SHIVA STRUCTURE: A POSSIBLE KT BOUNDARY IMPACT CRATER ON THE WESTERN SHELF OF INDIA

SANKAR CHATTERJEE, NECIP GUVEN, AARON YOSHINOBU, AND RICHARD DONOFRIO
Front cover: Cover illustration showing the three-dimensional reconstruction of the submerged Shiva crater (≈ 500 km diameter) at the Mumbai Offshore Basin, western shelf of India from different cross-sectional and geophysical data. The overlying 7-km-thick Cenozoic strata and water column were removed to show the morphology of the crater.
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SHIVA STRUCTURE: A POSSIBLE KT BOUNDARY IMPACT CRATER ON THE WESTERN SHELF OF INDIA

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ABSTRACT

Evidence is accumulating for multiple impacts across the Cretaceous-Tertiary (KT) transition, such as the Chicxulub crater in Yucatan Peninsula, Mexico, the Shiva crater offshore western India, and the much smaller B?tys?h crater in Ukraine. Among these, the submerged Shiva crater on the Mumbai Offshore Basin on the western shelf of India is the largest (~500 km diameter), which is covered by 7-km-thick strata of Cenozoic sediments. It is a complex peak ring crater with a multiring basin, showing a structural relief of 7 km. A ring of peak is surrounded by an annular trough, which is bounded by a collapsed outer rim. Four different ring structures have been identified: an inner ring (peak ring) with a diameter of 200 km, a second 250-km-ring, a third ring (final crater rim) of about 500 km, and a probable exterior elevated ring of about 550 km. The crater outline is irregular squarish with a tapering end to the northeast indicating a possible oblique impact in a SW-NE direction. We speculate that the Shiva bolide (~40 km diameter) crashed obliquely on the western continental shelf of India around 65 Ma, excavating the crater and shattering the lithosphere. The peak ring of the Bombay High area has a core of Neoproterozoic granite with a veneer of Deccan Trap that rebounded upward for more than 50 km during the transient cavity stage as revealed by the mantle upwarping. Pseudotachylyte veins of silica melt are observed within the drill cores of granitic target rock that may be linked to the impact-melting event. The combined Neoproterozoic granite and Deccan Trap target lithologies generated two kinds of impact melt ejecta that were emplaced radially in the downrange direction within the Deccan lava pile: rhyolitic dikes, and iridium-rich alkaline igneous complexes. The age of the crater is inferred from its brecciated Deccan lava floor and the overlying Paleocene Panna Formation within the basin, isotopic dating of the presumed proximal ejecta melts, and the magnetic anomaly of the Carlsberg Ridge that was created by the impact. Concentric geophysical anomalies, thermal anomalies, seismic reflection, and structural and drill core data endorse the impact origin of the Shiva structure. The KT boundary sections in India, often preserved within the Deccan lava flows, have yielded several cosmic signatures of impact such as an iridium anomaly, iridium-rich alkaline melt rocks, shocked quartz, nickel-rich spinels, magnetic and superparamagnetic iron particles, nickel-rich vesicular glass, sandstone spherules, high-pressure fullerences, glass-altered smectites, and possibly impact-generated tsunami deposits. The impact was so intense that its signature spread to nearby areas; it fragmented, sheared, and deformed the lithospheric mantle across the western Indian margin and contributed to major plate reorganization in the Indian Ocean. This resulted in a 500-km displacement of the Carlsberg Ridge and initiated rifting between India and the Seychelles. At the same time, the spreading center of the Laxmi Ridge jumped 500 km westerly close to the Carlsberg Ridge. The oblique impact may have generated spreading asymmetry, which caused the sudden northward acceleration of the Indian plate in Early Tertiary. The central uplift of a complex crater and the shattered basement rocks and overlying sedimentary layers form an ideal structural trap for oil and gas. Many of the complex impact structures and events at the KT transition such as the Shiva crater, Chicxulub crater, and the B?tys?h crater create the most productive hydrocarbon sites on the planet. The kill mechanisms associated with the Shiva impact appears to be sufficiently powerful to cause worldwide collapse of the climate and ecosystems leading to the KT mass extinction when the dinosaurs and two-thirds of all marine animal species were wiped out.
Mass extinctions in Earth’s history are generally attributed to bolide impacts or major flood basalt volcanism that had devastating effects on environment and climate leading to biotic crisis (Glen 1990, 1994). Even though Earth has clear evidence of a long history of extraterrestrial impact events, only the Cretaceous-Tertiary (KT) boundary impact has been studied well enough to find a causal connection between impact and mass extinction. The initial discovery of anomalous iridium (Alvarez et al. 1980), glass spheres (Smit 1999; Smit and Klaver 1981), and shocked quartz (Bohor 1990; Bohor et al. 1984) at the KT boundary sections in many parts of the world was interpreted as the evidence for a large bolide impact. The impact theory was bolstered with the discovery of the Chicxulub crater buried beneath the shore of the Yucatan Peninsula, Mexico. Chicxulub measures about 180-380 km in diameter and matches the predicted size and age of the long-sought KT impact site (Hildebrand et al. 1991, 1995). It has been dubbed “the smoking gun” for the KT impact event that caused the catastrophic biotic crisis. Subsequent work including geochemistry (Blum et al. 1993), radionuclide age of the melt rock from the Chicxulub crater (Swisher et al. 1992), impact ejecta layers (Sessi 1999), and tsunami deposits (Bourgeois et al. 1988) at several KT boundary sections around the Gulf of Mexico lend further support to the hypothesis that Chicxulub does indeed mark ground zero for a colossal bolide impact at 65 Ma.

However, Keller et al. (2003, 2004) have accumulated a large body of evidence from well data within the Chicxulub crater indicating that this crater predates the KT boundary. They suggest that the crater was formed 300,000 years before the KT boundary and was much smaller (<120 km diameter) than originally hypothesized. These authors argue that there are several other craters of the appropriate age incising the 24-km-wide Blythrych crater of Ukraine (Kellely and Gurov 2002), 20-km-wide Silverpit crater of the North Sea (Stewart and Allen 2002), and the gigantic Shiva crater of India (Chatterjee and Rudra 1996) that may support a multiple impact hypothesis for the KT mass extinction (Fig. 1). In this view, the KT mass extinction was caused not by a single bolide, but by a barrage of them (Chatterjee 1997). Doubt has been cast recently on the interpretation of the impact origin of the Silverpit crater, when it was reported that Silverpit might be a sinkhole basin caused by salt withdrawal resulting in a convective array of normal faults (Underhill 2004).

The Shiva crater, located on the western continental margin of India around the Bombay High area, has emerged as a viable candidate for the KT impact site (Chatterjee 1992, 1997; Chatterjee and Rudra 1996; Chatterjee et al. 2003). Straddling the western coastline of India and almost entirely below water, the Shiva structure is located on the Mumbai Offshore Basin (MOB) and is buried by 7 km thick strata of post-impact Tertiary sediments. It has the morphology of a complex crater, with a series of central structural uplifts in the form of a peak ring, an annular trough, and a collapsed outer rim. If confirmed as an impact site, the Shiva crater would be the largest impact crater known on Earth, about 500 km in diameter. The purpose of this paper is to integrate available geological, geophysical, and geochemical data on the Shiva structure and to examine its likely impact origin at KT boundary.

**Location of the Shiva Crater**

The exact location and size of the Shiva structure are controversial because it is largely submerged and buried by thick sediments on the western shelf of India, as well as by thick Deccan lava piles on its eastern margin. Thus, it is inaccessible for direct study. Moreover, the close spatial and temporal coincidence of the Shiva crater with the India-Seychelles rifting event and the widespread Deccan volcanism make it
more difficult to delineate the size and location of the crater.

Hartney (1986) and Alt et al. (1988) proposed that the subcircular Amirante Ridge and its enclosed basin southwest of Seychelles, might be the western rim of a possible impact crater, but its eastern rim lies along the western coast of India, hidden by the overlying Deccan Traps. They proposed that the force of the impact was so powerful that it could have cracked the lithosphere, such that the Deccan Traps represent impact-related melts that filled the crater to form an immense lava lake, the terrestrial equivalent of a lunar mare.

Chatterjee and Rudra (1996) elaborated upon this impact site at the India-Seychelles rift margin, and identified the eastern half of the crater at the Mumbai Offshore Basin (MOB), where the crater is bounded by the Panvel Flexure near the Mumbai coast and the Narmand Fault in the western Arabian Sea. They reconstructed the size and shape of the impact structure by incorporating the Amirante arc and named it Shiva crater after the Hindu god of destruction. They proposed that the Carlsberg rifting, which might be triggered by the impact itself, splits the Shiva crater into halves and separated India from the Seychelles. Today, one part of the crater is attached to the Seychelles, and the other part is attached to the western coast of India.

Chatterjee and Rudra (1996) argued that if the Amirante Basin were indeed the western rim of the Shiva crater, the Mahe granite on the Seychelles, which superficially looks like a shatter zone chaotic assemblage of gigantic blocks (Baker 1967), should bear some sign of an impact such as shock metamorphism. However, detailed analysis of the Neoproterozoic Mahe granite failed to detect any shocked quartz (A. Gilkinson, pers. comm.). Moreover, radiometric ages from the
The western continental margin of India is an Atlantic-type passive margin, differentiated into four structural and sedimentary basins from north to south: the Kutch, Mumbai, Konkan, and Kerala Offshore basins containing large oil and gas fields (Biswas 1987). The Shiva crater, located on the Mumbai Offshore Basin, was discovered in 1974 using seismic data and is bounded by several fault and rift systems. The stratigraphy, structure, tectonic framework, geophysical characteristics, 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 Commission (ONGC) of India and described in several reports (Bastu et al. 1982; Bhandari and Jain 1984; Biswas 1987; Mathur and Nair 1993; Mehrotra et al. 2001; Rao and Talukdar 1980; Zotholi et al. 1995). Our interpretation of the Shiva crater is largely based on the published literature by the workers of the ONGC.

![Diagram](image-url)
Impact structures are recognized by their crater morphology and by the physical and chemical effects of impact. Terrestrial impact craters appear to display a regular progression of crater morphology from small simple craters, through complex central peaks and peak-ring craters, to large multi-ring crater basins (Grieve 1990; Melosh 1989). A simple crater is a bowl-shaped depression with a raised rim, as illustrated by the Barringer crater in Arizona; it is generally less than a few kilometers across. With increasing diameter (~1 km across), a complex-type crater develops, with a distinct central peak, annular trough, and a collapsed outer rim. As crater size increases, a peak ring, typically an irregular ring of hills and mounds that lacks prominent asymmetric bounding scarps, replaces this central peak. With further increase in crater size, peak ring craters evolve into multiringed basins, as commonly seen on the surfaces of the Moon and Venus.

The Shiva structure has an irregular shape, more squarish than circular like the Barringer crater, with a diagonal of 500 km, and is defined by large peripheral boundary faults. Melosh (1989) explained how joints, faults, and planes of weaknesses in the target rock, as well as the angle of impact, could modify the crater shape from typical circular to various shapes, such as rectangular, elliptical, polygonal, multiring, and abrunt basins. The unusual squarish shape of the Shiva structure possibly reflects an intersecting set of boundary faults (Fig. 3).

We interpret the morphology of the Shiva crater as a complex multiringed basin, defined by the collapsed outer rim in the form of faulted margin with an elevated rim around the perimeter. The eastern border of the crater lies on the Indian continent and is bordered by the Pandel Fault, whereas the northern border is limited by the Narmada Fault in the Arabian Sea (Chatterjee and Rodhe 1996); the Kori Arch bounds the western border, and the Ratnagiri fault delineates its southern border (Fig. 3). The crater rim is followed inward by the annular trough, which was largely filled with thick Cenozoic sediments. The annular trough is preserved in the shape of the Surat Depression, Saurashtra Depression, Shelf Margin Depression, Murad Depression, and the Panha Depression. An inner concentric ring comprised of irregular mountain peaks on the Bombay High-Deep Continental Shelf (DCS) block replaces the central peak. It is separated from the annular trough by a circular thrust fault. The inner peak ring diameter is about 200 km, roughly half the rim-to-rim diameter of the crater. Such peak-ring craters have been recognized on the Earth, Moon, Mars, and Mercury, with similar morphology and similar diameter of the inner and outer ring ratios (Melosh 1989). The peak ring consists of several subsurface mountains including the Bombay High, Maka High, Panha-Bassein High, Heera High, and several other unnamed peaks, which stand several kilometers above the surrounding basement. Based on seismic data and well data each peak consists of a core of Neoproterozoic granite, which was overlain by a veneer of Deccan trap and thick Cenozoic sediments (Fig. 3).

In addition to its peak ring, at least three different ring structures have been identified. A circular faulted rim with a diameter of 250 km borders the peak ring that probably marks the position of the transient cavity rim. From this second rim, the beginning of the annular trough can be seen outwardly, and it is filled with 7-km-thick Cenozoic sediments. A third ring, about 500 km diameter, represents the outer faulted rim of the crater. This is bordered by a raised margin represented by the Saurashtra Arch, Kori Arch, and the Ratnagiri Arch in the Arabian Basin, which may represent the fourth ring. If the outermost fourth ring with a topographic high locates the final crater rim, the Shiva has a crater diameter of 550 km instead of 500 km (Fig. 3).

It is generally accepted that multi-ring basins result from very large impacts, but the mechanism by which they form is being debated (Melosh 1989). Most of what is currently known about multi-ring basins is based on remote-sensing studies of the Moon, Mars, and Mercury. If our interpretation is correct, Shiva is the most pristine and largest impact crater known on Earth and one of four known multi-ring terrestrial craters with the Vredenfort, South Africa, Sudbury, Canada, and Chicxulub, Mexico craters being the other three.

Mather and Nair (1993) provided a series of stratigraphic cross-sections of the Mumbai Offshore Basin across the Bombay High field. Two of these cross-
Figure 3. 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 multi-ringed 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 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 ring (Ring 2), with a diameter of 250 km, and is bordered by the annular depression consisting of several basins such as Panna Basin, Surat Basin, Saurashtra Basin, Shelf Margin Basin, and Murad Basin, where the crater fill Cenozoic sediments excised 7 km in thickness. The annular basin is bordered by the faulted crater rim (Ring 3), about 500 km, consisting of Panvel Flexure, Narmada Fault, Shelf Margin Fault, and the 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 Figure 4. The epigamic Laxmi Ridge, a continental sliver about 700 km long and 100 km across in the Arabian Sea, lies west of the Shiva crater (modified from Chatterjee and Rudra 1996; Mathur and Nair 1997; Talwani and Reif 1998; Zutshi et al., 1999).
sections, N-S and E-W across the Bombay High, are shown in Figure 4, where the overlying Tertiary sediments were removed to expose the topography of the floor of the Shiva crater. The structural relief of the crater, from the lowest to the highest point of the central peak, exceeds 7 km at Saurashtra Basin in the northwestern corner of the crater (Mathur and Nair 1993).

Seismic stratigraphy and well drilling have identified the basement rock as the volcanic lava flows of the Deccan Traps that forms the undulating basin, with few lenses of Neoproterozoic granite that form the ring peaks of the Shiva crater. Apparently, the target rocks were both Neoproterozoic granite and the overlying Deccan Trap. The thickness of the Neoproterozoic basement rock, the Deccan lava floor, and the Deccan Trap breccia unit within the crater are unknown from published accounts. Thus, the total vertical rebound of the central peak cannot be estimated at the moment. The uplift in the center of a complex crater amounts to about one tenth of the crater’s final diameter (Grieve 1990). Thus, the uplift associated with the 500-km-wide Shiva crater is estimated to be 50 km. Geophysical anomalies indicate that the lithospheric mantle in this region has been considerably fragmented, sheared, and deformed around Shiva crater, whereas the crust-mantle boundary has been uplifted more than 50 km. These unusual geophysical anomalies, discussed later, have been attributed to an impact event and indicate the amplitude of the uplift (Pande and Agarwal 2001). The crystalline rocks beneath the Shiva crater are shattered and brocket to a great depth, inferred from seismic velocity beneath the crater and low gravity anomalies (Rao and Talakdar 1980; Srivastava 1994).

Figure 4. Cross-sections across the Shiva crater to show the relief of the crater basin; the overlying Cenozoic sediments were removed (see Figure 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 Mathur coast (modified from Mathur and Nair 1993).
The subsurface stratigraphy of the Shiva crater is known primarily from petroleum exploration of drill holes and geophysical anomalies data (Basu et al. 1982; Bhandari and Jain 1984; Mathur and Nair 1993; Rao and Talukdar 1985; Wadaney 2004; Zutshi et al. 1993). The sedimentary fill in the depocenter consists of nearly horizontal strata of Cenozoic sediments, Paleocene to Holocene, in age, representing a typical shallow marine shelf sequence exceeding 7 km in thickness. The basin accumulated large volumes of shallow marine carbonates, shales, siltstones, and sandstones. Thick piles of Early Eocene to Middle Miocene carbonate sediments dominate the lithology of the basin. These depositional environments fluctuated but prevailed until the Holocene. Presence of larger benthic foraminifera in parts of the Cenozoic sections and lack of planktic forams suggest a warm, shallow-water marine or lagoonal environment in the crater basin. The Cenozoic formations of the crater basin include in ascending order, the Panna, Bassein, Ali Bug, Ratnagiri, and Chinchini. Zutshi et al. (1993) provided the seismic stratigraphy of this crater basin. It shows five seismic reflection marker beds, designated from bottom to top as H5, H4, H3, H2, and H1 (Fig. 5). The H5 seismic horizon is reflection-free, chaotic zone, probably representing the highly fractured floor of the crater basin consisting of Deccan Trap basalts and Neoproterozoic granite. The H4 seismic horizon coincides with the top of the Panna Formation.

The Panna Formation, the lowest unit of Tertiary sediments, lies unconformably on a thick layer of breccia embedded in reddish claystone and siltstone, referred to here as the ‘Deccan Trap Breccia.’ The breccia unit, in turn, overlies either the Deccan lava pile or the Neoproterozoic granitic basement of unknown thickness. Since the age estimates for the Deccan lavas in western India cluster around 65 Ma (Courtillot 1990; Duncan and Pyle 1988), it is suggested here that the Deccan Trap Breccia unit, sandwiched between the Early Paleocene Panna Formation and the Deccan Trap, indicates impact-related sedimentary deposits at the KT boundary.

The Panna Formation, overlying the KT boundary sequence, is composed of poorly sorted, angular sandstone and chert at the bottom followed by shale, limestone, and coal sequences. This unit is relatively thin on the central uplift, but becomes relatively thick on the flanks (~75 m). Seismic data indicate this formation to be as thick as 500 m in the deeper part of the basin in the annular trough, such as the Saurashtra basin. Although the Panna Formation is mostly unfossiliferous, it has yielded Globorotalia pseudoconomendrula from the middle of the sequence corresponding to the P4 planktic foraminiferal Zone of the Late Paleocene (Basu et al. 1982). The occurrence of nummulite fossils such as Nummulites dewerti and Asollina spinosa also support similar Thanetian age of the Late Paleocene (Rao and Talukdar 1980). However, recent biostratigraphic analysis suggests that the lower part of the Panna Formation may extend to the Danian Stage of the Early Paleocene (Zutshi et al. 1993).

The available stratigraphic information is consistent with the formation of the Shiva structure at about 65 Ma. The lack of Cretaceous or older sediments clearly indicates that the crater basin was formed at post-Cretaceous time. The Deccan Trap breccias may be linked to the impact event, followed by the deposition of Early Paleocene Panna Formation. The two units bracket the age of the crater basin at the KT boundary interval. Earlier workers (Basu et al. 1982; Biswas 1987; Zutshi et al. 1993) reached a similar conclusion regarding the KT boundary age for the structure of the Mumbai Offshore Basin. A radiometric age (~65 Ma) of the crater formation is provided by the impact melt rocks as discussed later.

**Evidence of Impact within a Crater Basin**

In addition to the complex crater morphology, direct and indirect evidence within the crater basin is compatible with the hypothesis that the Shiva structure was created by a bolide impact. Most ejecta from the impact cratering processes are emplaced ballistically by the flight of the debris expelled from the cra-
ter interior. However, some ejecta from the crater wall and rim slump back to the angular trough and form important crater filling units. The Shiva impact basin have produced enormous volumes of crater-filling units, such as impact breccias and impact melts. Because much of the soil covers from the crater basin are proprietary, the nature and extent of the crater-filling ejecta and melt cannot be determined at this stage. The basement rock of the basin is often interpreted as the Deccan Trap. Could it be actually impact melt rock? Without further petrographic analysis two alternatives cannot be tested. We believe that the impact was so intense that lava-like fluid ejecta bodies were emplaced radially within and outside the crater, but their relationships, compositions, distributions, and relative stratigraphic positions suggest possible relationships to stages of crater excavation and collapse. Impact lithologies such as breccias and impact melt rocks are physical and chemical mixtures of pre-existing target lithologies. From the lithology of the floor of the Shiva crater it appears that the target rock was composite: the Neoproterozoic crystalline basement overlain by the older flow of the Deccan Trap.

**Deccan Trap Breccia** — Impact on a continental target rock generally preserves a thick sequence of crater-filling ejecta units such as in the Ries crater of Germany (Hörz 1982) and the Manson crater in Iowa.
Brecias associated with the Ries crater of Miocene age are probably the best-studied impact deposits presently known. Two general types of impact-related deposits are known from Ries: (1) the Bunte Brecia comprised predominantly of clasts of sedimentary target materials; and (2) suevites, containing clasts of crystalline basement rocks and impact-melt rock. A large impact on an oceanic shelf is quite different from a continental target impact because it would generate a megatsunami where water flow in and out of the crater cavity would remove much of the ejecta components from the basin. In oceanic impacts some of the fall-out breccia is re-erected back into the crater basin. This is why the crater-filling ejecta in the Chixualuah and the Shiva are not significant. Emplacement of this breccia within the crater basin involved dynamic processes related to transient crater formation and collapse and to early post-impact filling (Grieve 1990). The Deccan Trap breccia at the base of the Panna Formation is a sedimentary-clast breccia, dominated by fragments of Deccan Traps and their weathered products in the form of clay matrix (Fig. 5). However, the thickness and composition of the breccia are not known (Bau et al. 1982). Unfortunately, this breccia unit has never been investigated for cosmic signatures such as iridium anomalies, shocked quartz, spherules, and impact melt rocks.

Deccan Traps/Impact Melts at the Floor of the Shiva Basin.—During large impact cratering processes, postshock temperatures are sufficiently high to cause whole rock melting of the target, leading to the formation of impact melts within the crater basin (Grieve 1998). The peak ring of the Shiva crater is underlain by elevated volcanic rocks referred to as “Deccan Traps” (Bau et al. 1982) that lie between the breccia unit and the Neoproterozoic granite (Fig. 5). Boreholes drilled by ONGC within the Shiva crater have penetrated thick (~7 km) Tertiary sediments, and at places the underlying basalt is known, based on seismic data, to be over 4 km thick (Mahadevan 1994). In contrast, the greatest thickness of the Deccan Trap in Indian subcontinent is about 3 km in the Western Ghats section. We speculate that such a thick lava pile (~4 km) in the crater basin may indicate impact-generated melt sheet rather than lavas of the Deccan volcanics. Petrographic analysis of the core samples may settle the genesis of this enigmatic lava sheet in the future.

Pseudotachylite.—Pseudotachylite is a dark, fine-grained rock that resembles volcanic glass. It forms in characteristic high strain rates such as seismic events (e., Sibun 1975) or bolide impacts (Fiske et al. 1995) where many variables including lithology, pore-fluid pressure, ambient temperature, and strain rate act to generate melt phase during the event. The morphology of impact-generated pseudotachylite is defined by mm-scale vein networks of dark glass in contrast to the larger (cm-scale), anastomosing lenses that occur in seismically related fault zones (e., Fiske et al. 1995). Impact-related pseudotachylites were first described in association with the Vredefort crater in South Africa, where they were interpreted to be produced by shock compression and release during impact and also providing the timing for the impact event (Reimold 1995). Cores of Neoproterozoic granitoid rocks (target rock) derived from petroleum exploration drilling under the Bombay High area contain evidence for cataclasite (rock pulverization) and probable pseudotachylite veins. Petrographic studies of two samples display deformed veins 400-1000 microns thick of aphanitic, micro- to cryptocrystalline material that intrudes into feldspar crystals within a mylonitized feldspathic gneiss (Fig. 6A, 6B). 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., McNulty 1995). SEM images and Energy-dispersive X-ray spectra (EDXS) indicate that the composition of the pseudotachylite is pure silica glass (Fig. 6C). It is likely that the silica melt rock is the result of shock pressure induced by the Shiva impact.

Bètolic Dikes.—Melt rocks, which are created by strong shock waves that emanate from the site of the impact, are very common near large impact craters. We hypothesize that two distinct impact melt rocks coexist in and around Shiva crater—“white” and “black” impact melts—because of involvement of two distinct target lithologies: Neoproterozoic granite and Deccan Trap. The former gave rise to “white” hyotlite dikes that are more restricted in distribution due to high viscosity and confinement within the crater ba-
Figure 6. Pseudotachylite vein in the basement granite drill core from the Shiva crater. A-B, thin section micrographs of basement granite (crossed nicsols), showing thin vein of pseudotachylite cutting across K-feldspar grain. The granite hosting the pseudotachylite is strongly shock metamorphosed by the impact. C, SEM photograph of the basement granite showing the highly magnified view of the pseudotachylite vein containing pure silica melt. The impact was so powerful (>100 GPa) that it obliterated the PDFs of shocked quartz grain and turned it into a melt component.
sin; the latter is more extensive because of low viscosity with meteoritic contamination and represents the 'black' alkaline igneous complexes that were emplaced outside the crater rim as fluid ejecta noted in lunar craters; both kinds of melt rocks were emplaced within the Deccan Traps (Fig. 7). Similar bimodal impact melt rocks are known from the Wabar crater, Saudi Arabia (Hötz et al. 1989).

The Deccan lava pile obscures the floor of the Shiva crater from observation on the continent near the Mumbai coast, west of the Panvel Flexure. It is thickest along the Western Ghats region (~2000 m) but thins progressively inward in an eastern direction. Considerable volumes of acid and basic tufts, and rhyolite and trachyte lava dikes associated with the Deccan lava pile, occur within the crater basin along the Mumbai coast. But their origin is still debated, ranging from partial melting of the granite basement rock (Selvam 1989) to partial melting of basic rocks (Lightfoot et al. 1987). Direct derivation of these rhyolite and trachyte dikes from the mantle would appear to be precluded by their silica-rich nature. The ages of these felsic dikes straddle the ~65 Ma KT boundary (Sheth and Ray 2002) and may have erupted in response to impact melting of the basement target rock. The Neoproterozoic granite appears to be the target rock as indicated by geophysical anomaly indicating the presence of unusually thin crust in the Mumbai area with missing granitic layer. The pseudotachylite veins observed within the drill core samples of the Neoproterozoic granite may be genetic and temporal extension of the rhyolite dikes.

Geophysical Anomaly.—The western coast of India, though a passive plate margin, is seismically very active, indicating large-scale geodynamic instability (Ramalingeswararao 2000). This part of the Indian plate has been associated with several major geodynamic and tectonic events at the KT boundary time, including Deccan volcanism, impact, continental breakup, and seafloor spreading. Although extensive geophysical investigations have been carried out by the ONGC around the Bombay High because of oil

Figure 7. A, 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 rind 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. B, artificial crater produced by low-angle (~35°) oblique impact in the laboratory mimics the shape and fluid ejecta distribution of the Shiva crater (simplified from Schultz and Gault 1990).
exploration, very few data have been published. One
of the rare published accounts is the satellite-derived
gravity data over the Bombay High area, which can be
found in the annual report of ONGC (Srivastava 1996).

The geophysical expression of the Bombay High area
is similar to the central peak ring in other large impact
craters (fig. 8). The most notable geophysical signa-
ture associated with terrestrial impact structures is a
negative gravity anomaly (Grieve 1998; Pilkington and
Grieve 1992). Fracturing and brecciation of hundreds
of meters of basement rocks inside the impact basin
caused by the impact, produce a characteristic nega-
tive gravity anomaly at the central peak reflecting a
mass of low-density material. These gravity lows are
generally circular and typically extend to, or slightly
beyond, the outer rim of the structure.

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
center 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 west-
ern rim of the crater. The cause of the high gravity
anomaly near the Mumbai coast is discussed in a later
section. The negative anomalies around the peak-ring
correspond to the relatively low densities of the up-
lifted core of the lighter Neoproterozoic granite, over-
lain by the Tertiary sediments filling the crater. They
may also reflect mass deficiency such as fractured
crystalline basement rock beneath the crater. We
speculate that the central peak-ring of the Shiva crater
consisting primarily of Neoproterozoic granite sur-
rounded by the detser Deccan Trap basalt, may ex-
plain the gravity gradient within the crater.

The most striking gravity feature near the Mumbai
coast is the high Bouguer anomaly that may be linked
to a large intrusive of alkaline igneous complex of im-
 pact melt, called the 'Napai' structure (Chatejee and
Rajm 1996), which is about 12 km high, has a maxi-
mum diameter of 35 km at the base, and is linked to
the impact (Negi et al. 1993; Pandey and Agarwal 2001).
In this region, the Panvel Flexure, an arcuate feature
that bounds the eastern rim of the crater, is about 120
km long and formed around 65 Ma (Seth 1988). It is

Figure 8. Satellite-derived gravity over Shiva crater from closely
spaced repeat passes of ERS-altimeter shows a distinctive low
gravity anomaly (-5 mgal) over the central peak ring; it gradually
rises toward the crater rim (+40 mgal) as in other impact craters
(modified from Srivastava 1996).
marked by a line of hot springs, dikes, deep crustal faults, and seismicity, where the floor of the crater slopes westward toward the shelf edge basin (Kaila et al. 1981). It experiences a tectonic control on the attitude of the Deccan lava pile. To the east of the flexure, the basaltic flows are horizontal; to the west of the flexure, the basaltic flows dip west to west-southwest at 50°-60° toward the coast. The abrupt change of dip along the flexural axis may indicate the slope of the crater wall, which is concealed by the thick Deccan lava flows (Fig. 9) (Chatterjee 1992).

Geothermal Anomalies.—Pandey and Agarwal (2001) studied in detail the gravity, geothermal gradient, and heat flow distribution beneath the western continental margin of India around the Mumbai coast. They estimated the average heat flow at the eastern margin of the crater, which lies on the continental crust but is covered by a thick pile of Deccan lava, to be very high (>80 mW/m²). They conclude that the lithospheric mantle beneath this part of the Shiva crater has been considerably thinned, thinned, deformed, and weakened due to mantle upwelling with a missing granitic layer (Fig. 9). They attributed this anomalous high heat flow and mantle upwelling to a possible cataclastic and geodynamic event around 65 Ma, such as the Shiva impact. The uplift of the geotherms accompanying the collapse of the giant Shiva crater might lead to pressure release melting of deep mantle/diamond-layer and create the large Deccan igneous provinces. Elkins-Tanton and Hager (2005) proposed a model for impact-triggered Deccan volcanism in which the cratered lithosphere could rise isostatically into a dome (Fig. 9), as seen in the west coast of India, warp-

![Figure 9. Schematic diagram of the eastern part of the Shiva crater near Mumbai coast to show the upwarping of the mantle more than 50 km and the possible deformation and destruction of the lithosphere because of Shiva impact; on the right side of the diagram, east of Mumbai, thick Deccan lava pile was removed to show the floor of the Shiva crater (modified from Kaila et al. 1981; Pandey and Agarwal 2001).](image-url)
ing isotherms at the lithosphere/asthenosphere boundary, in which adiabatic melting could occur.

The mantle upwelling zone at the Munsaleh coast does not coincide axially with the crater peak ring, but is displaced more easterly toward the coast. We attribute this offset of the thermal anomaly at due to an oblique impact event (discussed later) where the eastern rim of the crater was more severely affected because of the downrange direction of the bolide trajectory; this view also is supported by the asymmetric distribution of the fluid ejecta (Chatterjee and Radzi (1996). Existence of two such gravity anomalies of opposite nature, one above the peak ring, the other nearly above the crest of the mantle upwelling separated by a distance of only 160 km, is intriguing and suggests complex geodynamic activity due to an oblique impact and its unequal stress distribution in the lithosphere in the region.

AGE OF THE DECCAN TRAPS

Very rapid emplacement of the Deccan traps has been one of the key arguments for its catastrophic role in the KT mass extinction. The outpouring of the enormous continental flood basalts of the Deccan Trap, spreading over vast areas of western and central India and the adjoining Seychelles microcontinent covering more than 1,500,000 km², also marked the close of the Cretaceous time (Figs. 7, 10). The lava pile is the

Figure 10. Paleoposition of India-Seychelles during the KT boundary time showing the location of KT boundary sites around the Deccan volcanic province (grey circles). The KT boundary sites containing cosmic ejecta in India, from west to east are: Anjar, Gujarat; Barmer, Rajasthan; Jabalpur, Madhya Pradesh; Um Sobhynkew, Meghalaya; and Artyur, Tamil Nadu (modified from White and McKenzie (1989) and other sources).
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. Chatterjee and Radh (1996) reviewed the age of the Deccan traps on the basis of geochronologic, paleomagnetic, and paleontologic constraints. 

"Ar-"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 (Courtillot 1990; Courtillot et al. 1988; Duncan and Pyle 1988; Hofmann et al. 2000; White and McKenzie 1989). Thus this enormous volcanic mass had been laid down in less than 1 Kyr. Paleomagnetic studies in the thick Western Ghats section indicate that Deccan volcanism began during the 30N magnetic chrons, climaxd during the following reversed interval 29R at the KT boundary, and ended in the 29N chrons (Courtillot 1990).

In marine section, the lowest level of Deccan lava tests on a sedimentary layer that contains the typical Late Maastrichtian index foraminiferal fossil *Axonophrus mayaramensis*, which thrived close to the KT boundary and then disappeared. It thus appears from the combined evidence of radiometric dating, paleomagnetic evidence, and fossil studies, that the estimated duration of Deccan volcanism is about 900 Kyr around the KT boundary (Fig. 11).

![Diagram of stratigraphy and geologic events related to the KT boundary](image)

**Figure 11.** A synthesis of paleomagnetic, paleontologic, and geochronologic data from the Deccan Trap lava pile showing the stratigraphic position of the KT boundary and its relationships with the intertrappean beds such as Langhian Formation. Various cosmic signatures, such as iridium anomaly, high-pressure fullerences, shocked quartz, Ni-rich spinels, magnetic nanoparticles, ejecta deposits, and dust ejecta have been found from different KT boundary sections of India, which are linked to the Shiva impact (modified from Courtillot 1990; Chatterjee and Radh 1996).
The Deccan lava flows were not extruded all at once; volcanic activity was punctuated periodically when sedimentary beds were deposited between the flows. These fluvial and lacustrine deposits are called intertrappean beds that contain abundant remains of plants, invertebrates, fish, frogs, crocodilians, turtles, dinosaurs and their eggs, and mammalian teeth (Chattarjee and Radhakrishnan 1996). Many of these KT boundary sections are located within the intertrappean sediments layers, which are sandwiched between two Deccan flows. Thus, KT boundaries in India are well-constrained stratigraphically and can be recognized by paleontologic evidence, radiometric age of the lava flows, and cosmic signatures. Impact debris contains variable concentrations of projectile and target materials that can be shocked, melted, or vaporized. Presumably, evolution of impact ejecta can occur over extended periods of time as these materials are transported, deposited, and interact with each other and the atmosphere.

Distributions of Shiva Ejecta at the KT Boundary Sections

There are several KT boundary (KTb) sections in India, particularly in and around Deccan volcanic province, which have yielded several cosmic marker horizons attributed to Shiva impact. The oblique impact of Shiva in a SW-NE trajectory caused multi-staged emplacement impact. Seven types of material have been interpreted as distal ejecta from the Shiva crater. They include fluid ejecta, shocked quartz, iridium anomalies, highly magnetic nanoparticles, fullerences, glass spherules, and Ni-rich spherules, which are believed to have come from different sources of the impact site. Iridium, Ni-rich spinel, magnetic nanoparticles, and high-pressure fullerences probably came from vaporized meteorites, shocked quartz from uneroded basement granite, whereas ejecta layers and fluid ejecta came from the melted components of target rocks. In addition, impact-generated tsunami deposits have been recognized in the Ariyalur section of Tamil Nadu. The widely separated KT boundary sections are difficult to recognize in the field because distal ejecta marker beds are usually represented by thin stratigraphic horizons. Notable KT boundary sites in India containing evidence of impact ejecta horizons from west to east are: (1) Anjar section, Gujarat; (2) Vadnagar section, Rajasthan; (3) Jabalpur section, Madhya Pradesh; (4) U. Th. Sthanekw section, Meghalaya; and (5) Ariyalur section, Tamil Nadu (Fig. 10). Of these, the Anjar, Barmar, and Jabalpur sections are continental and are associated with the Deccan volcanic plume, whereas U. Th. Sthanekw is marine, and the Ariyalur section is mixed. These KT boundary sections with their ejecta components are described below along with the Deccan Traps.

Proximal Fluid Ejecta.—One of the most important effects of a large impact is the sudden conversion of nearly all of impactor's kinetic energy into heat to produce a vast volume of impact melts. Ejekins-Tanton and Hager (2005) postulated three stages in the impact process that can create melt: (1) initial impact causes shock melt; (2) excavation of material from the impact site can cause instantaneous decompression melting beneath the impact site; and (3) development of a dome in the lithosphere-asthenosphere boundary either through instantaneous liquid flow of the shocked lithosphere or through later isostatic rebound. In the absence of Shiva crater in India, we can identify all three stages. We propose that the post-Deccan alkali igneous complexes represent the initial shock melt, which was emplaced radially as fluid ejecta. The bulk of the Deccan Traps, which erupted right at the boundary, likely represent the second stage, the decompression melting process. The lithosphere-asthenosphere dome on the east coast (Fig. 9) adjacent to the Shiva crater probably represents the fluid stage of the impact-triggering process.

The impact-melt volumes generated from the 500-km diameter Shiva crater estimated from the crater scaling of Grieve and Cintala (1992) would be enormous, close to 10 km³. These lava-like impact melts are very common at lunar craters and are emplaced downrange outside the crater rims (Howard and Wilshire 1975). Asymmetric distribution of fluid ejecta downrange indicates an oblique impact event. Lava-like fluid ejecta outside the crater rims are rare on terrestrial craters, presumably because of their relatively
One of the intriguing features associated with the Deccan flood basalt volcanism is the occurrence of several post-theorite alkali igneous complexes of neomarine-carbonatitic affinities along the rims of the Shiva Crater (Fig. 7). 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 theotheritic lavas (Bose 1980; De 1981). Basu et al. (1989) have recognized two pulses of eruption of these igneous complexes—early and late phases; one is pre-Deccan, the other is post-Deccan volcanism. They have shown that the Mundwara-Sauru alkali igneous complexes, which are far outside these post-Deccan intrusions, were erupted at 68.5 Ma, which is about 3.5 Ma before the main phase of the Deccan eruption. These pre-Deccan alkali complexes have high 3He/4He ratios indicative of a primitive origin. However, most of the spectacular plug-like alkali igneous complexes such as Anjar, Kadi, Jalwar, Phaneri Muta, Amba Dongar, Bahwa, Murad, and Napsi structure post-Deccan (Fig. 7a) with clearly defined zones of gravity highs (Biswa 1988). They probably represent magma fluidic events. The asymmetric distribution of fluid ejecta of these alkali igneous complexes indicates a trajectory of the Shiva bolide from the SW to NE. Recent 40Ar/39Ar dating of some of these alkali igneous complexes indicates 65 Ma, precisely coinciding with the KT boundary (Basu et al. 1993; Prade et al. 1988). Chatterjee and Rodda (1996) speculate that these volcanic plugs represent the fluid ejecta of the Shiva impact in the down range direction. Schultz and O’Hearn (1996) described similar asymmetric distributions of fluid ejecta resulting from an oblique impact that flowed down range at a distance more than the crater diameter (Fig. 7b).

There are several features that suggest the impact origin of the alkali igneous complexes. First, Deccan lavas are poor in iridium content (~10 pg/g), but these post-Deccan alkali complexes are enriched with iridium (~178 pg/g) (Shukla et al. 2001) and show evidence of crustal contamination (Basu et al. 1993; Paul et al. 1977). We speculate that the target rock for these alkali igneous complexes were both early phases of the Deccan Traps and crystalline basement granites, which were melted and contaminated by the impact event as indicated by high Ir/Idima anomalies. Similar meteoritic contamination of impact melts is known from the Woman crater, Saudi Arabia (Hötzl et al. 1989). Second, impact melt rocks have higher K/Na ratios than the target rocks (Grieve 1987) as in the case of these alkaline igneous complexes. Third, the asymmetric radial distribution pattern of these alkali complexes around the Shiva crater is expected in the downrange direction of fluid ejecta (Fig. 7). Fourth, they have restricted distribution and occur within Deccan volcanics as post-theorite 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.
rich in iridium concentrations as high as 178 pg/g (Shukla et al. 2001) and are interpreted as impact-generated fluid ejecta. The association of high-pressure, high-temperature forms of buckyball fullerenes, with high iridium concentrations, is a good indicator of an extraterrestrial impact, whereby the contaminated fluid ejecta in the Anjar section indicates proximate impact site. The occurrence of multiple levels of enriched iridium and fullerenes in the Anjar section is puzzling. It may indicate either multiple impact events at the KT boundary as discussed earlier (Chatterjee 1997; Keller et al. 2003), where the Br-3 layer may correspond with the Chicxulub impact event and Br-1 may coincide with the Shiva impact. Alternatively, three iridium layers may indicate reworking of the upper basaltic flow F4 due to secondary processes such as downward fluid mobilization in the Anjar area (Courtillot et al. 2000). However, Parthasarathy et al. (2002) discount this reworking hypothesis. Since iridium and fullerenes are insoluble in water it is unlikely that their coexistence in three different layers, separated by thick sediments, is due to fluid mobilization. These three iridium layers appear to be primary ejecta layers in situ deposited in quick succession from different va-
porized meteoritic sources from different sites. If so, the Anjar section may hold the crucial evidence for three distinct episodes of global impact events during the KT transition. Similarly at the KT boundary section in Oman, two distinct iridium anomalies, separated by more than 1 m-thick sediments, mark the pre-KT and KT impacts (Ellwood et al. 2003). The Oman KTB section provides further proof of multiple impacts. There is growing evidence that multiple impacts occurred at the KT transition, including Chicxulub, Shiva, and Beloye, which may correspond to the multiple iridium layers (Chastain 1997; Keller et al. 2003) (Fig. 1).

Recently, Bhandari et al. (2002) reported association of nanoparticles of magnetic and superparamagnetic iron oxide plates with iridium from the KT boundary section of the Anjar, which are attributed to impact origin. Apparently these nanoparticles probably formed during condensation of the high-temperature impact vapor plume. Meteorites in general have high concentrations of iron (≤20%) in the form of silicates, metal, magnetite, and other iron-bearing minerals. Bhandari et al. (2002) reported similar cosmic magnetic particles from KT boundary sections of Meghalaya and other parts of the world.

Barmer KTB Section, Rajasthan—A thin (≤4 cm) unconsolidated layer of siliceous deposit at the KT boundary section of Barmer Basin, Rajasthan, in association with early phase of the Deccan volcanism, contains several distinct ejecta components, such as Ni-rich vesicular glasses, sandine spherules, shocked magnetite ferriolite spines, and soot (Siddodia et al. 2005). The siliceous deposit unconformably overlies the Late Cretaceous shallow marine Fategarh Formation and is overlain by the Akli Formation of Paleocene-Eocene age (Fig. 12B). The igneous intrusive rocks within Fategarh Formation have yielded radiometric age ranging from 68 to 65 Ma, close to the KT boundary age (Basu et al. 1993). Siddodia et al. (2005) recognized glass shards, quartz beads, terrigenous, hollow spheroids, and other melt ejecta components from this bed under microscopic examination. They point 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. They interpret this siliceous 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 sandine spherules and skeletal magnetite ferrite are petrographically very similar to those found around the Gulf of Mexico associated with the Chicxulub crater (Smit 1999). Magnetite ferriolite spinel crystals from the Barmer section occur as micrometer-sized skeletal forms. Their composition, small size, and skeletal morphology suggest they are condensation products of a vaporized bolidic (Bohor 1990). Similarly, sandine spherules from the Barmer section also indicate a large impact event (Smit and Klaver 1981). We believe that the boundary layer at the Barmer section is impact-related because it is rich in Ni-rich glass spherules, sandine spherules, and skeletal magnetite ferriolite as seen in other KTB sections; we discount the volcanic origin proposed by Siddodia et al. (2005) because it lacks a coherent assemblage of volcanic crystals such as xenoliths and xenocrysts, which are common in ash-flow tuffs (Jezel 1990). Thus the ejecta components from the Barmer section may imply remnants of hot, early ejecta from the nearby Shiva impact.

Jabalpur KTB Section, Madhya Pradesh—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. The Lameta Formation has yielded various Late Maastrichtian dinosaurs such as abelisaurids and titanosaurians (Chatterjee and Rudra 1996). Chatterjee (1992) reported iridium levels of 0.0 ppb in the uppermost sandstone unit and similar levels at lower Lameta marls (Figs. 14, 15A). It is noted that this level of iridium is low by one to two orders of magnitude compared to levels reported from other KT boundary sections (Alvarez et al. 1980). The low value may indicate percolation of mobile iridium components through porous sands during diageneis of boundary interval sediments.

Basu et al. (1988) briefly reported planar deformation features (PDF) in shocked quartz grains from the upper part of the KT boundary sandstone layer of Jabalpur using a petrographic microscope (Fig. 15B). This unit is characterized by a bimodal distribution of grain size with a dominant mode of medium-grained sand and a relatively minor mode of silt and clay frac-
Figure 13. A, KT boundary section at Barmer, Rajasthan, showing the ejecta layer. B, scanning electron photographs of cosmic spheroid. C, vesicular glass. D, the same enlarged to show its Ni-rich region. E, skeletal structure of magnesioferrite spinel (simplified from Sisodia et al. 2005).

Figure 14. KT boundary section at Bara Simla Hill, Jabalpur, Madhya Pradesh, showing the stratigraphic position of the ejecta layer with shocked quartz below the Deccan lava flow; corresponding iridium profile on the right column (modified from Chatterjee 1992).
Figure 15. KT boundary ejecta layer at Bara Simla Hill, Jabalpur, Madhya Pradesh. A, stratigraphic position of the thick (~2.7 m) ejecta layer between Deccan Traps and Lameta Formation containingLate Maastrichtian dinosaur bones. B-E, shock-metamorphic features of quartz grains from the ejecta layer. B, quartz grain showing planar deformation features (PDFs), which are decorated with fluid inclusions. The planes are closely spaced, numerous, straight and continuous throughout the grain. Some vitrification has also taken place along these planes. Long-dimension of the grain is 300 μm. Cross-polarized light. C-E, SEM photographs of shocked quartz grains from the ejecta layer showing three sets of planar deformation features etched with HF. Silica glass that partially filled the planar features has been etched out by the acid, leaving criss-cross pillars of a less soluble silica phase. F, a pure pellet of silica melt where the PDFs have been destroyed because of high shock pressure (> 60 GPa); the hole indicates the passage of the escaped vapor.

observations. The PDF-bearing quartz grains are relatively large (300 μm to 400 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 (Bhor et al. 1987; Izen 1990). These criteria include well-defined sharp and straight features, which are parallel within a set, and continuous in multiple sets of narrow spacings extending across most of the grains (Fig. 15B). Quartz grains were mounted on a Universal Stage and PDF angles were measured (A. R. Basu, pers. comm.). The orientation of the poles to sets of planar features makes discrete angles with c-axis of quartz, with π and ω being strongly prominent. These orientations are indicative of impact or shock-induced deformation. Measurements of 148 planar elements from 62 quartz grains show peak PDF concentration at about 23° to poles and about 32° to the optical c-axis of quartz grains, indicating PDF dislocations along the crystallographic planes w (1013) and π (1012) respectively and implying shock pressures over 16 GPa (Grieve
Here we document 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). Clay-free mineral grains were prepared to determine their shock metamorphic effects. The residues consist primarily of silica, but also trace amounts of metallic particles. The mineral grains were immersed in 20% HF for 5 minutes and then coated with carbon and gold. SEM revealed the surface textures of the grains and EDXS showed their chemistries simultaneously. The X-ray spectra of the shocked minerals show pure silica composition with only Si- and O-lines. Quartz grains showing such multiple sets of shock-induced planar features are only found at meteorite impact sites (Fig. 15C-E) as well as from other KT boundary sections (Bohor 1990; Bohor et al. 1987; Iizett 1990). Usually in shocked quartz grains from the KT boundary, multiple sets of PDF are glass filled and therefore represent true shock deformation features (Bohor 1990). In many cases of Jabalpur samples, the acid has etched out silica glass that partially filled the planar features, leaving 'pillars' of less soluble silica phase (Fig. 15C-E). Most quartz grains shocked to ≥60 GPa melt completely and lose their crystalline structure altogether (Grieve 1990). We have recovered a dense phase of silica melt grain from the ejecta layer of the Jabalpur section, where the PDFs of quartz grain completely degenerated and turned into a glass spherule (Fig. 15F). We could not find any evidence of stishovite or coesite from the Jabalpur samples.

Shocked quartz grains from the Jabalpur section (300-400 μm) are coarse 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) (Bohor 1990; Bohor et al. 1987; Iizett 1990). 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 favors the proximate source. Here, the KT boundary section appears to be very thick (2.7 m), possibly reworked, 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.

The absence of shocked quartz grains in other KT boundary sections of India is puzzling. We speculate that because of the giant Shiva impact (corresponding to shock pressures 100 GPa or more), the shocked quartz grains at the target rock must have been formed at the instant of impact but were quickly eroded when the melt sheet formed. The absence of shocked quartz grains in other KT boundary sections implies that the bulk of the Shiva ejecta was melt, not moderately shocked quartz grains. It is important to note how little we know about large body impact products and how the products vary as a function of size, gravity, and velocity of bolide. This comparison of impact products from a Chicxulub bolide may be poorly comparable to a Shiva-size bolide. There are many processes in nature when scaling larger not only produces larger effects, but produces new products of a different kind.

The clay fractions of the upper sandstone unit are of ≥90% smectite, which has been interpreted as the weathering product of a precursor glass or other silicate of impact material. Micromerites and glassy material resulting from an exogenous-to-impactary impact has been offered as the possible terrestrial material to the Jabalpur KT boundary clay (Schaer 1990) because structural formulas and chemical compositions of the Indian smectites are compatible with those from typical KT boundary clay layers, such as Stevens Klint of Denmark (Kastner et al. 1984).

Uranium thorium section. Meghalaya.—The Um Sohryngkw river section of Meghalaya contains uninterrupted marine sequences of Cretaceous to Paleocene age that includes four successive formations from bottom to the top: Mahadeo, Langpur, Theria, and Lakadong (Fig. 16). The KT boundary layer, a 1.5 cm thick limonitic layer based on planktonic foraminifera, lies within the Mahadeo Formation about 10 m below the Mahadeo/Langpur contact (Pandey 1990). This layer is rich in iridium, osmium and nickel spinels (Fig. 10D) (Bhandari et al. 1993; 1994; Rubin et al., in press). The iridium profile at the KT boundary is about 12 ng/g, ten times higher than the
background level. Ni-rich spinels in the Meghalaya section 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 and have been reported from different KT sections (Robin et al. 1992). These spinels are characterized by magnesiowüstite 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. Along with iridium and spinels, Bhandari et al. (2002) also reported cosmic magnetic nanoparticles from the KT boundary section of Meghalaya.

Ariyalur KT Section, Tamil Nadu.—The KT boundary section at Anadavady stream section, Ariyalur, Tamil Nadu, is composed of 16-m thick, coarse clastic marine deposits, indicative of high-energy deposition. Here the continental Dawson-bearing Kallanedu Formation (Late Maastrichtian), equivalent to the Lameta Formation of Jabalpur, is overlain by the early Danian shallow marine Ninyur Formation (Fig. 17). The KT boundary age of the Ariyalur section is based on the paleontological evidence (Sahni et al. 1996). The Kallanedu Formation has yielded typical Late Maastrichtian palynological zone fossils such as Aquillapollenites bengalensis, whereas the overlying Ninyur Formation has yielded typical early Danian nautiloids such as Hercoglossa danica.

A 1-m thick oyster bed occurs at the contact with hummocky cross-stratifications with antiformal hummocks and synformal swales with dip angles and transection angles of < 15°, as seen in the tsunami deposits at the KT boundary in Texas (Huggett et al. 1988). Hummocky stratifications with shell fragments are generally interpreted as storm deposits. The oyster-bearing limestone is overlain by a 60-cm thick conglomerate bearing sandy limestone, which in turn is overlain by 40-cm thick fine-grained sandstone. This sandstone unit includes small (~100 micron) spherules of carbonate that may be impact-generated (A. Gilson, pers. comm.). Madhavaraju et al. (2003) reported two types of distinctive magnetic susceptibility, C-zero and C4, from the sandstone unit (Fig. 17) that fits well.

Figure 17. KT boundary section at Ariyalur, Tamil Nadu, showing 1.6 m-thick tsunami deposits (?) with oyster bed showing characteristic hummocky stratification, followed by sandy limestone with concretions, and fine sandstone with possible ejecta components. From magnetic susceptibility analysis, the KT boundary appears to be at the top of the sandstone (modified from Madhavaraju et al. 2003).
with those of other KTH sections in the world corre-
sponding to the 29R magnetic chron (Ellwood et al.  
2003).

We interpret these 2-m thick coarse-grained beds to the result of a major disturbance of the deposi-
tional environment such as a tsunami approximately 100 m high; the limestone bed, with oysters and sandy concretions, was ripped off from the shallow marine floor and dumped on the continental dinosaur-bearing 
Kallamata Formation quickly by high-energy waves 
(Fig. 17).

Since the Shiva crater was located on the western 
shelf of India (Fig. 1), tsunami deposits should be 
expected to be more abundant on the west coast rather 
than on the east coast. However, thick lava flows of 
the Deccan Traps (> 2 km thick) form the Western 
Ghati Mountain range along the western coast that 
prevented any marine transgression at the KT bound-
ary time. Thus the Deccan Trap Formation before the 
impact and its topography might have precluded the 
presence of abundant tsunami debris on the west coast. 
On the east coast of India, there was no such topo-
graphic barrier. This is possibly the reason for the 
 tsunami deposits in the Ariyalur section of the east 
coast. Mehrotra et al. (2001) reported the presence of 
reworked Carboniferous palynofoils in the Paleocene 
Panna Formation in the Bombay Bay high area, which is 
puzzling because Carboniferous sediments are not 
known from Peninsular India. But these palynofoils show 
affinity with those of Saudi Arabia and Africa 
across the Arabian Sea. They speculate that these 
palynofoils, entrappe within the sediments, might 
have been transported from the Saudi Arabia-Africa 
region by strong waves (tsunamis?) and were depos-
If this scenario is correct, tsunami deposits should be 
investigated in the KT boundary sections of Saudi 
Arabia-Africa. Coffin and Rabinozoter (1986) men-
tioned massive tsunami deposits in the KT boundary section on 
the continental margin of Somalia and Kenya 
that encompasses an area of more than 20,000 km², 
with a minimum thickness of 1 km. These tsunami 
 deposits on the western side of the Shiva crater may 
be linked to the Shiva impact.

SIZE AND TRAJECTORY OF THE SHIVA BOLIDE

Although hypervelocity impacts normally create 
circular craters, impacts at a low angle (\(< 15^\circ\) from 
the horizontal) often generate elongate craters, such as 
Messier and Schiller craters on the Moon (Wilhelms 
1987), Chicxulub crater in Mexico (Schultz and 
D'Hondt 1996), Shiva crater in India (Chatterjee and 
Rudra 1996), and the Rio Cuarto craters in Argentina 
(Schultz and Lanza 1992). Schultz and D'Hondt 
(1996) noticed several geophysical and morphological 
asymmetries in Chicxulub, where the crater rings are 
open to the northwest, like a horseshoe, which would 
be expected if the bolide came crashing in at angle of 
20° to 30° from the southeast, digging a deep pit at the 
Point where it landed and then continuing on a shallow 
40° north-northwest.

Craters formed by artificial oblique impact are 
generally oblong (Gault and Wedekind 1976; Moore 
1976). The shape of an artificial crater formed by 
oblique impact at 15° (Schultz and Gault 1990) is like a 
teadrop, where the pointed end indicates the down-
range direction (Fig. 7H). In an oblique impact the 
crater and its ejecta are bilaterally symmetrical about 
the plane of the trajectory, but the distribution of the 
ejecta is concentrated asymmetrically on the down-
range 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. 7). If the Shiva impact were the source of the 
alkaline igneous complexes, then this implies a signifi-
cant asymmetry in the distribution of fluid ejecta. 
We suggest that the likely mechanism to generate this asym-
metry would be a low-angle (< 30° from the horizontal) 
impact from southwest to northeast. This would 
provide a preferential direction for much of the fluid 
ejetc. If the Shiva projectile came from the south-
west direction, the fluid ejecta would progress down-
rane with a mean direction of NE. If so, the impact 
that produced the Shiva crater was probably oblique 
along a SW-NE trajectory as evident from the distri-
bution 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 rim 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. A low-angle impact from the southwest is consistent with the asymmetry of seismic, geothermal, and gravity anomalies at the Mambai coast (Fig. 9).

The distribution of KT boundary ejecta on 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, is directly on this northeast trajectory (Kyte and 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 vapor 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 (Fig. 18).

Wetherill and Shoemaker (1982) summarized the current knowledge of Earth-crossing and Earth-orbiting asteroids. They listed three large asteroids that exceed 10- km in diameter: Sisyphus (~11 km), Eros (~20 km), and Ganymede (~40 km). Using the crater scaling method (Grieve and Cinatla 1992), we estimate that a 40-km diameter asteroid (having a mass of 10^10 kg) about the size of Ganymede, striking at a speed of 15 km/s, would have created the Shiva crater with a 500 km diameter and ~10 km^3 of impact melt produced by three distinct stages (Elkins-Tanton and Hager 2005), as discussed earlier.

Figure 18: Distribution of KT boundary magnesioferrite spinel in the Pacific basin that lies along the trajectory of the Shiva bolide. These spinels might be derived from the Shiva impact site (modified from Kyte and Bostwick 1995).
The impact of a large bolide into the Earth may have set in motion a very complex array of events with intriguing consequences. For typical terrestrial impact velocities of 15-25 km/s, the impacting body penetrates the target rock approximately 2-3 times its radius and transfers most of its kinetic energy to the target (Gray 1987). Impact of the bolide may have produced a vast transient crater 50 km deep and 250 km across, which quickly collapsed under the force of the gravity, leaving a basin 500 km wide and 7 km deep. The energy from the 10-km-diameter Chicxulub bolide is estimated to be about 10^12 joules, equivalent to the explosion of 100 trillion tons of TNT, or about 10,000 times greater than the explosive energy of the world’s entire nuclear arsenal (Frankel 1999; Grieve 1990). If so, the Shiva bolide (~40 km diameter) would generate so much energy that it could create substantial instability leading to uplift, possibly resulting in shattering of the lithosphere, rifing, volcanism, and other rearrangements of the interior dynamics of the planet. Thus, the Shiva impact not only created the largest crater on Earth, but also initiated several other geodynamic anomalies. Some authors have suggested relationships between large impacts and phenomena such as magnetic reversals and plate movements (Clibe and Napier 1982), but these suggestions remain unproven. The Shiva provides for the first time tangible evidence linking huge impact with seafloor spreading and evolution and uplifting of nearby spreading ridges. It appears that both the Shiva impact and adjacent spreading centers such as the Carlsberg Ridge and Laxmi Ridge are part of a single thermal system. The Shiva impact produced cratering and associated tectonic rebound/collapse effects sufficient to locally disrupt the entire lithosphere and cause a major change in plate stress patterns such that stress would propagate quite rapidly away from the immediate region of the impact. It caused major changes in the Indian plate motion and lithospheric stress patterns. The impact might have important consequences on the evolution and propagation of nearby spreading ridges around the Shiva crater in the northwestern Indian Ocean. Whereas Late Cretaceous magnetic lineations in other oceans show no obvious signs of disturbances at the Tertiary boundary, the Late Cretaceous Indian plate boundary in the Indian Ocean provides evidence of major tectonic reorganization at or shortly after magnetostratigraphic chron 29R that might be linked to the Shiva impact. The effects of major plate tectonic changes at about chron 29R, when the Seychelles rifting from India, were not confined to the northwestern Indian Ocean; they are also observed over an extensive segment of former African plate boundary in the southwestern Indian and southern Atlantic oceans, involving both the Antarctic and South American plates. In the Agathus Basin, a westward-rift jump of more than 500 km occurred at the KT boundary time between the African and South American plates (Hartnady 1986).

India-Seychelles Rifting.—A new rift between Indo-Somalia and Seychelles was formed near the KT boundary (65 Ma) coinciding with the Shiva impact (Chatterjee and Scoetse 1999). At this time the Central Indian Ridge (CIR) jumped 500 km northward from its location in the Madagascar Basin to a new location between the Seychelles and Indo-Somalia to form the Carlsberg Ridge. The Mascarene basin spreading center became extinct as a possible response of this emplacement. This ridge jump (~500 km) caused a sliver of continent to split off from Indo-Greater Somalia, forming the Seychelles microcontinent. It resulted in sudden transfer of the Seychelles and Mascarene block to the African plate (Fig. 19). This ridge jump may be linked to the Shiva impact on the trailing edge of the Indo-Seychelles block (Hartnady 1986). This impact may have formed a large lithospheric crack between India and Seychelles and initiated the creation of the Carlsberg Ridge, triggering readjustments along the Indian-African and Antarctic-African plate boundaries (Chatterjee and Ratra 1996; Hartnady 1986). Hartnady (1986) speculates that anomaly 29 may appear near the base of the steep microcontinental slope of Seychelles. If these identifications are correct, then rifting occurred just before chron 29 and may correspond to chron 29R (KT boundary). At present, there is a time lag (~2 Ma) between the impact (29R) and its subsequent expression in chron 28R of the rifting of the Carlsberg Ridge.

Westward Jump of the Spreading Ridge of the Laxmi Basin.—The Laxmi Ridge, an enigmatic continental slice in the Arabian Sea, about 700 km long and
Figure 19. KT boundary plate reconstruction showing the paleopositions of India, Laxmi Ridge, Seychelles, and Madagascar. During the Shiva impact, there was plate reorganization in the northwest Indian Ocean when the Central Indian Ridge jumped more than 500 km northward to form the Carlsberg Ridge, thus initiating the rifting between India and Seychelles. At the same time an extinct ridge in the East Arabian Basin (EAB) between Laxmi Ridge and the Shiva crater jumped 500 km westerly to West Arabian Basin (WAB) between Seychelles and Laxmi Ridge. A-E represent different fracture zones (modified from Hörntdy 1986; Tahlawi and Reif 1996; Dymront 1998).
100 km across, occurs west of the Shiva crater (Figs. 3, 19). Although the origin of Laxmi Ridge is still controversial, gravity and seismic data indicate that it is quite different from a typical oceanic ridge and is probably continental in origin (Dyment 1998; Talwani and Reif 1998). It formed two basins, one on each side: the East Arabian Basin (EAB) and the West Arabian Basin (WAB). In the East Arabian Basin, a short duration of seafloor spreading commenced from the A28-A33 interval of geomagnetic chron, which finally ceased around 65 Ma (Bhattacharya et al. 1994). At the same time, with the extinction of the East Arabian Basin spreading center, the ridge suddenly jumped more than 500 km westerly to the West Arabian Basin on the other side of the Laxmi Ridge, as a possible response to the Shiva impact (Talwani and Reif 1998). This ridge jump is synchronous with the Mascarenese Basin jump of the Carlsberg Ridge. In the West Arabian Basin, regular sea-floor spreading anomalies have been identified; the oldest anomaly was chron 2R8. Apparently, the opening of the East Arabian Basin commenced around 84 Ma and ceased around 65 Ma, when the spreading center jumped from east to west of the Laxmi Ridge to the West Arabian Basin. The age relationship between the Shiva impact and the cessation and westerly jump of the spreading of the Laxmi Ridge is intriguing. We speculate that the sudden westerly jump of the Laxmi Ridge at KT boundary time may be linked to the Shiva impact, which readjusted the plate tectonic framework of the Arabian seafloor coinciding with the northerly jump of the Central Indian Ridge.

Origin of the Deccan Traps. The Deccan traps are one of the largest continental volcanic provinces of the world. It consists of more than 2 km of flat-lying basalt lava flows and covers an area of 500,000 km2, roughly the size of the State of Texas. Estimates of the original area covered by the Deccan lava flows including the Seychelles-Saya de Malha Bank are as high as 1,500,000 km2 (White and McKenzie 1989). The Deccan traps are flood basalt similar to the Columbia River basalts of the northwestern United States, formed by the Yellowstone hotspot.

Currently three models for the origin of the Deccan basalt volcanism have been proposed: mantle plume theory, plate rift theory, and impact-induced theory. In mantle plume theory, Deccan flood basalts were the first manifestation of the Ruman hotspot that rose from the core-mantle boundary and subsequently produced the hotspot trails underlying the Laccadive, Maldive, and Chagos islands; the Mascarenese 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 and Pyle 1988).

Although the hotspot model is very attractive, there are some geochemical problems with this model. Geochemical analysis indicates that the likely source for the Deccan volcanism is rift volcanism rather than Reunion hotspot (Mahoney 1988). Later, Mahoney et al. (2002) recognized several phases of non-MORB phases of Deccan volcanism. Further geochemical and geothermal evidence suggests that Deccan magmas were generated at relatively shallow (34-45 km) depth and rules out the possibility of its origin by a deep mantle plume (Sen 1988). To circumvent these criticisms, White and McKenzie (1989) proposed a model that combines both plume and riftting origins. They argued that the Deccan volcanism was associated with the breakup of the Seychelles microcontinent from India. The enormous Deccan flood basalts of India and the Seychelles-Saya de Malha volcanic province were created when the Seychelles split above the Reunion hotspot (Figs. 7, 10).

However, there is some conflict of timing between these two events: the onset of Deccan volcanism and rifting of India and Seychelles. What triggered the rifting of the Seychelles from India? Was it the Reunion hotspot or the Shiva impact? The Carlsberg rifting that separated Seychelles from India did not start before chron 2R8 (63 Ma), whereas Deccan volcanism started somewhat earlier around 300 (66 Ma) (Fig. 11). Thus the Deccan volcanism predates the India-Seychelles rifting event, making the causal link unlikely (Chatterjee and Rudra 1996).

A third view for the origin of the Deccan Traps is the impact-triggered model. 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 (Ali et al. 1988; Alvarez and Asaro 1990; Basu et al. 1988; Hattigudy 1988). Although the idea of genetic association be-
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), it is rejected because of conflict of timing; the slow outpouring of Deccan volcanism preceded the KT impact by 0.7 Myr or more (Fig. 11). Thus, impact cannot be the proximate cause for the initiation of the Deccan volcanism (Bhandari et al. 1995; Chatterjee and Rudra 1996). However, impact could enhance the volcanic activity by decompression melting beneath the impact site (Jones et al. 2002; Elkins-Tanton and Hager 2005). At the KT boundary (65 Ma), the trickle of Deccan lava eruption became a torrent and is evident from the thick pile of lavas; seismic shock waves from the Shiva impact might have galvanized the proximate Deccan-Reunion hotspot and induced spectacular burgeoning of the Tertiary Deccan volcanism by rifting India and Seychelles (Fig. 10). An impact of this magnitude could raise the crust-mantle boundary close to the surface by decompression, as seen in the western coast of India, and create a large volume magma chamber (Fig. 9). Jones et al. (2002) proposed a mechanism to explain how a major impact could trigger large-scale volcanism, such as the Siberian Traps at the end of the Permian, by decompression melting of the lithosphere. Thus, the Shiva impact might be indirectly responsible for rapid and spectacular areal distribution of the Deccan lava piles during its waxing stage. Sen (1988) noticed that continental lithosphere was involved in the melting and contamination process during the generation of the Deccan lava. Perhaps impact rather than the plume was the cause of the lithosphere melting during the KT boundary eruption. Although the close temporal coincidence between the Shiva crater and the Reunion hotspot that created the Deccan volcanism is statistically an unusual event, it is not entirely impossible; the modern analogy would be a large bolide striking close to the Yellowstone hotspot, Kilauea, Reunion, Kerguelen islands, or near any of the numerous active hotspots.

The pre KT Chicxulub impact nearly coincides with first phase of the Deccan volcanism (Keller et al. 2001). Is there any causal link between these two events, which are located almost in antipodal positions? Impact-induced antipodal volcanism are suggested from Mars. An alternative view, which involves Chicxulub impact but not an in-situ strike, sustains that lithospheric fracturing and Deccan flood basalt volcanism could be triggered by the transmission and focusing of shock waves from the impact (Boslough et al. 1996). Thus, Deccan volcanism could reflect Chicxulub impact, although cause and effect would be offset by 120° rather than 180° (Sutherland 1996). However, oblique impact at the Chicxulub may account for this antipodal discrepancy.

Northward Acceleration of the Indian Plate.—During most of the Mesozoic, the Indian plate moved northward at a rate of 3-5 cm/yr. The sudden acceleration of the Indian plate to the super fast rate of 15-20 cm/yr from Late Cretaceous (80 Ma) to Paleocene (53 Ma) time has long been a major puzzle in plate tectonics and has provoked many speculations (Patriat and Achache 1984). This faster rate was sustained for about 20 My during the Paleocene, soon after the KT impact and then slowed down as the Indian plate began to plow into the Eurasian continent. Negi et al. (1986) suggested from heat flow data that the Indian lithosphere was greatly thinned (about one third of that of other global shields), abnormally hot, and lighter during this period, which had important consequences for mantle rheology. It reduced the drag of the lithosphere against the asthenosphere, resulting in faster northward movement of the Indian plate. Apparently the Indian plate occupied itself deeper interior to become more mobile. We speculate that the acceleration of the Indian plate may be linked to the India-Seychelles rift at the KT boundary with the initiation of the Carlsberg Ridge. During the Paleocene, the Indian plate slowed its northward motion from about 20 cm/yr to 4.5 cm/yr as it collided with Asia (Chatterjee and Scotte 1999).

As discussed earlier, the Shiva impact might cause thermal erosion of the lithosphere, and thereby, produce a thinned lithosphere and high heat flow (Pandey and Agarwal 2001). The sudden northward acceleration of the Indian plate during the KT boundary time might also be linked to the oblique impact of the 40-km diameter Shiva bolide at a speed of 15-25 km/s in a northeast direction that generated a vast amount of tangential kinetic energy at the striking point. The impactor-driven force would have pushed the thin, hot and mobile Indian plate further northward, creating a spreading asymmetry. Dyment (1998) noticed that during anomalies 26 and 25, about 65% of the crust formed at the Carlsberg Ridge was accreted to
the African plate, while at anomalies 24-20, more than 75% benefited to the Indian plate. We speculate that these asymmetries result from the relative position of the Carlsberg Ridge and nearby Shiva impact, the ridge tending to remain near the crater. A unique aspect of the Indian plate at that time was its fast velocity, which moved northward from an almost stationary Antarctica. The asymmetric spreading of the Indian plate, resulting from the ridge propagation along the Carlsberg Ridge, may be related to the oblique impact of the Shiva bolide.

**PETROLEUM ENTRAPMENT**

KT boundary impact craters such as Shiva, Chixculub, and the Bolyshy depressions are among the most productive hydrocarbon sites on Earth. Donnelly (1981, 1990) recorded 17 confirmed impact structures/events occurring in petroleum-rich areas of North America, nine of which are being exploited for commercial hydrocarbons. Interestingly, all craters containing commercial oil and gas were accidental discoveries. They yield from 30 to over 2 million barrels of oil per day plus over 1.5 billion cubic feet of gas per day. The impact cratering process results in unique structures and extensive fracturing and brecciation of the target rock, which can be conducive to hydrocarbon accumulation. Reservoirs are found in sedimentary and crystalline basement rock and usually consist of central uplifts, rims, slump terraces, and ejecta and probably subcrater fracture zones (Fig. 20). Additionally, sediments overlying an impact structure can form numerous structural and stratigraphic traps, such as anticlines and pinchouts, which can be enhanced during crater isostasy.

In the Chixculub crater, the impact products such as carbonate breccia forms the reservoir rocks, whereas the overlying dolomitized ejecta layer forms the seal (Grajales-Nishimura et al. 2000). Chixculub reservoirs are most likely tsunami formed and are found in post-impact structural traps about 140 km—within two crater radii—southwest of the rim in the offshore bay of Campeche. Estimated reserves for the Chixculub event are ~30 billion barrels of oil and 12 trillion cubic feet of gas.

In the Shiva crater, the most prolific traps are those located on persistent paleo-highs of the peak ring area, where oil and gas is produced primarily from Middle Miocene reservoirs, with the most prolific being the platform carbonates such as the Lower Mi-

![Composite Diagram](image)

Figure 20. Diagrammatic cross-section of a complex impact crater showing how the central uplift and other shattered units may be effective petroleum trap. All the KT boundary impact craters, such as Chixculub, Shiva, and Bolyshy, have central peaks and are excellent structural traps for giant oil and gas fields.
oceanic Ratanagar Formation (Rao and Talukdar 1980). Fractured basement rock also has hydrocarbon potential. 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 one million barrels of oil equivalent or greater in size (Petroleum Consultants 1996).

The Bolyshy impact crater in the Ukraine is a circular depression about 24-km in diameter formed in crystalline basement rocks (Kelley and Gurov 2002). But while Chixculub and Shiva filled with seawater, the Bolyshy crater became a freshwater lake. The anular trough surrounds, the central uplift, which is about 580 m in height and 4 km in diameter. The Bolyshy structure is filled with post-crater sediments of argillites and siltstones. Commercial reserves of oil shales (sapropelites) occur in sedimentary crater fill, which constitute about three billion tons (Yurk et al. 1975). When processed, these oil shales could yield several billion barrels of oil.

**Biotic Consequences**

At the close of the Cretaceous, the Earth was devastated. Life was ravaged by one of the worst catastrophes. Of all five major extinctions that happened during the Phanerozoic, the KT extinction has captured the most public attention, because of the demise of dinosaurs. The dinosaurs dominated the landscape more than 160 My, living over a thousand times longer than the tenure of modern humans (Homo sapiens first evolved around 150 Kyra). After more than two decades of debate, the proximate cause for the KT extinction still remains controversial. There are two competing models: bolide impact (Alvarez et al. 1980) or flood basalt volcanism (Courtillot 1990; Officer et al. 1987). Three Phanerzonotic mass extinctions are now reported to be linked temporarily with both volcanism and impacts (White and Saunders 2005): the Permian-Triassic (P-Tr, 250 Ma), the Triassic-Jurassic (Tr-J, 200 Ma), and the KT extinction (65 Ma). Another major unresolved factor in the KTb impact story is the exact number of impacts involved (Glen 1990, 1994). Three impacts, Chixculub, Bolyshy, and Shiva are known to have occurred at the KT transition, spaced over an interval of time of approximately 300,000 years (Kelley et al. 2003, 2004), and are supported by the presence of multiple layers of iridium and fullerene anomalies in the Anjar section of Gujrat (Parthasarathy et al. 2002).

The Bolyshy impact was relatively small, affecting the local areas on the Ukrainian shield with little global influence. However, it probably occurred around the same time as Shiva. The Chixculub crater appears to have been formed 300 Ky before the KT boundary and cannot be the proximate cause for the end-Cretaceous mass extinction (Keller et al. 2004). A single large meteoric impact like the Shiva may be more harmful to life than a cluster of several smaller meteorites spread over 300 Ky. However, the Chixculub impact coincided with the early phase of the Deccan volcanism, and those two processes may have created high stress environments causing a gradual decrease of species diversity during the last 300 Ky before the KT boundary. Chatterjee and Rudra (1996) argued that although Deccan volcanism injected 10 times more CO₂ into the atmosphere to increase the greenhouse effect, reduce photosynthesis, create acidic oceans, dissolve shells of calcareous organisms, and collapse the marine food chain, Deccan volcanism could not be the proximate cause of the KT extinction, because dinosaur bones and their eggs have been found in intertrapped beds interlayered with Deccan lava flows (Fig. 11). Dinosaurs were thriving in India when Deccan lava was erupting. 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 CO₂ into the atmosphere and the change of the ocean chemistry by production of acid rain.
Elimination of Chicxulub, the Bolyshy impacts, and Deccan volcanism from the extinction equation leaves the Shiva impact as the sole candidate for the final blow to the apocalyptic disaster at the KT boundary, which claimed dinosaurs, pterosaurs, plesiosaurs, mosasaurs, radiolarians, ammonites, and more than 75% of animal and plant species on Earth. The pressure exerted by the Shiva impact could have exceeded 100 GPa; temperatures could have reached several thousand degrees Celsius, and impact energy would have generated more than a 100-million megaton blast (Grieve 1990). The biologic consequences of such a huge impact, which were nearly instantaneous in their globally devastating effects, would have depended 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. While the greatest damage is obviously at ground zero for a large impact, a very significant portion of the energy from the impact would have been dissipated and devastated the exosphere, the thin shell of air, water, soils, and surface rocks that nurture life, and cause the mass extinction. Even seismic shock waves would reach damaging proportions on a global scale and would trigger tsunamis that would flood most shorelines -100 km inward and destroy coastal cities (Chapman 2002). The trajectory of the Shiva bolide should have driven a fiery vapor cloud toward the northeast, creating a cor-

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