from the target rock of the impact site. Other fine-grained ejecta components, such as iridium anomaly, natural fullerenes, Ni-rich spinels and magnetic nanoparticles probably came from the vapourized meteorite and were deposited by airfall; these ejecta may be local or global. In addition, impact-generated tsunami deposits have been recognized in the Ariyalur section of Tamil Nadu (Chatterjee *et al.*, 2006).

Notable KT boundary sites in India containing evidence of impact ejecta horizons from west to east are: (1) Anjar section, Gujarat; (2) Barmer section, Rajasthan; (3) Jabalpur section, Madhya Pradesh; (4) Um Sohryngkew section, Meghalaya; and (5) Ariyalur section, Tamil Nadu (Fig. 3A). Of these, the Anjar, Barmar and Jabalpur sections are continental and are associated with Deccan volcanic pile, whereas Um Sohryngkew is marine and the Ariyalur section is mixed.

Proximal ejecta

Craters formed by artificial oblique impact are generally oblong (Gault & Wedekind, 1978). The shape of an artificial crater formed by oblique impact at 15º (Schultz & Gault, 1990) is like a teardrop, where the pointed end indicates the downrange direction (Fig. 3B). In an oblique impact the crater and its proximal ejecta are bilaterally symmetrical about the plane of the trajectory, but the distribution of the ejecta is concentrated asymmetrically on the downrange side. The shape of the Shiva crater and the distribution of melt ejecta are almost identical to those produced by oblique impacts in laboratory experiments (Fig. 3B).

Impact cratering is the only geologic process known to produce shock metamorphic effects. Most rocks shocked to 60 gigapascals or more melt completely (Grieve, 1990). The estimated size of the Shiva bolide was about 40 km in diameter, which would generate shock pressure at the target rock many hundreds of gigapascals leading to enormous volume of melt rocks. The Shiva was an unusual impact because of the combined granite and Deccan Trap target lithologies that would produce fractional and multiple ejecta components, which would be emplaced ballistically one after another as the shock pressure increased soon after the impact.

Using scaling laws of impact cratering process, we have computed the diameter of the Shiva bolide from the size of the Shiva crater and the amount of energy released at the impact (Melosh, 1989; Alvarez *et al.*, 1995). We assume a stony meteorite (diameter = 40 km; density = 3000 kg/m^3) travelling at 25 km/s strikes the western shelf of India with a Deccan Trap cover overlying a granitic basement with kinetic energy of 1.45 x 10^{25} Joules (3.47 x 10^9 Megatons). On contact, a shock wave is propagated into the target rock at nearly 20 km/s, shocking both the meteorite and the target up to a pressure of 1,000 GPa (Grieve, 1990; 1998). During crater forming process the target region will experience a range of impact pressures. As shock pressure increases from 10 to 1,000 gigapascals, there is a progressive shock metamorphism of the ejecta components of the target rock to be produced sequentially and temporally as the shock wave decays down and out into the granite basement: mineral crystals first develop shocked lamellae, then degenerate into glass spherules in the form of fireball and then melt completely into huge volume of lava chamber and finally vapourize. We have found these different stages of shock metamorphic ejecta components at the KT boundary of India.

Shocked quartz

The high-pressure shock wave generated by a meteorite impact produces planar deformation features (PDF) in quartz minerals in the form of shocked quartz. Such shocked quartz grains were discovered from the KT boundary sections of North America (Bohor *et al.*, 1984). Alvarez *et al.* (1995) calculated the ballistic emplacement of the shock quartz launched at Chicxulub and concluded that India should be forbidden zone for shocked quartz grains and predicted that they should be absent from the KT boundary sections of India. The discovery of thick shocked quartz layer at the KT boundary of India indicates its ballistic transport from the unmelted basement rock of proximal Shiva impact, not from the Chicxulub crater.

The KT boundary section in Jabalpur represents the uppermost unconsolidated sandstone layer (~2.7 m) of the Lameta Formation and is overlain by the Deccan flow. Basu *et al.* (1988) briefly reported planar deformation features in shocked quartz grains from the upper part of the KT boundary sandstone layer of Jabalpur using a petrographic microscope. The PDF-bearing quartz grains are relatively large (400 to 300 µm) that form about 2-3% of unetched samples and show many features commonly associated with impact. The planar features, both single and multiple, meet all criteria used to distinguish them from volcano-tectonic deformation (Bohor *et al.*, 1987; Izett, 1990).

Chatterjee *et al.* (2006) documented further evidence of shock metamorphism of quartz grains from the upper sandstone unit of Jabalpur section by SEM images and Energy-dispersive X-ray spectra (EDXS). Quartz grains showing such multiple sets of shock-induced planar features are only found at meteoritic impact sites as well as from other KT boundary sections (Bohor, 1990; Bohor *et al.*, 1987; Izett, 1990). Shocked quartz grains from the Jabalpur section (300-400 µm) are coarse

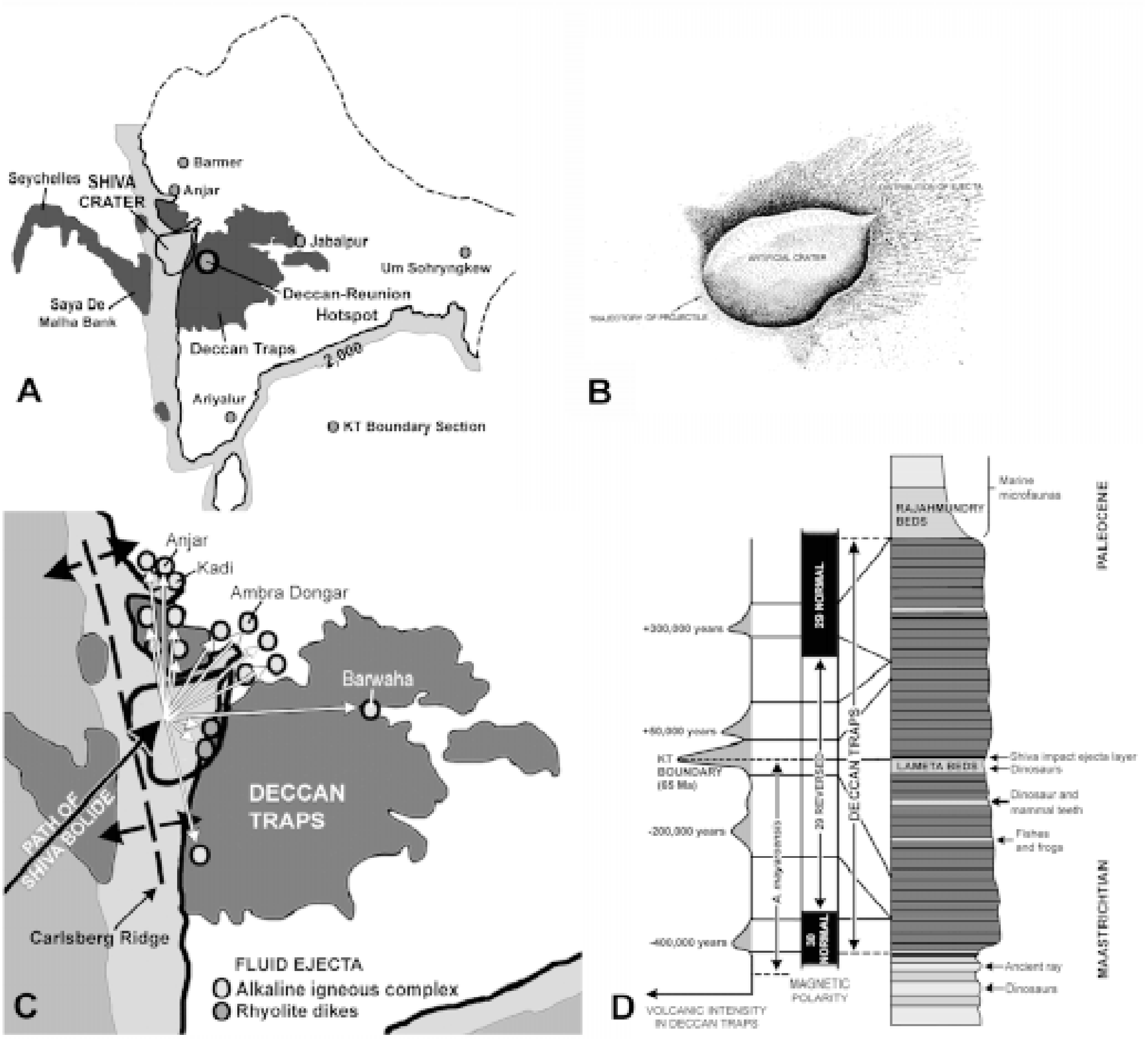


Fig. 3—A-Palaeoposition of India-Seychelles during the KT boundary time showing the location of KT boundary sites around the Deccan volcanic province (grey circles). The KTB sites containing cosmic ejecta in India, from west to east are: Anjar, Gujarat; , Rajasthan; Jabalpur, Madhya Pradesh; Um Sohryngkew, Meghalaya and Ariyalur, Tamil Nadu (modified from White & McKenzie, 1989 and other sources). B-artificial crater produced by low-angle (~15º) oblique impact in the laboratory mimics the shape and fluid ejecta distribution of the Shiva crater (simplified from Schultz & Gault, 1990). C-radial, asymmetric distribution of fluid ejecta downrange of the Shiva crater; teardrop shape of the crater and asymmetric distribution of melt rocks consistent with the oblique impact model along the NE downrange direction; alkaline igneous complex rocks were emplaced outside the crater rim, whereas rhyolite rink dikes are restricted within the crater rim; arrow indicates the trajectory of the meteorite; similar asymmetric distribution of fluid ejecta are known from craters of Moon, Mars and Venus. D-A synthesis of palaeomagnetic, palaeontologic and geochronologic data from the Deccan Trap lava pile showing the stratigraphic position of the KT boundary and its relationships with the intertrappeans beds such as Lameta Formation. Various cosmic signatures, such as iridium anomaly, high-pressure fullerenes, shocked quartz, Ni-rich spinel, magnetic nanoparticles, ejecta droplets and fluid ejecta have been found from different KT boundary sections of India that are linked to the Shiva impact (modified from Courtillot, 1990; Chatterjee & Rudra, 1996).

and relatively larger than most shocked quartz grain reported from Europe (100-200 µm) or the Pacific basin (< 100 µm) but somewhat smaller than those from North America (500-600 µm) (Izett, 1990; Bohor, 1990; Bohor *et al.*, 1987). Of course, particles of this size scale still can be airborne over large distances, but the enormous thickness of the KT boundary section in Jabalpur favours the proximate source. Here, the KT boundary section appears to be very thick (2.7 m) rather than a typical 1 cm thick deposit as in other KT boundary sites. This demonstrates the existence of a proximate impact site such as the Shiva crater, from which thick distal ejecta could be emplaced ballistically. Such a thick boundary layer could not be derived as airborne fallout from the Chicxulub impact structure.

Spherules and glass shards

In the case of a large impact, a significant portion of the target rock is melted and molten droplets may also be ejected from the crater. These droplets are called tektites or impact-melt spherules and their morphologies are highly variable. A thin (~ 4 cm) unconsolidated layer of siliciclastic deposit at the KT boundary section of Barmer Basin, Rajasthan, in association with an early phase of the Deccan volcanism, contains several distal ejecta components such Ni-rich vesicular glasses, sanidine spherules, shocked magnesioferrite spinels and soot (Sisodia *et al.*, 2005). The siliciclastic deposit disconformably overlies the Late Cretaceous shallow marine Fatehgarh Formation and is overlain by the Akli Formation of Palaeocene-Eocene age. The igneous intrusive rocks within Fatehgarh Formation have yielded radiometric age ranging from 67 to 65 Ma, close to the KT boundary age (Basu *et al.*, 1993). We suggest the glassy ejecta produced by shock devolatilization of the target rock into fireball of silicate vapour preceded the emplacement of the large volume of fluid ejecta.

Sisodia *et al.* (2005) recognized glass shards, quartz beads, ferruginous hollow spheroids and other melt ejecta components from this bed under microscopic examination. They interpret this siliciclastic deposit as possible ejecta or volcanic components having originated through a combination of ballistic and debris flow deposit. They argue that some ejecta particles such as sanidine spherules and skeletal magnesioferrites are petrographically very similar to those found around the Gulf of Mexico associated with the Chicxulub crater (Smit, 1999). Similarly sanidine spherules from the section also indicate a large impact event (Smit & Klaver, 1981). We believe that the boundary layer at section is impact-related because it is rich in Ni-rich glass spherules, sanidine spherules and skeletal magnesioferrite as seen in other KTB sections. We discount the volcanic origin proposed by Sisodia *et al.* (2005) because it lacks a coherent assemblage of volcanic crystals such as xenoliths and xenocrysts, which are common in ash-flow tuffs (Izett, 1990). Thus the ejecta components from the section may imply remnants of hot, early ejecta from the nearby Shiva impact (Chatterjee *et al.*, 2006).

Mathur *et al.* (2005) reported magnetic glassy spherules from the underlying phosphorite deposit of the Fatehgarh Formation, which were probably deposited by a tsunami-generated turbidity current. These spherules are associated with the Late Maastrichtian bone bed loaded with shark teeth such as *Igdabatis* that may indicate a mass killing event. Some of the spherules are glassy due to quick quenching, indicative of high temperature origin. These spherules are very similar to those KT boundary impact-generated ejecta layers around the Caribbean and Gulf of Mexico region. However, these authors maintained that these ejecta did not come from the Chicxulub, but from nearby impact site.

Fluid ejecta

Crystalline target rocks, such as those of the Sadbury and Chicxulub craters, characteristically yield enormous melt sheets when struck by a large meteorite. Melt rocks are very common near large impact craters. The melt is created by strong shock waves that emanate from the site of the impact (Melosh, 1989). Nearly all of impactor's kinetic energy is converted into heat to produce vast volume of impact melts. These lava-like impact melts are very common at lunar craters and are emplaced downrange outside the crater rims (Howard & Wilshire, 1975). Asymmetric distribution of fluid ejecta downrange indicates an oblique impact event.

One of the intriguing features associated with the Deccan flood basalt volcanism is the occurrence of several post-tholeiitic alkali igneous complexes of nepheline-carbonatite affinities along the radii of the Shiva Crater (Fig. 3C). They are manifested in plug-like bodies and minor intrusions in the western and northwestern province and are limited in space and volume compared to the vast expanse of tholeiitic lavas (Bose, 1980; De, 1981). Some of the spectacular plugs of alkali igneous complexes in the Deccan volcanic province are Anjar, Kadi, Jwahar, Phenai Mata, Amba Dongar, Barwaha, Murud and Napsi structure and are clearly defined zones of gravity highs (Biswas, 1987). The asymmetric distribution of fluid ejecta indicates a trajectory of the Shiva bolide from the SW to NE. Recent $^{40}Ar/^{39}Ar$ dating of these alkaline igneous complexes indicates 65 Ma, precisely coinciding with the KT boundary (Basu *et al.*, 1993). Chatterjee and Rudra (1996) speculate that these volcanic plugs represent the fluid ejecta of the Shiva impact at the down range direction. Schultz and D'Hondt (1996) described similar asymmetric distribution of fluid ejecta on Venus resulting from an oblique impact that flowed down range at a distance more than the crater diameter.

There are several features that suggest the impact origin of the alkaline igneous complexes. First, Deccan lavas are poor in iridium content (~10 pg/g), but these alkali complexes are enriched with iridium (178 pg/g) (Shukla *et al.*, 2001) and show evidence of crustal contamination (Paul *et al.*, 1977; Basu *et al.*, 1993). We speculate that the target rock for these alkaline igneous complexes were both Deccan Traps and crystalline basement granites, which were melted and contaminated by the asteroid impact as indicated by high iridium anomaly. Similar meteoritic contamination of impact melts is known from the Wabar crater, Saudi Arabia (Hörz *et al.*, 1989). Second, impact melt rocks have higher K_2O/NaO ratios than the target rocks (Grieve, 1987) as in the case of these alkaline igneous complexes. Third, the asymmetric radial distribution pattern of these alkaline complexes around the Shiva crater is emplaced in the downrange direction of fluid ejecta. Fourth, they have restricted distribution and occur within Deccan volcanics as post-tholeiitic intrusives or plugs; they are conspicuously absent in other parts of the Deccan volcanic province. Fifth, their age matches exactly with the KT impact event.

If the Shiva impact were the source of the alkaline igneous complexes, then this implies a significant asymmetry to the distribution of fluid ejecta. We suggest that the likely mechanism to generate this asymmetry would be a low-angle (< 30º from the horizontal) impact from southwest to northeast. This would provide a preferential direction for much of the fluid ejecta. If the Shiva projectile came from the southwest direction, the fluid ejecta would progress downrange with a mean direction of NE. If so, the impact that produced the Shiva crater was probably oblique along a SW-NW trajectory as evident from the distribution of the longer diameter of the oblong crater; the tip of teardrop indicates that the downrange direction was NE. Howard and Wilshire (1975) described flows of impact melt of large lunar craters both outside on crater rims and inside on the crater walls, where asymmetric distribution of fluid ejecta can be used to determine the impact trajectory. The asymmetric distribution of fluid ejecta on the NE side of the Shiva crater indicates the downrange direction.

Cosmic ejecta

The extremely fine particles of the following ejecta components apparently came from the vapourized meteorite, but the actual source, whether Shiva or Chicxulub bolide, is difficult to pinpoint at this stage because of atmospheric global circulation of the ejecta blankets in the stratosphere and subsequent airfall and deposition at the KT boundary layer.

Iridium anomaly

An anomalous high concentration of the trace element iridium has been found in two KT boundary sections of India: the Um Sohryngkew river section of Meghalaya and the Anjar volcano-sedimentary section in Gujarat. The KT boundary layer of Meghalaya is a 1.5 cm thick limonitic layer that lies within the Mahadeo Formation about 10 m below the Mahadeo/Langpur contact (Pandey, 1990). This layer is rich in iridium and osmium (Bhandari *et al.*, 1993, 1994). The iridium profile at the KT boundary is about 12 ng/g, ten times higher than the background level.

The Anjar volcano-sedimentary section in Gujarat is located at the western periphery of the Deccan flood basalt province and is probably the most thoroughly studied KT boundary sections in India. It consists of nine lava flows (F1-F9) and at least four intertrappean beds (Bhandari *et al.*, 1996; Parthasarathy *et al.*, 2002). The third intertrappean bed, about 6 m thick occurring between F3 and F4, is well known for high concentrations of iridium (650-1333 pg/g) and osmium (650-2230 pg/g) (Bhandari *et al.*, 1996; Courtillot *et al.*, 2000). Three thin limonitic layers are present in the lower 1.5 m of the third intertrappean bed, which is rich in iridium anomaly.

Natural fullerenes

Along with iridium anomaly, fullerenes have been reported from the KT boundary section of Anjar (Parthasarathy *et al.*, 2002). Fullerenes are known from the Sudbury impact structure (Becker *et al.*, 1994) and from the KT boundary sections of North America (Heymann *et al.*, 1994) and are considered cosmic signature for impacts. The concentration of high-pressure form of fullerenes (C_{60}) in other KT boundary sections of North America is low, about 0.41 ppm (Heymann *et al.*, 1994), whereas in the Anjar section this value is three times high, about 1.3 ppm. The association of high-pressure, high-temperature forms of buckyball fullerenes, with high iridium concentrations is a good indicator of a proximate extraterrestrial impact site such as the Shiva crater.

Nickel-rich spinels

Ni-rich spinels, another cosmic signature, have been reported from the KT boundary section of Meghalaya associated with the iridium anomaly (Robin *et al.*, 1997). They are almost absent below and above the KT boundary but show an abrupt increase in concentration with the maximum iridium spike. Ni-rich spinels are believed to have an unequivocal cosmic origin, derived during the vapourization of the meteorite crust during entry into atmosphere and have been reported from different KTB sections (Robin *et al.*, 1992). These spinels are characterized by magnesioferrite compositions with high concentrations of Ni and low Ti and Cr, which make them distinct from virtually all known terrestrial igneous or metamorphic occurrences. The number of spinels in the peak (2 spinels/mg) is, however, small as compared to that found in most other KTB sections.

Sisodia *et al.* (2005) reported magnesioferrite spinel crystals from KT boundary Barmer section of Rajasthan as micrometer-sized skeletal forms. They pointed out that high nickel concentration (0.5 to 2% Ni) in glass spherules is generally considered as an indicator of an extraterrestrial component because of its high abundance in various types of meteorites and low concentration in terrestrial sources. Their composition, small size and skeletal morphology suggest they are condensation products of a vapourized bolide (Bohor, 1990).

The distribution of KT boundary ejecta in the NE direction of the Shiva crater is consistent with the trajectory of the bolide. Moreover, the enormous strewnfield of magnesioferrite spinel distribution, along with shocked quartz in KT boundary sediments of the Pacific basin, lie directly on this northeast trajectory (Kyte & Bostwick, 1995) of the Shiva bolide. These authors noticed that composition of these cosmic spinels from the Pacific is markedly different from those found in western Europe and the South Atlantic. We believe the compositional variations of cosmic spinels in KT boundaries indicate two impact sources: Chicxulub structure for the European and Atlantic distribution and the Shiva structure for the source of the Pacific impact debris. As the vapour cloud would progress downrange from the Shiva structure toward the Pacific, the earliest and highest temperature phases would drop as airborne particles, first at Meghalaya and then over the Pacific (Chatterjee *et al.*, 2006).

Magnetic nanoparticles

Recently, Bhandari *et al.* (2002) reported association of nanoparticles of magnetic and superparamagnetic iron oxide phases associated with iridium-rich layer from the KT boundary section of the Anjar and Meghalaya, which are attributed to impact origin. Apparently, these nanoparticles probably formed during condensation of the high-temperature impact vapour plume. Meteorites in general, have high concentrations of iron (e”20%) in the form of silicates, metal, magnetite and other iron-bearing minerals.

DECCAN VOLCANISM

The outpouring of the enormous continental flood basalts of the Deccan Trap, spreading over vast areas of western and central India and adjoining Seychelles microcontinent covering more than 1,500,000 km^2, also marked the close of the Cretaceous time (Courtillot, 1990). The lava pile is the thickest in the western part of the Deccan volcanic province, reaching an exposed thickness of about 2 km in parts of Western Ghats, but becomes gradually thin in the east, where it attains no more than about 100 m (Fig. 3). Chatterjee and Rudra (1996) reviewed the age of the Deccan traps on the basis of geochronologic, palaeomagnetic and palaeontologic constraints. ^{40}Ar/^{39}Ar dates of the stratigraphically controlled thick sequences of Deccan lava piles around the Western Ghats section cluster around a narrow span of age from 64.4 to 65.3 Ma, with a major eruptive phase around 65 Ma, coinciding with the KT mass extinction (Duncan & Pyle, 1988; Courtillot, 1990; Courtillot *et al.*, 1988; Hofmann *et al.*, 2000; White & McKenzie, 1989). Thus this enormous volcanic mass had been laid down in less than 1 kyr. Palaeomagnetic studies in the thick Western Ghats section indicate that Deccan volcanism began during the 30N magnetic chron, climaxed during the following reversed interval 29R at the KT boundary and ended in the 29N chron (Courtillot, 1990). In marine section, the lowest level of Deccan lava rests on a sedimentary layer that contains the typical Late Maastrichtian index foraminiferal fossil *Abatomphalus mayaroensis*, which thrived close to the KT boundary and then disappeared. It thus appears from the combined evidence of radiometric dating, palaeomagnetic evidence and fossil studies, that the estimated duration of Deccan volcanism is about million years around the KT boundary (Fig. 3D).

Currently two models for the origin of the continental flood basalt of Deccan volcanism have been proposed: Mantle plume theory and impact-induced theory. In mantle plume theory, flood basal episodes are thought to mark the initiation of a subcontinental hotspot and most such episodes were followed by rifting and continental fragmentation (White & McKenzie, 1989). Deccan flood basalts were the first manifestation of the Reunion hotspot that rose from the core-mantle boundary and subsequently produced the hotspot trails underlying the Laccadive, Maldive and Chagos islands; the Mascarene Plateau; and the youngest volcanic islands of Mauritius and Reunion (Morgan, 1981). The age of the hotspot tracks decreases gradually from the Deccan traps to the Reunion hotspot, thus appearing to be consistent with the northward motion of the Indian Plate over a fixed plume (Duncan & Pyle, 1988).

A second view for the origin of the Deccan Traps is the impact-triggered model by decompression melting of the lithosphere. The spatial and temporal coincidence of Deccan volcanism with the Shiva crater led to the suggestion that the Deccan Traps might mark the site of the asteroid impact (Hartnady, 1986; Alt *et al.*, 1988; Alvarez & Asaro, 1990). Although the idea of genetic association between impact and volcanism is very appealing, especially from cratering studies of the Moon where impacts caused lava to fill the crater basins (lunar maria), this hypothesis is rejected here because of conflict of timing; the onset of Deccan volcanism preceded the Shiva impact by 400 Kyr or more. Thus, there is no evidence for the Shiva impact-Deccan volcanism connection (Bhandari *et al.*, 1995), but impact could enhance the spectacular outburst of Deccan volcanism at the KT boundary (Chatterjee & Rudra, 1996).

The Deccan lava flows were not extruded all at once but contain several pulses. Volcanic activity was punctuated periodically when sedimentary beds were deposited in between the flows. These fluvial and lacustrine deposits are called Intra- and Intertrappean beds that contain abundant remains of plants, invertebrates, fish, frogs, crocodilians, turtles, dinosaurs and their eggs and mammalian teeth (Chatterjee & Rudra, 1996; Sahni *et al.*, 1996).

POSSIBLE KILLING MECHANISMS AT THE KT BOUNDARY

The KT extinction occurred about 65 Ma when dinosaurs and two-thirds of all living species vanished from the face of the Earth. This extinction event defines the geological boundary between the Cretaceous and Tertiary periods. Two main theories have emerged to account for this dramatic event:

Deccan volcanism (Courtillot, 1990) and double asteroid impacts (Chatterjee, 1997). The KT boundary age for Shiva opens up intriguing questions about how two large impacts in quick succession associated with humongous Deccan eruptions might be linked to dramatic environmental changes affecting the organisms on Earth.

Role of Deccan Volcanism

The Deccan volcanism has been implicated as a possible contributor to the KT mass extinction mainly due to their high amounts of volatiles, aerosols and dusts released into the atmosphere (McLean, 1985; Officer *et al.*, 1987; Courtillot, 1990). It has been estimated that various pulses of Deccan eruptions could have released up to 100,000 megatons of sulphur dioxide and carbon dioxide into atmosphere causing aid rain and other environmental stress (Courtillot, 1990). Volcanic pollution from the Deccan volcanism has been one of the key arguments for its catastrophic role in the KT mass extinction because it would increase greenhouse effect, reduce photosynthesis, create acidic oceans, dissolve shells of calcareous organisms and collapse marine food chain (McLean, 1985; Officer *et al.*, 1987). Deccan eruptions might have caused major environmental destabilizations for the last 400,000 years before Earth got hammered with the Chicxulub and Shiva bolides (Fig. 3D). However, the presence of dinosaur bones and eggs in intertrappean layers clearly indicates that the dinosaurs thrived in the midst of this chaos right until the iridium anomaly that indicates the impact hit. If it had been a brief volcanic manifestation, it would create biotic crisis. However, the duration of Deccan volcanism was nearly 1 million year. Such a time span would let the atmosphere and the ocean act as strong climatic buffers, preventing any major crisis in the ecosystems. Deccan eruption could not have been a proximate or the main cause of the KT extinction (Chatterjee & Rudra, 1996). The kill mechanisms associated with Deccan volcanism were slow and gradual and do not appear to be sufficiently powerful to cause worldwide collapse of ecosystems suddenly at the KT boundary leading to the one of the largest mass extinctions. Thus, the influence of Deccan lavas for the biotic crisis is indirect, perhaps through greenhouse warming generated by the injection of large amounts of SO_2 and CO_2 into the atmosphere and change of the ocean chemistry by production of acid rain that might have devastating effects on marine organisms. As the sea turned into more acidic, the calcareous organisms would be obliterated and the marine food chain would collapse. The cruelest KT extinctions struck the seas for which the Deccan Traps might be the early perpetrator. In fact impacts and Deccan volcanism may explain the unusual simultaneous extinction phenomena at land and sea at the KT boundary. However, Deccan volcanism would lack some of the titanic lethal features that are generally associated with a large body impact, such as gigantic shock wave leading to vapour plume, global fire, thermal pulse, evaporation of the photic zone of the continental shelves, sea regression, chondritic metal toxicity and volatilization of target rocks (Toon *et al.*, 1997; Kring & Durda, 2003). The double impacts at the KT boundary were the final insults to the already overstressed global ecosystems initiated by the Deccan volcanism.

Role of Double impacts

For more than a decade, most scientists believed that the extinction of the dinosaurs was caused by a single event: the crash of a large asteroid on the Yucatan peninsula of Mexico with an explosive force like a hundred million hydrogen bombs. However, with the discovery of additional craters at the KT boundary such as the 24 km wide Boltysh crater of Ukraine (Kelley & Gurov, 2002) and the 500 km wide Shiva crater of India (Chatterjee & Rudra, 1996), multiple impact events may provide causal mechanism for the KT extinction (Chatterjee, 1997; Keller *et al.*, 2003, 2004). The Boltysh impact was relatively small, affecting the local areas on the Ukranian shield with little global influence. Thus the Chicxulub and the Shiva impacts appear to be the ultimate killers for the KT extinction that claimed dinosaurs, pterosaurs, plesiosaurs, mosasaurs, rudists, ammonites and more than 75% of animal and plant species on Earth. Given the range of dating uncertainty, the two impacts that made the craters may have occurred simultaneously (Chatterjee & Rudra, 1996) or been separated by 300,000 years (Keller *et al.*, 2003, 2004). Even, if their times of impact prove to have been only close, the one-two punch could still have added to the global turmoil that wiped off the dinosaurs and other creatures.

Computer simulation suggests that the explosion of a large asteroid (>10 km size) that created the Chicxulub crater (about 180 km diameter) would produce kinetic energy of 1.6 x 10^{15} joules (equivalent of 100 trillion tons of TNT) that exceeds considerably the power released by the eruption of the Deccan volcanism or the world's nuclear arsenal (Grieve, 1990; Alvarez *et al.*, 1995). The pressure exerted on the meteorites and the target rocks can exceed several hundred gigapascals and the temperature can reach several thousand degrees Celsius to melt the target rocks (Grieve, 1990; Frankel, 1999). The Shiva bolide (~40 km diameter) would generate lethal amount of kinetic energy of 1.45 x 10^{25} joules that combining with the Chicxulub punch would rock the Earth and trigger biotic catastrophe.

The biologic consequences of twin impacts would, which are nearly instantaneous in their globally devastating effects, depend on many factors, including the energy of the impact event, the type and location of target materials, the type of projectiles and the prevailing ecology (Grieve, 1998). While the greatest damage is obviously at ground zero for a large impact, a very significant portion of the energy from the impact would be dissipate and devastate in the ecosphere, the thin shell of air, water, soils and surface rocks that nurture life and cause the mass extinction. When two asteroids hit the earth in antipodal positions, dust and fireball emerged from the craters would spread out hundreds of kilometers and hid the Sun.

Plants and phytoplankton died in the prolonged darkness. Even seismic shock waves would reach damaging proportions on a global scale and would trigger a tsunami that would flood most shorelines ~100 km inward and destroy coastal life (Chapman, 2002). Kring and Durda (2003) reviewed some of the consequences of the impact-generated catastrophes that would set off a wave of wild fires to consume Earth's forests. In the immediate vicinity of the crater, the shock wave, air blast and heat produced by the impact explosion would kill many plants and animals. Both Chicxulub and Shiva have been interpreted as low-angle oblique impacts that would prolong global catastrophes (Schultz & Gault, 1990). Like the Chicxulub, the Shiva impact occurred in a shallow sea and immediately lofted rocky, molten and vapourous debris into the atmosphere. The bulk of debris rained down on the Indian continent, but much of it rose all the way to stratosphere, which expanded to envelop the entire Earth. Material then began to fall back under the influence of gravity. The reentering debris heated the atmosphere so severely that it ignited terrestrial forests and plant covers globally. Robertson *et al.* (2004) proposed that infrared thermal pulse from a global rain of hot spherules splashed from the KT impacts was the primary killing agent. According to this model, for several hours following the impact, the entire Earth was scorched with infrared radiation from reentering ejecta that would have killed unsheltered organisms directly and ignited global fires that consumed Earth's forests and their dwellers. Soot and impact-generated dust choked the sky to create perpetual night that halted photosynthesis so that plants and phytoplankton died and food chains collapsed. Other environmental consequences of impact would be ozone layer destruction, toxicity of the environment, acid trauma, nuclear winter, earthquakes and tsunamis. The climatic calamity decimated flora and fauna globally (Alvarez *et al.*, 1980; Anders *et al.*, 1991; Toon *et al.*, 1997; Kring & Durda, 2003).

The trajectory of the Shiva bolide should have driven a fiery vapour cloud toward the northeast, creating a corridor of incineration across east-central India that would reach the Pacific Ocean and even the Gulf of Mexico. Surprisingly, the highest concentration of pure meteoritic debris has been found not around the Yucatan, but in the several KT boundary sites in the North Pacific Ocean (Kyte & Bostwick, 1995). Even a tiny fragment of the killer asteroid, rich in nickel and iridium, has been recovered from this site (Kyte, 1998). The KT boundary Pacific sites lie directly along the trajectory of the Shiva impact (Chatterjee *et al.*, 2006).

If both Shiva and Chicxulub craters were formed simultaneously by splitting of a large asteroid on a rotating Earth (Chatterjee & Rudra, 1996), the two worst places to be affected were India and Mexico where the bolides landed almost in antipodal positions, although combined lethal consequences encompassed the entire globe at different tempo and modes. The killer objects from outer space may have arrived in pairs or even in swarms, perhaps explaining why the KT extinctions seen in the fossil record were uneven in a global context, more severe along the 'Alvarez Impact Belt' near the equator than the two polar regions (Chatterjee & Rudra, 1996; Glen, 1990; Sutherland, 1996).

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