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KT EVENTS IN INDIA: IMPACT, RIFTING, VOLCANISM AND DINOSAUR EXTINCTION

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For more than a decade, a number of impact sites have been linked to the mass extinction at the KT (Cretaceous/Tertiary) boundary. The prime candidate today is the Chicxulub Crater in Yucatán Peninsula, Mexico. Recently another potential KT impact scar — the Shiva Crater — has been identified from subsurface data at the India-Seychelles rift margin. The crucial evidence in support of this impact structure comes from the Bombay High field, a giant offshore oil basin in India, and associated alkaline intrusives within the Deccan Traps. The KT boundary age of the crater is inferred from its Deccan lava floor, Palaeocene age of the overlying sediments, isotope dating (~65Ma) of presumed melt rocks, and the Carlsberg rifting event (chron 29R) within the basin. Seismic reflection data and India-Seychelles plate reconstruction at 65Ma reveal a buried oblong crater, 600km long, 450km wide and 12km deep, carved through Deccan Traps and into underlying Precambrian granite. It represents the largest impact structure of Phanerozoic age. The crater shows the morphology of a complex impact structure and basin, with a distinct central uplift in the form of a series of peaks, an annular trough and a slumped rim. The oblong shape of the crater and the asymmetric distribution of fluid ejecta indicate oblique impact in a SW-NE trajectory. We speculate that a 40km diameter meteorite crashed on the western continental shelf of India around 65Ma, excavating the Shiva Crater, shattering the lithosphere and inducing the India-Seychelles rifting. The crater appears to narrow in the form of a teardrop to the NE or downrange where the ejecta melt rocks were emplaced radially outward by the impact shock. The shape of the Shiva Crater and the asymmetric ejecta distribution mimic those of artificial craters produced by oblique impacts in laboratory experiments. The synchrony and near-antipodal positions of the Shiva and Chicxulub Craters may indicate two alternative modes of their origin. Either, both craters originated from splitting of a larger diameter meteorite, or, large impact on one side of the Earth produced a similar signature on the far side by axial focusing of seismic waves. Since India was ground zero for both an impact and Deccan volcanism, their causal relationships and biotic effects were assessed. It appears that Deccan volcanism began 1Ma before the KT event and was not triggered by the impact. Its origin is attributed to the Deccan-Reunion hotspot. The extensive areal distribution of Deccan Traps is owing to intercanyon flows along the drainage of the Narmada, Godavari and the Cambay basins. During the early stage of Deccan eruption, sauropods, theropods and ankylosaurs flourished in India, but they died out suddenly at the KT impact boundary. Although both impact and Deccan volcanism are hypothesized as contributing to the deleterious environmental consequences leading to biotic crisis at the KT boundary, the impact is suggested as having played the major role as the killing mechanism. ☐ *Impact, Cretaceous-Tertiary boundary, India, dinosaur, extinction, volcanism.*

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Since its emergence and subsequent eruption of diversity, life has shown a tenacious and wildly successful hold on this planet. But the rich history of life has been repeatedly punctuated by equally awesome displays of its destruction. It is estimated that 99% of plant and animal life that have ever lived on Earth are now extinct (Wilson, 1992). The history of life is replete with major episodes of biotic catastrophes or mass extinctions, when 50% or more of the unrelated species died out fairly rapidly. All mass extinctions, however, have been followed by at least a partial evolutionary recovery in which the number of species on Earth has increased again.

There are five major episodes of mass extinctions during the past 600 million years: Late Ordovician (440Ma), Late Devonian (365Ma), Late Permian (245Ma), Late Triassic (210Ma) and Late Cretaceous (65Ma). Of these mass extinctions, the one that has captured the greatest

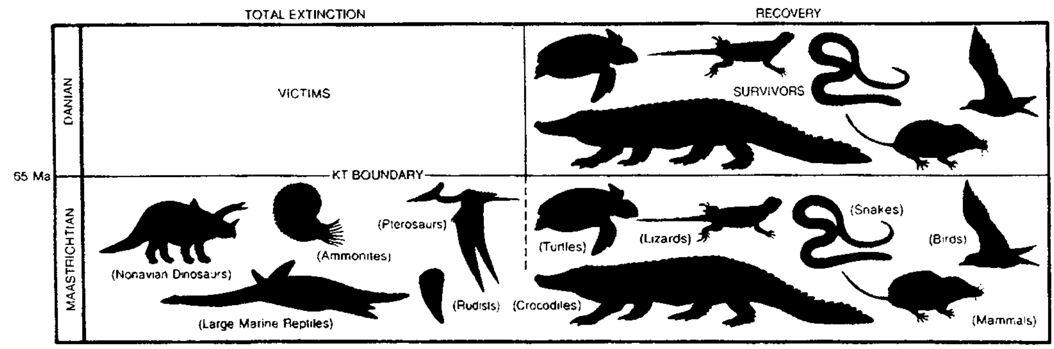

FIG. 1. Victims and survivors after the KT extinction. The primary victims were nonavian dinosaurs, pterosaurs, large marine reptiles such as plesiosaurs and mosasaurs, and various invertebrates such as ammonites and rudists. Lizards, snakes, turtles, crocodiles, birds and mammals endured this catastrophe and rebounded. Both birds and mammals underwent explosive evolutions after this crisis.

attention of earth scientists has been the KT (Cretaceous/Tertiary) extinction when the dinosaurs and two-thirds of all marine animal speices were wiped out. The sudden extinction of dinosaurs has puzzled both scientists and public for more than a century. Having survived for 160 million years, dinosaurs seemed indestructible. Not only the dinosaurs died out during that relatively brief period; all land animals weighing more than 25kg disappeared from the planet. All pterosaurs, plesiosaurs, mosasaurs as well as several families of birds and marsupial mammals, and hundreds of plants were also suddenly wiped out at this time. The small calcareous plankters that float at the ocean surface and the ammonites and rudists from the depths also vanished. The Earth was devastated. Life was ravaged by one of the worst catastrophes.

There were survivors, of course, after the KT disaster (Fig. 1). Neornithine birds, placental mammals, crocodiles, turtles, lizards and snakes all survived as groups — despite the extinction of some species. From this catastrophe, opportunities arose for the survivors. The KT extinction had opened the door for the age of mammals and the rise of birds and changed the course of evolutionary history. What triggered this catastrophe that led to such an unprecendented ecological crisis? Over the years, many theories, some bizzare and some plausible, have been offered to explain the mystery behind the extinction of dinosaurs. There is no shortage of murder suspects. Any explanation of the causes of biotic crises must focus on finding agents of destruction that affected environments, climates, ecology and organisms.

By the end of the Cretaceous, harsh changes of environments were taking place as a result of plate movements, mountain buildings, volcanic emissions and sea regressions. Exactly what caused the biotic crisis remains highly controversial. Currently two competing models have been proposed to explain this apocalyptic disaster at the KT boundary: meteorite impact hypothesis and volcanic hypothesis. The impact theory postulates that the environments were lethally altered or destroyed at the end of the Cretaceous by the collision of a large meteorite leading to biotic crisis. The volcanic theory argues that the pollution in the atmosphere and oceans by the massive outpourings of Deccan flood basalt in India had devastating effects on ecology.

In 1980, the Alvarez group proposed that the KT extinction was caused by the impact of a 10km meteorite. This proposal has generated a great deal of interest among scientists and the public. But the key piece of evidence was still missing. If a huge meteorite had indeed crashed into the Earth, where was the crater? Critics searched for alternate explanation. The end of the Cretaceous was also a time of massive continental flood basalt volcanism, especially the Deccan Traps in India. Many palaeontologists believe that such cataclysmic volcanism may have been the culprit in the KT extinction (McLean, 1985; Officer et al., 1987). Over the past 15 years, exciting new insights have poured in from virtually every branch of earth and planetary sciences to understanding the effects of these catastrophic events — impact and volcanic — on earth's ecosphere and the evolution of life. Recently the Chicxulub structure in the northern coast of Yucatán Peninsula of Mexico has emerged as a prime candidate for the KT impact site (Hildebrand et al., 1991). In this paper we describe another buried KT impact structure — the Shiva Crater at the India-Seychelles rift margin, and its relevance to the Chicxulub structure, Deccan volcanism and mass extinction (Chatterjee, 1992; Chatterjee & Rudra, 1993).

THE IMPACT MODEL

Like other planets in the solar system, the Earth resides in a swarm of asteroids and comets. It is now apparent that the Earth has been heavily bombarded during its history by meteorites of various sources, sizes and compositions (Clube & Napier, 1982). The incontrovertible evidence for large cosmic collisions is the occurrence of circular craters associated with considerable local structural disturbance and shock metamorphism (French & Short, 1968). Because of the dynamic nature of the terrestrial lithosphere where such forces as erosion, volcanism, deposition, orogeny and plate tectonics constantly restructure the surface, impact craters are often erased or obscured, unlike the more static surfaces of the Moon, Mercury and Mars. To date over 150 impact craters have been recognized on the Earth's surface and the list is growing. They range in size from approximately 100m to 200km and in age from Precambrian to Recent (Grieve, 1987; 1990; Grieve et al., 1988). The spatial distribution indicates concentrations in cratonic areas. Other craters may be submerged under oceans and remain inaccessible or undetected. Scientific interest in the role of impact in geological and biological evolution has been enhanced by several developments in recent years. Among the most prominent of these are the hypotheses of Alvarez et al. (1980) concerning terminal Cretaceous extinction and lunar and planetary exploration by manned and unmanned spacecraft. As interest in bombardment mounts, previously unknown or cryptic impact sites are recognized with increasing frequency. As a grim reminder that the threat of impact on our planet is a real possibility, the world's attention was focused during late July, 1994, on the spectacular collision of comet Shoemaker-Levy 9 on the surface of Jupiter, leaving scars the size of Earth on the giant planet (Levy et al., 1995; Weissman, 1955).

Hypervelocity impacts can have a large range of effects that depend on the strength and density of the projectile and the nature of the target material. The most obvious result of larger collisions is seen in the spectrum of crater sizes and morphologies. The recovery of meteorite fragments and shock effects within or surrounding a crater are the most persuasive evidence for an impact origin, but when large craters are deeply eroded or buried, the evidence of impact is obscured or blurred. Such evidence may be identified indirectly from shock-metamorphic effects on the target rock and ejecta components, as well as distinctive geochemical signatures attributable to a particular type of meteoritic projectile (Grieve, 1990). These signatures may be preserved locally near the impact site, or globally at a particular stratigraphic level containing the ejecta fallout. Together they may provide clues to the nature of the target material and the impactor. Impact craters of this obscure nature are the most controversial and require additional information for verification.

In 1980, the Alvarez group advanced a startling theory to explain the sudden demise of dinosaurs — the most succesful land animals ever to arise on Earth. They discovered an abnormally high concentration of iridium (about 30 times more than the surrounding rocks) at the KT boundary level of Gubbio, Italy. Soon a comparable iridium anomaly was found globally at different KT boundary sections (Orth, 1989). Since iridium is a very rare element in the earth's crust, but fairly abundant in chondritic meteorites, the Alvarez team proposed that the iridium spike at the KT boundary is cosmic in origin, implying the strike of a large meteorite. There was enough iridium in the KT boundary, they calculated, to equal a 10km-diameter asteroid. They proposed that this giant asteroid crashed into the Earth with a velocity of 90,000km/hour to cause the worldwide catastrophic event. This impact lofted so much debris into Earth's atmosphere as to creater a 'nuclear winter'that caused much of the life on Earth to perish. A blackout of sun would kill plants and destory the food chain. The global distribution of the iridium layer was caused by the impact and vaporization of the bolide. The impact theory was reinforced by additional evidence such as shocked quartz (Bohor et al., 1984; 1987; Owen & Anders, 1988), stishovite (McHone et al., 1989), micro-diamonds (Carlisle & Braman, 1991), impact glasses (Izett et al., 1990), osmimium isotope ratios (Turekian, 1982), Ni-rich spinels (Robin et al., 1994), rhodium (Bekov et al., 1988), carbon soots (Wolbach et al., 1988), tsunami deposits (Bourgeois et al., 1988), and extraterrestrial amino acids (Carlisle & Braman, 1993) in the KT boundary layer at different sites.

Among all this cumulative evidence, the shocked quartz is a distinctive signature of impact event as it can form at a force more than 10 gigapascal (GPa) that travels through quartz-bearing grains of the target rock to porduce microscopic shock lamellae (Grieve, 1990). Pressures and temperatures produced by a large body impact are much greater than those generated by other geologic processes, such as volcanic activity, mountain building and earthquakes.

However, the strongest evidence in favor of the KT impact event would be to locate a crater marking the point of collision. Such a crater should be 150km or more in diameter (Grieve, 1982). The search for an impact site of the right age (~65Ma), and the right size (150km) has continued, including reassessment of many enigmatic structures. Now, after a decade-long search, the Chicxulub structure on the Yucatán Peninsula of Mexico (Hildebrand et al., 1991) and the Shiva Crater at the India-Seychelles rift margin (Chatterjee, 1992) appear to be two potential candidates for the long-sought KT impact scar.

THE VOLCANIC MODEL

Although the impact hypothesis is very compelling, not everybody believes that impacts killed the dinosaurs and other organisms at the KT boundary. Critics have advanced a volcanic alternative. The end of the Cretaceous was also a time of massive continental flood basalt volcanism, especially the Deccan Traps of India. Recent radiometric dating suggests that the main pulse of Deccan volcanism may have occured close to the KT boundary at 65 million years ago (Duncan & Pyle, 1988; Courtillot, 1990). Many palaeontologists argue forcefully that such cataclysmic Deccan volcanism may have been the main contributing factor for the biotic crisis at the KT boundary (Clemens, 1982; Officer et al., 1987; Hallam, 1987; Keller, 1989; Stanley, 1987; Zinsmeister et al., 1989; Courtillot, 1990). Other contemporary episodes of volcanism at the KT boundary such as in Cameroon and the Coral Sea have been linked to the KT event (Sutherland, 1994). The proponents of the volcanic model argue that the KT extinction was neither global, nor instantaneous, but occurred over an extended period of time, because different organisms disappeared at different levels at or near the KT boundary. Such step-wise extinction pattern could be best explained by prolonged emissions of volcanic pollutants. Large amounts of iridium have been discovered to be spewing from the Hawaiian and Reunion volcanoes, suggesting that the iridium anomaly at the KT boundary could have also had a volcanic origin (Olmez et al., 1986). There is no doubt that such a massive volcanic outburst over an extended period would have deleterious environmental consequences. Proponents of the volcanic model claim that many of the supposed impact signatures at the KT boundary layer, such as iridium enrichment, shocked quartz, microspherules, clay mineralogy and carbon soot, could have volcanic explanations (Officer, at al., 1987; Courtillot, 1990). The impact proponents disagree. They point out that the Deccan volcanism was not of an explosive type and could not account for the global distribution of the iridium anomaly, shocked quartz and tektites at the KT boundary layer (Alvarez, 1986; Alvarez & Asaro, 1990). Moreover, the lamellar features in quartz grains associated with explosive volcanism show curvatures contrary to the planar and parallel lamellae in impact-related shocked quartz recoved from the KT boundary (Izett, 1990). The gradual extinction pattern seen among organisms may be an artifact of preservation and poor sampling quality. Others argue that because Deccan volcanism had little effect on the diversity of local Indian biota, its catastrophic role in global life is questionable (Prasad et al., 1994).

SEARCH FOR THE KT IMPACT SITE

Since Alvarez et al (1980) presented their geochemical evidence for an impact event at the KT boundary, the search for the proposed impact crater has continued. There are a number of candidates for the KT impact site, none of which are very compelling at present. The 35km Manson structure in north-central Iowa is such a candidate (French, 1984; Anderson & Hartung, 1988), but new work suggests that this crater is older (~74mya) and played no role in the KT mass extinction (Izett at al., 1993). Twin impact structures in the Kara Sea in the former USSR, the Kara (diameter, 60km) and Ust-Kara (diameter, 25km), have been proposed as possible impact sites (Koeberl et al., 1988), but recent geochronologic data suggest that these structures are also older than the KT boundary event (Koeberl et al., 1990).

Even the general location of the KT impact, whether continental or oceanic, remains controversial. Trace element and isotopic studies of the highly altered KT boundary-layer components tend to support the oceanic impact hypothesis (Gilmore et al., 1984; Hildebrand & Boynton, 1990). On the other hand, the presence of shocked quartz at several KT boundary sites would indicate a continental site (Bohor at al., 1987). The apparent contradiction can be reconciled if the single impact occurred at a continental margin involving both oceanic and continental crust, or multiple impacts at different sites.

It was soon realized that the size and abundance of the ejecta, such as shocked quartz grains and tektites, may give some clues as to the location of the impact crater. Bohor et al. (1987) and Izett (1990) concluded that the largest sizes and greatest abundance of shocked quartz grains in KT boundary sediments occur in western North America, suggesting that the impact occurred on or near the continent. The discovery of tsunami deposits at the KT boundary sections on the Brazos River, Texas (Bourgeois et al., 1988), near Braggs, Alabama, (Smit et al., 1994), in the Caribbean (Hildebrand & Boynton, 1988), and Deep-Sea Drilling Program holes 536 and 540 in the southwestern Gulf of Mexico (Alvarez et al., 1992) as well as the identification of tektites at Beloc, Haiti (Izett et al., 1991; Maurrasse & Sen, 1991) and Arroyo el Mimbral, northeastern Mexico (Smit et al., 1992), narrowed the search further to the Caribbean region. Impact breccia has been recovered from Albion Island of Belize, near the Mexican border (Ocampo & Pope, 1994). At least four possible Caribbean sites have been suggested, including the Colombian Basin, western Cuba, Haiti and the Yucatan Peninsula.

Hildebrand & Boynton (1990) placed the KT impact location in the Colombian Basin between Colombia and Haiti on the basis of seismic data and DSDP core samples, but the putative crater is not only under water but buried under 1,000m of sediment and is subject to other interpretations, such as tectonic origin or a change in the thickness of the oceanic crust. Bohor & Seitz (1990) speculated that the impact site was near Cuba, about 1,350km from the site proposed by Hildebrand and Boynton, on the basis of a boulder bed interpreted as ejecta components, but the boulder bed is found to be of local, weathering origin and the Cuban site has been rejected (Dietz & McHone, 1990). The Massif de la Hotte on the southern peninsula of Haiti, a mountainous region with Cretaceous sediments, has also been proposed as the KT impact site (Maurrasse, 1990), but closer examination of the area clearly indicates that it is not an impact site (Officer et al., 1992).

The most promising KT impact site appears to be the Chicxulub Crater on the northern margin of the Yucatán Peninsula, Mexico (Penfield & Camargo, 1982; Hilderbrand et al., 1991; 1995). It is a circular structure about 180km in diameter, buried under 1,100 m of carbonate strata, extending out under the Gulf of Mexico, and defined by magnetic and gravity anomalies (Fig. 2A).

THE CHICXULUB CRATER

The subsurface stratigraphy of the Chicxulub structure is known primarily from petroleum exploration bore holes drilled by Pemex, the Mexican national petroleum company, in the 1950s (Lopez-Ramos, 1975; Meyerhoff et al. 1994). Unfortunately, most of the critical core samples were destroyed in a warehouse fire. At present, samples of the Chicxulub structure are limited; as a result, the subsurface stratigraphy is open to various interpretations. In hindsight, it is ironic that drilling and exploration were stopped as soon as the andesitic bodies at a depth of 1500-2000m were encountered; these may have provided the critical evidence for the impact. Penfield & Camargo (1982) suspected an impact origin for the Chicxulub Crater on the basis of concentric geophysical anomalies with associated extrusive material such as andesitic bodies. Recently located samples from the old Pemex wells, including brecciated carbonates, andesites and crystalline basement have been studied extensively and inferred to support the impact scenario for this site. For example, Hildebrand et al. (1991) reported shocked quartz within Chicxulub breccias and documented chemical and isotopic similarities between andesites and tektite deposits from the KT boundary sections of Haiti and Mexico. These findings indicate that the Chicxulub Crater may be the source for the Haitian and Mexican tektites. Kring & Boynton (1992) interpreted the rocks initially thought to be andesites as probable impact melts, whereas Blum et al (1993) found an isotopic match between the Haiti glass and the Chicxulub melt. Subsequently, Sharpton et al. (1992) recognized that the breccia above the melt rock is suevite breccia, a distinct signature of an impact crater. They recognized that the Chicxulub melt rocks show high levels of iridium and their age corresponds well with the KT boundary. Single crystal $^{40}Ar/^{39}Ar$ dating places the melt rock at 65Ma (Swisher et al., 1992). All this combined evidence suggests that the Chicxulub

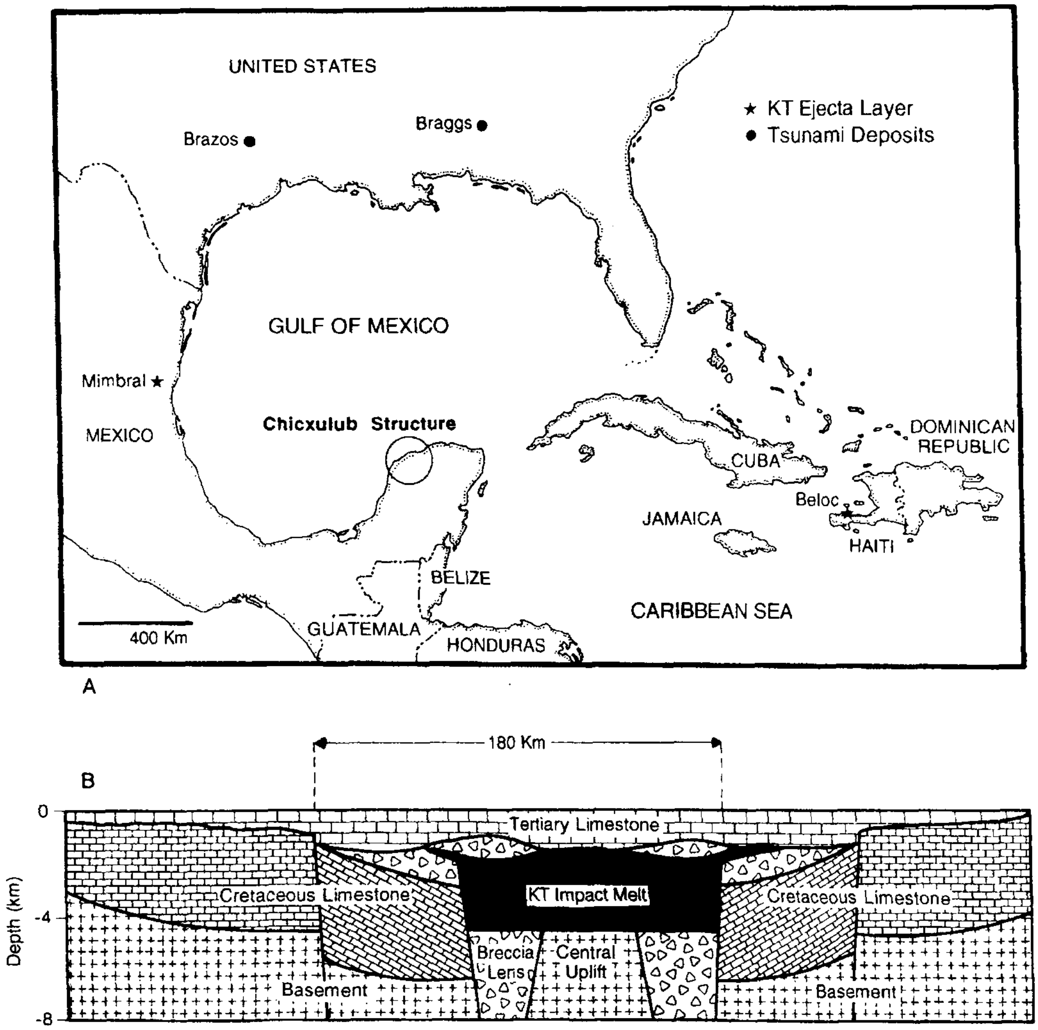

FIG. 2. A, Location of the Chicxulub structure on the northern edge of the Yucatán Peninsula, Mexico, showing distribution of proximal impact deposits. B, Cross-section; estmated crater diameter is 180km (simplified from Hildebrand et al., 1994).

structure may be a prime candidate for the long sought KT impact crater (Fig. 2B).

It appears from the above discussion that two lines of evidence support the impact scenario for the Chicxulub structure: evidence of shock metamorphism, iridium enrichment, brecciation and impact melt within the crater itself, and the distribution of proximal ejecta components at the KT sections in Haiti, Mexico, Texas, Alabama, the Caribbean and adjacent areas (Fig. 2A). However, in recent times both interpretations have faced strong criticisms. For example, some workers dispute the impact origin of the Chicxulub structure and interpreted it as a buried volcanic complex of Late Cretaceous age (Officer et al., 1992; Meyerhoff et al., 1994). Their counterargument is based on the original subsurface correlation proposed by Lopez-Ramos (1975) and the unpublished well log for the Yucatán No. 6 well, drilled in 1966 over the Chicxulub structure. One of the authors, Dr Arthur A. Meyerhoff, was a consulting geologist to Pemex at the time Yucatán No. 6 was drilled and had first-hand information on the biostratigraphy of the site. This well penetrated a superimposed sequence of Pliocene-Miocene, Oligocene, Eocene-Palaeocene and Maastrichtian-Campanian sediments, and bottomed in andesitic rocks and Cretaceous limestone, dolomite and anhydrite. The most damaging evidence against the impact origin is the inverted stratigraphy of the Cretaceous horizon in relation to the andesite. These dissenters point to the presence of 350m of undisturbed Late Cretaceous sediments with index fossils (foraminifera) overlying the andesitic body. If the andesitic rocks were indeed impact melt from KT boundary time, the overlying strata must be Palaeocene or younger in age. Palaeontologic evidence indicates otherwise; these strata are of Campanian and Maastrichtian age lying conformably over the andesite. Swisher et al. (1992) explained this stratigraphic inversion as fallback breccia of Cretaceous limestone infilling the crater. However these overlying Cretaceous strata are not disturbed, brecciated and shocked, and thus pose a problem for the KT impact age of the andesite body.

Meyerhoff et al. (1994) indicated the following additional discrepancies in the impact origin hypothesis of the Chicxulub structure:

1) The Chicxulub structure is too shallow (~2000m) for an impact of this dimension; expected excavation depth would be around 10km or greater (Melosh, 1989).

2) Several layers of bentonitic breccia occur interbedded with the Cretaceous limestones without any structural disturbance or obliteration, so their impact origin is suspect.

3) If the andesite were of impact origin, one would expect highly homogeneous composition with appreciable thickness; in contrast, chemical analysis suggests that the Chicxulub andesite is thin, chemically inhomegeneous with a wide range of major oxide compositions (Sharpton et al., 1992).

4) In an impact structure, the impact melt represents the aggregate composition of the target rock (Engelhardt, 1984); in Chicxulub, on the other hand, the target country rock is metamorphosed quartzite and rhyolite, whereas the presumed impact melt is andesite.

5) The anhydrite at the bottom of the Yucatán No. 6 well would have been completely vaporized at the point of collision, if there was an impact; its presence below the putative melt rock is anomalous.

6) Unlike the planar and parallel lamellae in shocked quartz associated with an impact site, the lamellar features in quartz grains in Chicxulub breccia show curvatures typical of volcanic origin.

7) Later thermal events in the Chicxulub volcanic sequence might have reset the radiometric age of the andesite; these authors indicated that out of ten samples analyzed by Sharpton et al. (1972), nine gave spurious results; accordingly, the correlation between the KT impact event and the presumed andesite melt is tenuous at best.

8) The Chicxulub volcanics are not local impact melt, but part of a well-known Late Cretaceous igneous province surrounding the Gulf of Mexico.

Not only the impact origin of the Chicxulub structure, but also the interpretation of proximal deposits of ballistic ejecta and impact-wave disturbances in the Caribbean and Gulf Coast is in dispute. Recent studies have shown that many of these so called impact-generated deposits may in fact represent gravity-flow or turbidite deposits occurring over an extended period of time, whereas supposed impact droplets are altered volcanic particles (Lyons & Officer, 1992; Keller et al., 1993; Stinnesbeck et al., 1993; Beeson et al, 1994; Adatte et al, 1994).

The presumed connection between the Haitian glasses and Chicxulub has been questioned by Koeberl (1993) on the basis of geochemical evidence. He pointed out that, at the time of impact, the Chicxulub area was covered by evaporitic and carbonate deposits several kilometers thick. Yellow glasses found in the KT section of Haiti are not tektities and cannot be linked to evaporitic target rocks of the Chicxulub. Similarly, the interpretation of some breccias within Chicxulub as impact breccias may be wrong. However, proponents of the Chicxulub Crater have dismissed most of these criticisms (Alvarez et al. 1994; Hildebrand et al., 1994).

Thus, the Chicxulub impact is open to question, and more study is needed before a final assessment can be made. The only way to settle this question decisively is by drilling new holes into the Chicxulub structure, as in the case of the Manson Crater, to determine more precisely when and how it formed.

THE SHIVA CRATER

Although the Chicxulub structure has emerged as the leading candidate for the KT impact scar, another promising KT impact site has been identified at the India-Seychelles rift margin in the northwest Indian Ocean, almost antipodal to the Chicxulub structure. Hartnady (1986) suggested

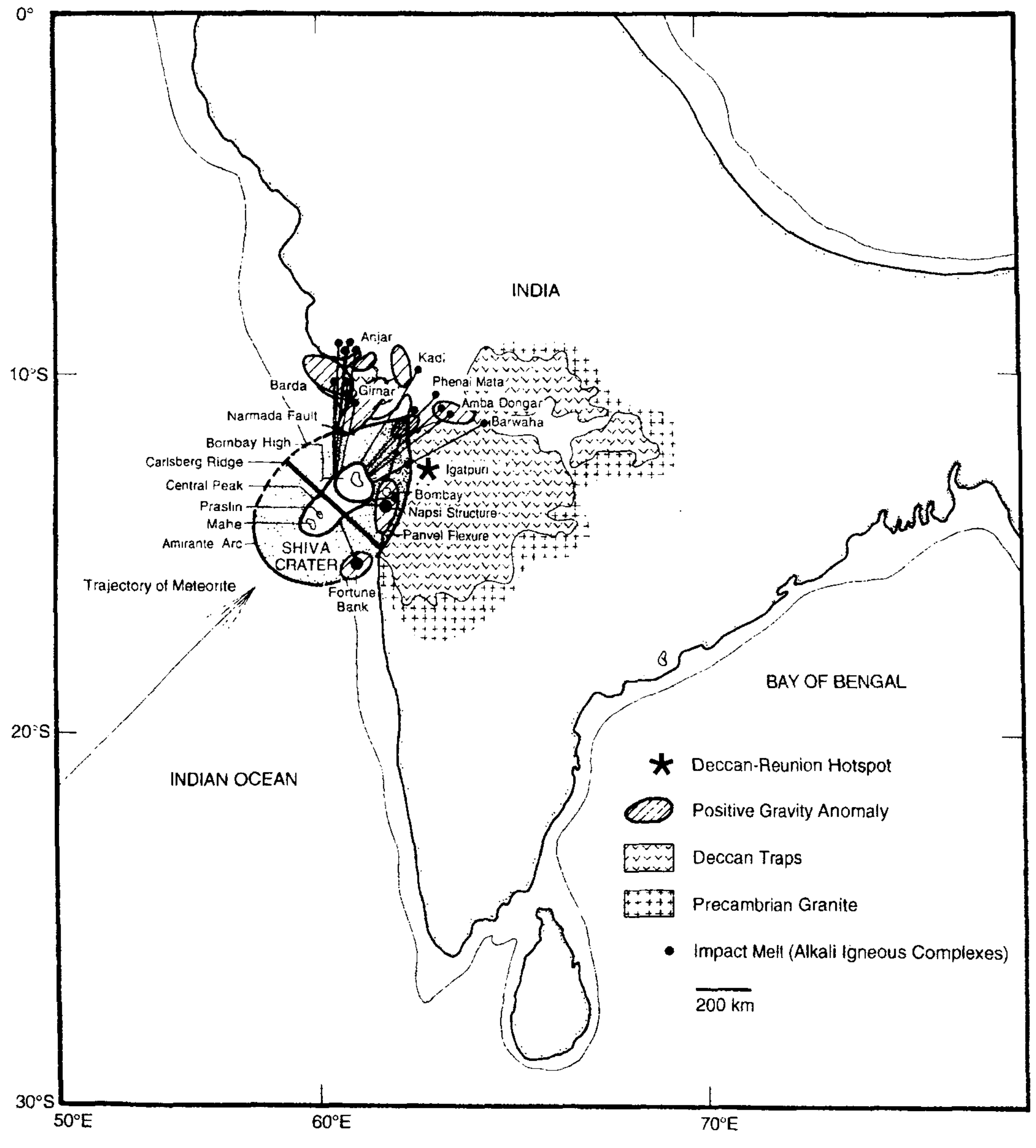

FIG. 3. Location of the Shiva Crater at the India-Seychelles rift margin during KT boundary; arrow indicates trajectory of meteorite; radial, asymmetric distributions of alkaline igneous complexes (impact melt rocks) downrange of the Shiva Crater are shown by closed circles (data from Bose, 1980); areas of positive gravity anomaly (data from Biswas, 1988) coincide with the ejecta melt distribution; asterisk indicates location of the Deccan-Reunion hotspot.

that the Amirante Basin, south of the Seychelles Island, may be a possible KT impact site. The basin has a subcircular shape of about 300km in diameter, bounded on the northeast by the Seychelles Bank and partially ringed on the southwest by the structure of the Amirante Arc. Sediments from the adjacent Amirante Passage have yielded Late Maastrichtian foraminifera *Abathomphalus mayorensis* (Johnson et al., 1982), while basalt samples dredged from the

Amirante Arc look like Deccan Trap and have a similar radiometric age (Fisher et al., 1968). Both palaeontologic and radiometric age indicate that the arc was formed near the KT boundary. However, its arcuate structure is enigmatic. It does not appear to be a recent or ancient trench, as it lacks volcanic activity, seismicity, and any significant accretionary sedimentary prism on its 'landward' side (Johnson et al., 1982). Thus the interpretation of the Amirante Arc as a crater rim is a distinct possibility. The proposed impact also may explain the puzzling jump of the Carlsberg Ridge at the KT boundary during the rifting of India and the Seychelles. Hartnady noticed that the Carlsberg Ridge between the Seychelles and Madagascar jumped more than 500km to the northeast to lie between India and the Seychelles and initiate rifting between these two landmasses. He could not find any evidence for plate reorganization in the Atlantic or Pacific Oceans during this time. He attributed this major plate tectonic adjustment to the enormous force of a large meteorite. As additional evidence, he pointed to massive tsunami deposits in the KT boundary section of Somalia and Kenya, which may be linked to this impact event.

Although Hartnady's model initially had attracted wide attention, one major problem of his idea is the enigmatic morphology of the Amirante Basin. It is semicircular in outline, preserving half of a supposed crater rim. What happened to the other half of the crater? Although circularity is not diagnostic of impact origin, there must be evidence of some structure off the coast of Seychelles. Is it possible to find the missing rim?

Alt et al. (1988) remedied the deficiency of the Amirante Basin model as the point of collision. They argued that during KT boundary, the Seychelles was adjacent to the west coast of india. They concurred with Hartanady (1986) that the western rim of the crater survives in the Amirante Arc, but the eastern rim lies along the west coast of India, hidden by the overlying Deccan Traps. They speculated that the impact was forceful enough to create not only the enormous crater approximately 600km in diameter, but also to cause pressure-release melting in the asthenosphere. Basalt then filled the crater basin to form an immense lava lake, the terrestrial equivalent of a lunar mare. The synchrony of initiation of spreading along the Carlsberg Ridge, the emplacement of the flood basalts at the Deccan plateau, Saya de Malha bank and Amrante Basin, as well as close spatial association around the crater basin, indicate that the array of simultaneous tectonic and volcanic features might have been triggered by a single physical cause — an enormous impact.

Chatterjee (1990; 1992) elaborated upon this KT impact scenario at the India-Seychelles rift margin, and identified the eastern rim of the crater along the Panvel Flexure, near the Bombay coast (Figs. 3-6). The Panvel Flexure is an arcuate segment of the crater about 120km long on the Deccan Traps, and it is difficult to explain in terms of conventional tectonics. It is marked by a line of hot springs, dikes, deep crustal faults and seismicity (Kaila et al., 1981; Powar, 1981). Since the Indian shield is usually aseismic, the seismicity along the flexure is unusual, indicating tectonic instability. The geothermal gradient is abnormally high along this flexure (36-78°C/km^{-1}) with evidence of thinned lithosphere (31-39km), suggesting melting conditions at shallow depths (Negi et al., 1992). The Panvel Flexure may represent the eastern rim of the crater in the form of a collapsed rim structure. It exercises tectonic control on the attitude of the Deccan lavas. 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° to 60° toward the coast. The abrupt change of dip along the flexure axis may indicate the slope of the eastern crater wall, which is now concealed by Deccan lavas. Seismic data indicate that the basement topography below the Deccan lava west of the flexure has a crater-like depression (Kaila et al., 1981). Completing the oval by combining the Amirante Arc and the Panvel Flexure, the extent of the crater can be extrapolated. It is a giant oval crater, 600km long and 450km wide, showing the morphology of a complex impact scar. Chatterjee (1992) named this impact structure the Shiva Crater, after the Hindu god of destruction and renewal (Fig. 3). However, the Shiva Crater is difficult to interpret because it is submarine and largely concealed by the Deccan lava. Many of the impact signatures are thus erased or obscured. Moreover, the rifting of the Seychelles from India, which occurred along the width of the crater, has obliterated the geomorphology of the structure. A series of geodynamic and volcanic events that occurred near KT boundary time must be untangled and put into proper chronologic order to unveil the crater morphology. Recent exploratory data from the Bombay High, a giant offshore oilfield located 160km west of the city of Bombay, has produced a wealth of infomation supporting an impact origin for the Shiva Crater.

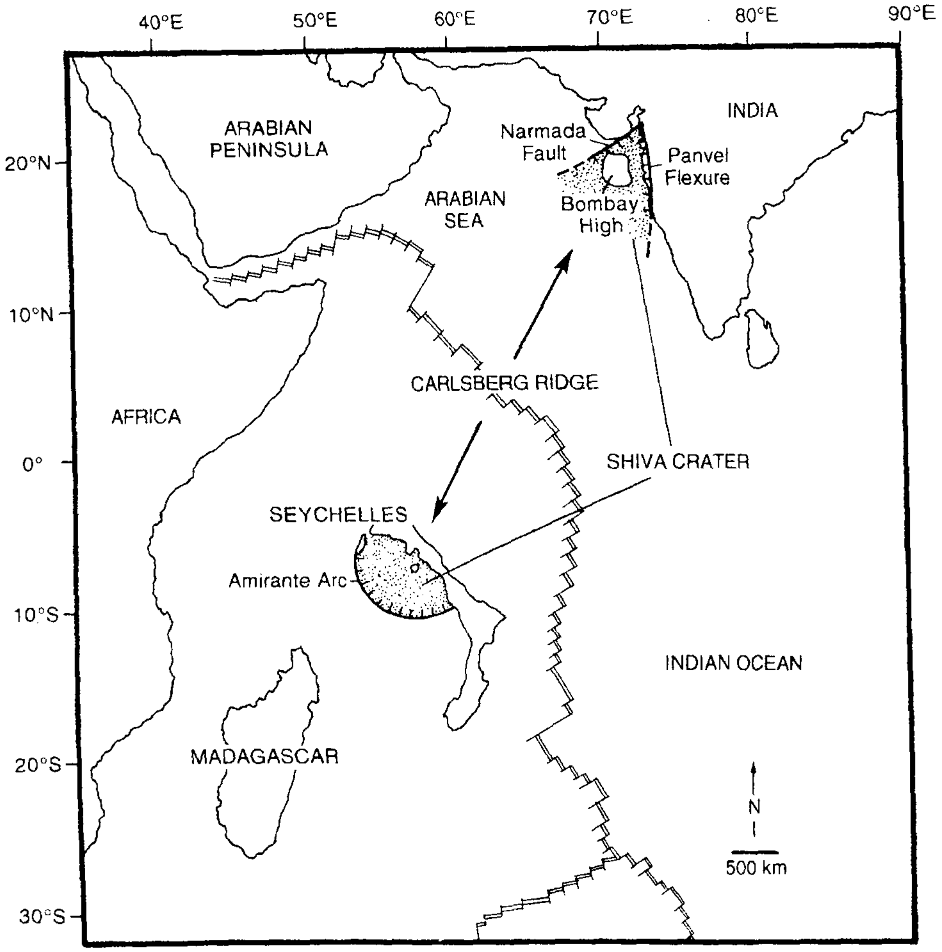

FIG. 4. Present day location of the split Shiva Crater in reference to India and Seychelles on either side of the Carlsberg Ridge. Today, part of the Shiva Crater is attached to the southern part of the Seychelles, the other-half to the western part of India. The crater was joined 65 million years ago when the Seychelles was part of India before the spreading of the Carlsberg Ridge.

INIDA-SEYCHELLES FIT. Today, the Seychelles microcontinent is separated from the western coast of India by 2,800km because of spreading along the Carlsberg Ridge (Fig. 4). This midoceanic ridge shows symmetrical magnetic anomalies of 5, 23, 24, 25, 26, 27, 28 and 29 on either side of the ridge axis between India and the Seychelles (Norton & Sclater, 1979; Naini & Talwani, 1982). Using both palaeomagnetic and palaeontologic evidence Chatterjee (1992) has restored the India-Seychelles fit for the KT boundary time (Figs. 3 & 8). The reconstruction places the western coast of India against the Seychelles-Saya de Malha Bank at about the time of Deccan volcanism and shows matching geological provinces. The largely submerged continental block that bears the Seychelles Islands contains enormous flood basalt deposits in the submarine plateau of the Saya de Malha Bank, which are inferred to be an extension of the Deccan volcanism (Meyerhoff & Kamen-Kaye, 1981; Backman et al., 1988), especially the Bushe Formation of the Upper Deccan Basalt Group (Devey & Stephens, 1992). The link between KT magmatism on the Seychelles and India is emphasized by matching the geochemistry and geochronology of alkaline rocks (White & McKenzie, 1989; Devey & Stephens, 1992). Similarly, the Late Proterozoic Mahe Granite on the Seychelles (Baker & Miller, 1963) is isochronous (70050Ma) with the Siwana-Jalor Granite (Auden, 1974) of western India, the crystalline basement below the Deccan lava. Various tectonic and volcanic features, when restored for the Indo-Seychelles block at 65Ma, reveals the presence of a large oval, oblong structure, the Shiva Crater (Figs. 3, 5).

ANATOMY OF THE SHIVA CRATER. Since the Shiva Crater was spilt by the Carlsberg Ridge and each half is now buried under a thick pile of lava flows, and because the structure is largely submarine, geophysical exploration and drilling data are essential to understanding its morphology and structure. Morever, overlying lava flows and thick sediments obstruct a direct examination of various impact signatures such as shock metamorphic effects, breccia and impact melt that are generally associated with complex craters. Today, one part of the crater is attached to the western coast of India, the other to the Seychelles (Fig. 4), but of course both parts were joined at the KT boundary (Fig. 3).

The most critical evidence regarding this impact structure comes from recent oil exploration in the Bombay High offshore basin, which represents the eastern-half of the crater. Bombay High is a giant offshore oilfield (~120,000^{2}km) located 160km west of Bombay in the Arabian Sea at a depth of about 75m (Fig. 5). The structure is 60km long and 20km wide, trending WNW-ESE with a faulted eastern flank. The stratigraphy of this enigmatic structure is known from extensive drilling and seismic data by the Oil and Natural Gas Commission (Rao & Talukdar, 1980; Basu et al., 1982; Bhandari & Jain, 1984). The Bombay offshore basin shows part of the crater rim (Panvel Flexure and Narmada Fault), annular trough (Surat Basin, Dahanu Depression, and Panna Depression) and the central uplift (Bombay High) (Fig. 5A). The morphology of the western-half of the Shiva Crater around the Seychelles microcontinent is also known from oil exploration data (Meyerhoff & Kamen-Kaye, 1981; Kamen-Kaye, 1985; Devey & Stephens, 1992). Here we see part of the crater rim (Amirante Arc), annular trough (Amirante basin) and the central peaks (Mahe and Praslin granitic cores). When the Shiva structure is restored to KT boundary time (Fig. 5), it shows the structure and morphology of a giant, complex crater, oval in outline with: 1, a collapsed outer ring, 600km long and 450km wide; 2, an annular trough, presumably filled with KT melt rocks; and 3, a distinct central core in the form of linear uplifted peaks of older Precambrian granite.

The Shiva Crater is defined by a collapsed outer ring, which is partially preserved in the form of the Amirante Arc, Panvel Flexure and the Narmada Fault (Figs. 3 & 5). The outer rim is surrounded by a gravity high, especially in both the Panvel Flexure and Narmada Fault areas (Biswas, 1988) and may be linked to the distribution impact melt. Part of the outer ring along the northwest and southeast edges was obliterated by spreading of the Carlsberg Ridge. The outer ring is followed by the annular trough which was largely filled with ponded Deccan lava (and possibly by suevite and impact melt). Part of the trough is preserved in the Surat Basin, Dahanu Depression and Panna Depression around the Bombay High, and the Amirante Basin, southwest of the Seychelles. The uplift in the center is represented by a large peak followed by two small irregular peaks, all composed of older Precambrian granitic cores: the Bombay High on the western coast of India and the Praslin and Mahe Islands of the Seychelles. Jansa (1993) pointed out that the central uplift in oceanic impact sites is generally cylindrical in shape, as is the Shiva Crater. The lateral continuity of the central peaks was disrupted by the Carlsberg Rift and may indicate a collapse structure. The central uplift associated with the 600km Shiva Crater is estimated to be 150km wide, about one-fourth of the crater's final diameter, as is expected in a complex crater (Melosh, 1989). Figure 5B is a geologic cross-section of the 600km diameter Shiva structure along the longitudinal axis. The depth of the crater can be estimated from the thickness of the sedimentary basins around the annular trough as well as from the height of the central peaks. The sedimentary fill around the trough of Bombay High consists of shallow marine Tertiary sediments exceeding 5,000m, overlying the Deccan basalt floor (Bhandari & Jain, 1984). Such thick sediments indicate that the crater basin is more than 5km deep above the Deccan floor. The thickness of the Deccan lava, and the presence of impact melt within the crater are unknown, but Meyerhoff and Kamen-Kaye (1981) have described a well log on the Saya de Malha Bank which penetrated 832m of basalt overlain by 2400m of upper Palaeocene to Quaternary sediments. Based on their seismic work, Shor & Pollard (1963) suggested that approximately 2km of Deccan basalt overlie the granitic basement some 80km southwest of the

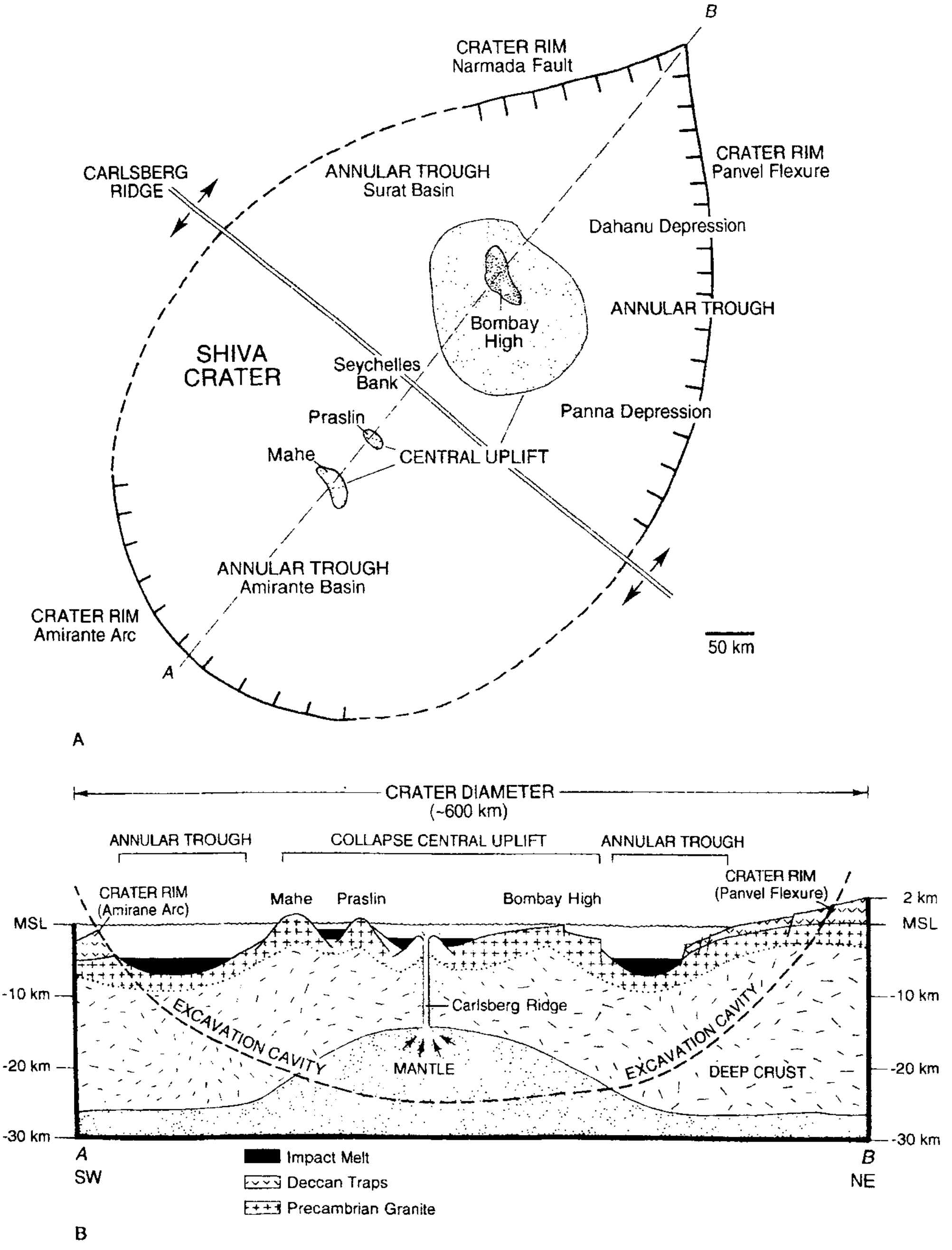

FIG. 5. Morphology of the Shiva Crater. A, plan view showing a central uplift (Bombay High, Praslin and Mahe granitic core); an annular trough (Surat Basin, Dahanu Depression, Panna Depression and Amirante Basin); and a slumped outer rim (Narmada Fault, Panvel Flexure and Amirante Arc). The oblong crater is about 600km long, 450km wide and more than 12km deep; it is bisected by the Carlsberg Ridge. B, schematic cross-section along the line AB; the post-impact Deccan lava flows are removed to show the morphology of the crater and possible sites of impact melt sheets; (seismic profile data from Rao & Talukdar, 1980; Kaila et al., 1981).

Mahe Peak. If we now add to this the 2km thick lava pile in the Western Ghats section near the Panvel Flexure, the depth from rim to actual floor may exceed 10km (Fig. 5B).

AGE OF THE SHIVA CRATER. Although the age of the Shiva Crater is not precisely known, combined evidence from various components of the structure, such as the formation of the rim, biostratigraphy of the annular trough, age of the melt sheets, timing of the central uplift, association of Deccan volcanics and the Carlberg rifting event suggests that the crater formed at the KT boundary. As discussed earlier, the preserved rim of the Shiva Crater, such as the Amirante Arc (Hartnady, 1986; Alt et al., 1988), the Panvel Flexure (Auden, 1949; Chatterjee, 1992) and the Narmada Fault (Biswas, 1988) evolved at KT boundary time. Seismic stratigraphy has identified the basement rock as reflection-free or chaotic Precambrian granite in the form a central uplift with a thin veneer of Deccan lava at the base (Rao & Talukdar, 1980; Basu et al., 1982; Bhandari & Jain, 1984). The oldest sediment overlying the Deccan Trap or crystalline basement is the Panna Formation of Palaeocene age (Fig. 6). The upper boundary of the Panna Formation coincides with H-4 seismic horizon. The Panna Formation is composed of poorly sorted, angular sandstone, claystone and trap fragments at the bottom, followed by shale and coal sequence. This unit is relatively thin on the uplift, but attains a large thickness (75m) on the flank. Seismic data indicate that the formation may be as thick as 500m in the annular trough region, but wells have not penetrated the bottom layer. Although the formation is mostly unfossiliferous, it has yielded *Globorotalia pseudomenardii* from the middle of the sequence corresponding to P4 planktic foraminiferal zone of Late Palaeocene, indicating a short palaeontologic hiatus after the KT event. Since the impact took place in a shallow-marine setting, the hiatus may be linked to erosion by a megatsunami generated by the impact. The KT boundary section lies farther down at the bottom of the sequence. Jansa (1993) suggested that in oceanic impacts most of the fall-out breccia is reworked back into the crater cavity. If so, the lowest unit of the Panna Formation, if recovered in future, should be investigated for an iridium anomaly and shock metamorphic minerals (Fig. 6B). The crater floor is composed of younger Deccan flows from the adjoining Western Ghat section that took place around ~65Ma (Couirtillot, 1990; Duncan & Pyle, 1988). The Deccan floor at the annular trough and the overlying Panna Formation narrow down its age to close to the KT boundary. Recent isotopic dating of the Shiva melt rock, as discussed in the following section, has yielded an ^{40}Ar/^{39}Ar date of 65Ma (Basu et al., 1994). Finally, the Carlsberg rifting within the crater basin was formed during the magnetic chron 29R (Naini & Talwani, 1982).

Although it is generally believed that the Bombay High was formed during the breakup of India-Seychelles at the KT boundary (Basu et al., 1982), no tectonic mechanism has been offered to explain this spectacular uplift (~ 10km high) of the Precambrian granite with a thin veneer of Deccan Traps at the passive margin of the Bombay shelf (Fig. 6B). We propose that this structural high represents one of the central peaks of the Shiva impact that originally underlay the transient crater. The other two central peaks, Praslin and Mahe Islands in the Seychelles (Fig. 5A), also rebounded upward at the same time as they contain similar Precambrian granites and younger KT intrusive rocks (Devey & Stephens, 1992). These central peaks are composed of deformed and fractured rocks that have been stratigraphically uplifted distances comparable to the crater depth (Melosh, 1989). The fractured nature of the central peak of the Bombay High can be seen in Figure 6B. The crystalline rocks beneath the Shiva Crater are shattered, as in the Ries Crater of Germany, as inferred from the low seismic velocity beneath the H4 horizon (Rao & Talukdar, 1980). Similarly, Baker (1967) reported a 'megablock zone' — a chaotic assemblage of gigantic blocks of granite, each up to 13m high, often marked with surface fluting at the Mahe uplift in the Seychelles. Evidence from drill holes, geochronology and seismicity suggest that the magmatism at the Seychelles Bank occurred at the KT boundary, producing both Deccan lavas and alkaline igneous complexes (Devey & Stephens, 1992).

IMPACT MELT ROCKS. The Shiva impact must have produced enormous volumes of impact melt, breccias and shocked materials between the central structure and the rim. Yet, these impact signatures are difficult to interpret because of mobilization and mixing of thick lava flows from Carlsberg Ridge, subsequent burial by the Deccan lava, as well as lack of drilling and seismic data below the Deccan floor. However, there is some indirect evidence that indicates a lava-like impact melt was emplaced radially within and outside the crater.

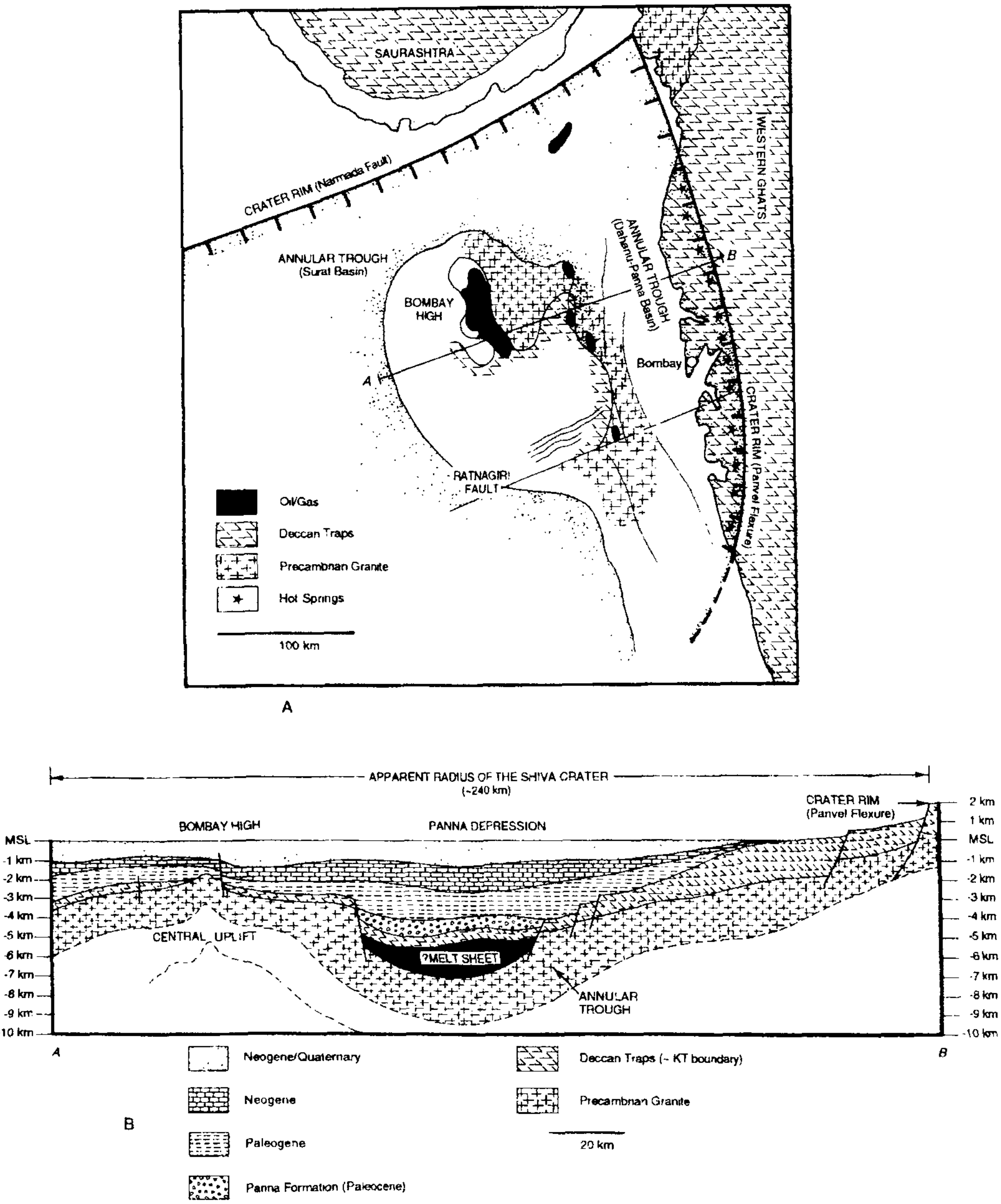

FIG. 6. A, Location and tectonic framework of Bombay High in relation to India representing the eastern-half of the Shiva Crater (simplified from Rao & Talukdar, 1980). B, seismic cross-section along the line AB to show the central uplift (Bombay High), annular trough (Panna Depression) and the crater rim (Panvel Flexure) (simplified from Rao & Talukdar, 1980).

One of the most intriguing features following the Deccan flood basalt volcanism is the occurrence of several post-tholeiitic alkali igneous complexes of nepheline-carbonatite affinities, along the radii of the Shiva Crater (Figs 3, 7). They are manifested in plug-like bodies and minor intrusions in the western and northwestern part of the Deccan volcanic province and are limited in space and volume compared to the vast expanse of tholeiitic lavas (Bose, 1980; De, 1981). They are clearly defined by zones of gravity highs (Biswas, 1988). Extrusive rocks are relatively rare except in the Kutch rift zone, indicative of fissure eruption. Devey & Stephens (1992) described contemporary alkaline intrusives in several islands in the Seychelles microcontinent, especially in Mahe, North Island and Silhouette Island within the Deccan lavas. Geochemically they are very similar to the Murud alkaline dikes of Bombay. Recent $^{40}Ar/^{39}Ar$ dating of these alkaline complexes indicates 65Ma, precisely coinciding with the KT boundary (Basu et al, 1993; Pande et al, 1988; Devey & Stephens, 1992). In the Anjar section of the extrusive alkaline complexes, cosmic iridium and osmium anomalies have been reported from the interbed (Bhandari et al., 1994). Their distributions are shown in Figures 3 & 7A.

Two spectacular volcanic plugs within the Shiva Crater need discussion. One is Fortune Bank igneous center south of the Seychelles, the other is a newly discovered buried structure near Bombay. The Fortune Bank is an unusual submarine volcanic center, about 15kms high and 50km across, with anomalous magnetic and gravity signatures within the Deccan volcanics (Girling 1992). Devey & Stephens (1992) interpreted this structure as a large alkaline intrusion contemporary with similar volcanics around the Seychelles. Negi et al. (1993) identified a large volcanic cone-like intrusive, about 12km high and 35km in diameter, buried 6km below the Deccan Trap near Bombay, east of the Panvel Flexure. It is defined by a high gravity and thermal anomaly. They found that the crustal thickness in this site is half of the normal Moho depth, and the granitic basement is almost missing in this region. They interpreted the structure as a large fossil conduit, formed at the point of collision of a large KT meteorite. For ease of description, we designate this igneous complex the *Napsi structure* after the last names of the discoverers (*N*egi, *A*grawal, *P*andey, *Si*ngh). Since alkaline intrusives are known from this area, and they show high gravity anomalies relative to the surrounding Deccan Trap, we interpret the Napsi structure as a massive alkaline complex similar to the Fortune Bank (Fig. 7A).

The origin of these alkaline igneous complexes within the Deccan volcanics has been debated for many years. They have been linked to fractional crystallization of parent tholeiitic magma (West, 1958), an early stage of Carlsberg rifting (Thompson & Nelson, 1972; Devey & Stephens, 1992) and a late stage of Reunion mantle plume (Bose, 1980; De, 1981; Basu et al. 1993). How is it possible to derive from the same mantle source large volumes of tholeiite extrusives followed by limited occurrences of alkaline intrusives? Why are the alkaline rocks so heavy relative to the Deccan Traps and so easily demarcated by gravity anomalies? How can we explain the abundance of these alkaline rocks in and around the Shiva Crater in the form of volcanic cones? Some of these buried volcanic cones, such as Napsi structure and Fortune Bank even dwarf Mount Everest. Alkaline igneous complexes are commonly found as melt sheets associated with several Canadian craters (Grieve, 1987). The spatial and temporal correlations of these alkaline igneous complexes with the Shiva Crater are intriguing, making a causal relationship likely. All these alkaline igneous complexes show the following features indicative of impact origin:

1, The centers of alkaline magmatism are clustered around the Shiva Crater in radial fashion but conspicuously absent in other parts of the Deccan province (Figs 3 & 7A);

2, Their age matches exactly with the KT impact event;

3, They are all defined by positive gravity anomalies;

4, They have restricted distributions and occur within the Deccan volcanics as post-tholeiitic intrusives or plugs;

5,Their parent melt composition was homogeneous, but later differentiation within the plug has produced varieties and compositional layering as in the case of impact melts in several Canadian craters such as Brent and Manicougan;

6, They show higher alkali content than the country rock;

7, They show evidence of crustal contamination.

This evidence suggests that the alkaline igneous rocks around the Shiva Crater were formed by crystallization from impact melted country rocks. We hypothesize that these alkaline rocks represent melt ejecta produced by impact-induced mixing and melting of the target rocks, and were emplaced radially on downrange side of the trajectory (Fig. 7A). The close isotopic and age relationship of the impact melt with the younger Deccan volcanics such as the Ambenali Formation (Pande et al., 1986; Devey & Stephens, 1992) indicates remelting of these rocks. We believe three groups of rocks, younger Deccan volcanics, platform carbonates and evaporites, and

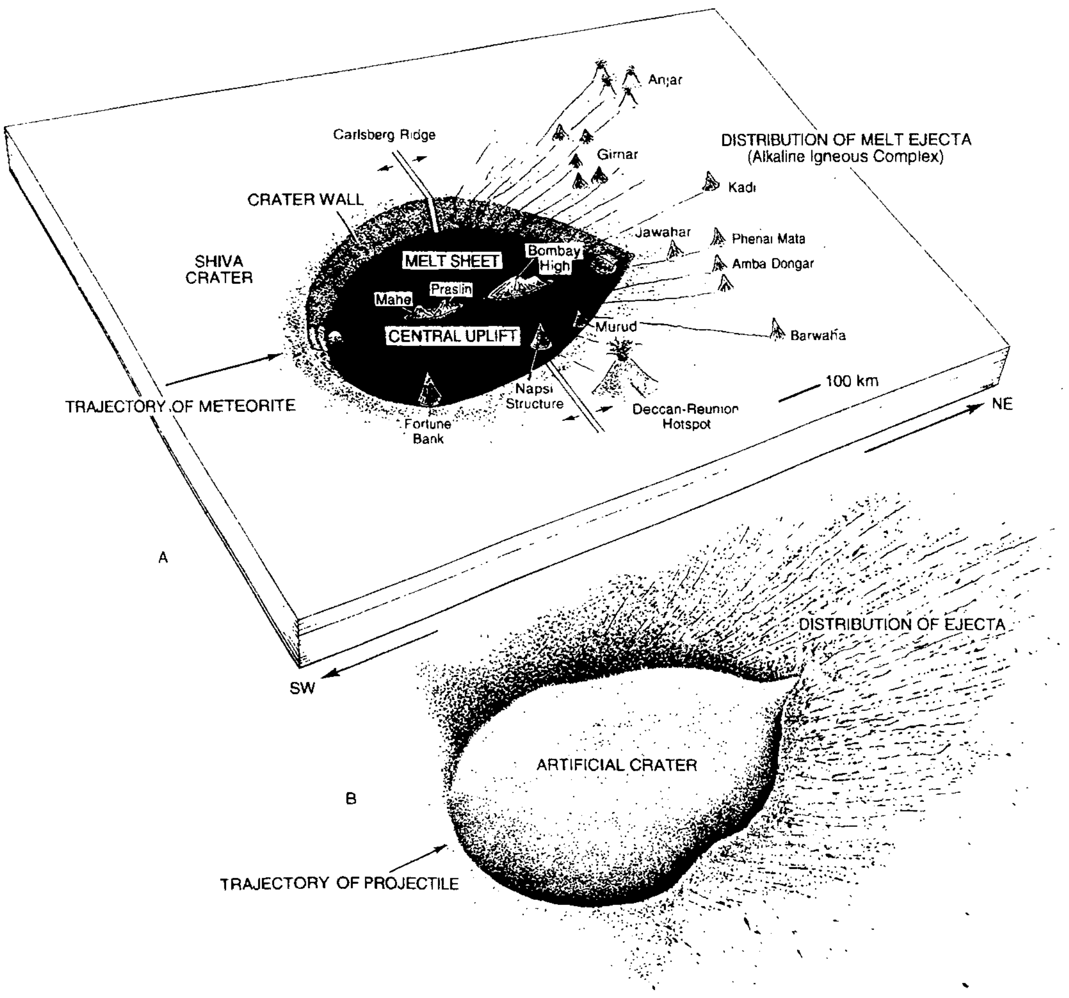

FIG. 7. A, Schematic three-dimensional view of the Shiva Crater showing the radial distribution of the impact melt rocks in the form of volcanic plugs; younger Deccan volcanics are removed to show the morphology of the crater; oblong, teardrop shape of the crater and the asymmetric distribution of the melt rocks consistent with an oblique impact event along the NE downrange direction. B, Artificial crater produced by low-angle (~15°) oblique impact in the laboratory mimics the shape and ejecta distribution of the Shiva Crater (simplified from Schultz & Gault, 1990).

Precambrian basement were involved in the genesis of the melt rocks of the Shiva Crater. The younger Deccan volcanics covering the Precambrian basement of the Bombay and Seychelles region at the KT boundary were the main target rocks. However, the Precambrian granite itself was also involved in the impact, as indicated by the unusually thin crust in the Bombay area with missing granitic layer (Negi et al., 1993) as well as by evidence of crustal contamination in the alkaline suites (Paul et al, 1977; Basu et al., 1993). The Shiva Crater was also inferred to have been excavated on a shallow sea platform containing thick carbonate and evaporitic rocks such as we see today around the Bombay High and Rann of Kutch. Thus the melt rock can be interpreted as the mixing product of Deccan Traps, Precambrian granite and the thick Late Cretaceous sequences of carbonate/evaporite-rich sediments. These Cretaceous sediments are still preserved in the adjacent Kutch, Saurashtra and Rajasthan areas, covered by the Deccan Traps, and are encountered by subsurface drilling (Biswas, 1988). However, the alkaline rocks are

TABLE 1. Large Earth-crossing and Earth-approaching asteroids (diameter > 10km; after Wetherill & Shoemaker, 1982).

NUMBER	NAME	CLASS	DIAM. (Km)
1866	Sisyphus	Apollo	11.4
433	Eros	Amor^3	19.6
1036	Ganymed	Amor^3	39.6

generally undersaturated with a high K_2O/NaO ratio relative to the Deccan tholeiites (Bose, 1980). Such an 'anomaly' is not unusual with an impact event. Alkaline volcanic rocks are commonly present as impact melt in most of the Canadian craters. Grieve (1987) discussed the compositional variation of these alkaline melt rocks, where melt sheets have a higher K_2O/NaO ratio than the target rock. The reason for this alkali enrichment is not clear; he believed that either it is caused by selective elemental vaporization and condensation during the melt and vapor formation, or hydrothermal alteration. Since the impact was largely oceanic, the latter explanation of enrichment of alkali from sea water is likely. The gravity high of the alkaline igneous complexes most likely reflects mass concentration associated with dense impact melt and uplift of the silicate basement rock along the crater rim (Figs. 3, 7A).

The radial distribution of melt sheets in the down-range direction of the Shiva Crater is intriguing (Fig. 7A). They might have developed either during the passage of the shock waves when fluid ejecta was emplaced downrange, or during the collapse of the transient crater when radial fractures were formed. Melosh (1989) discussed the mechanism by which radial fracture patterns develop during the collapse of a large, multi-ring crater. Radiating fractures from the central uplift to the rim are known from the Manicougan Crater of Canada (Grieve et al., 1988) and the Wells Creek Structure of Tennessee (Stern, 1968).

SIZE AND TRAJECTORY OF THE IMPACTOR. Throughout its history the Earth has been impacted by countless meteorites. There are two broad categories of meteorites with orbits that bring them close to the Earth: comets and asteroids. Comets are composed in large part of water, ice and other volatiles and therefore are more easily fragmented than rocky or metallic asteroids. Although smaller meteorites pose little threat, impacts by large objects (diameter > 1km) constitute the greatest hazard, with their potential for global environmental damage and mass mortality. The most famous large impact on planet Earth is the KT event that killed the dinosaurs and other contemporary biota. Wetherill & Shoemaker (1982) have summarized the current knowledge of Earth-crossing and Earth-orbiting asteroids and their probability of impacting the Earth. They estimate that out of 1,000 near-Earth asteroids (NEA) that have diameters greater than 1km, three exceed the 10km range. These are 1866 Sisyphus (11.4km), 433 Eros (19.6km) and 1036 Ganymede (39.6km) (see Table 1). Both Eros and Ganymede can be perturbed into Earth-crossing orbits by close encounters with Mars. They speculate that asteroids as large as 20km in diameter probably have struck the Earth in the last few billion years, and 10km diameter bodies apparently may impact every 40 million years. Recently Paola Farienella of the Universty of Pisa in Italy and colleagues simulated eight computer models to calulate the probability of colliding the 20km-wide asteroid Eros with the Earth. One forecast of this catastrophic impact is alarming; it could happen in the next 1.14 million years (Desonie, 1996). Because of this continued threat from space, NASA has organized an International Spacegurad Survey Network to detect and monitor near-Earth-objects. In February 1996 NASA sent its Near Earth Asteroid Rendezvous (NEAR) spacecraft to examine Eros from a close distance. The spacecraft is scheduled to arrive in close proximity to this asteroid in 1999 to scrutinize its surface in great detail for the understanding of its origin (Bell, 1996).

Although hypervelocity impacts normally create circular craters, impacts at a low angle (≤15° from the horizontal) often generate elongate craters such as the Messier and Schiller Craters of the Moon (Wilhelms, 1987) and the Rio Cuarto Crater in Argentina (Schultz & Lianza, 1992). Craters formed by artificial oblique impact are generally oblong (Moore, 1976; Gault & Wedekind, 1978). The shape of an artificial crater formed by oblique impact at 15° (Schultz & Gault, 1990) is like a teardrop, where the pointed end indicates the downrange direction (Fig. 7B). In an oblique impact, the crater and its ejecta are bilaterally symmetrical about the plane of the trajectory, but the distribution of ejecta is concentrated asymmetrically on the downrange side. The shape of the Shiva Crater and the distribution of melt ejecta are almost identical to those of the artitificial crater (Fig. 7A). If so, the impact that produced the Shiva Crater was probably oblique along a SW-NE trajectory as evident from the direction of the longer diameter of the oblong crater; the tip of teardrop indicates that the downrange direction was NE. Howard & Wilshire (1975) described flows of impact melt of large lunar craters both outside on crater rims and inside on crater walls, where asymmetric distribution of this melt sheet can be used to determine impact trajectory. The rim pools tend be concentrated on the inferred downrange side.The asymmetric concentrations of sheet melts on the NE side of the Shiva Crater indicate the downrange direction (Fig. 7A).

We estimate that a 40km diameter asteroid, about the size of the Amor object Ganymed, could have created the Shiva Crater, initiated the Carlsberg rift and excavated the crustal materials into mantle reservoirs resulting in basaltic volcanism (Fig. 5A). An impact of this magnitude may be a rare event, but seems possible, because of the presence of even larger craters on the Moon and Mars. Currently there are at least three known craters which are close to 200km across: Vredefort in South Africa (2,000Ma), Sudbury in Canada (1,849Ma) and Chicxulub (65Ma) in Mexico. The Shiva Crater is not unique, but nearly so. The only older similar structure in its size range is the eastern shore (Nastapoka Arc) of Hudson Bay in Canada: this 600km wide depression is believed to be an impact scar of Archean age (Dietz, 1993). If properly understood, the Shiva Crater is the largest impact structure produced in the Phanerozoic and is consistent with the environmental havoc wreaked at the KT boundary.

A new model of lithosphere thinning by meteoritic impact is proposed here to explain the origin of the Carlsberg ridge, rift volcanism and the Shiva Crater. In this model the lithosphere could be excavated and shattered by a projectile of considerable size (~40km) to initiate a midoceanic ridge. Asteroids strike the Earth at an average speed of 25km/sec and transfer considerable kinetic energy to the target rocks (Shoemaker, 1983). The pressures exerted on the meteorite and target rock can exceed 100GPa; temperatures can reach several thousand degrees Celsius; and impacting energy would generate a 100-million megaton blast (Grieve, 1990). Such a hypervelocity impacting body penetrates the target rocks to two or three times its radius (Grieve, 1987). An asteroid of 40km diameter would produce cratering and associated tectonic rebound-collapse effects sufficient to shatter the 80km thick lithosphere that could form plate boundaries and continental rifts. This concept opens up a new field of research to investigate whether plate tectonics may be influenced by impacts of large bodies.

NEW LINKS BETWEEN THE CHICXULUB AND THE SHIVA CRATERS.

A Multiple-impact Model. If both the Chicxulub and Shiva Craters are real and were formed at KT boundary time, is there any genetic link between them? Hartnady (1989) suggested that if a low-angle, oblique primary impact occured in the Southern Hemisphere near India, then bolide ricochet may have resulted in secondary impacts a few minutes later in the Northern Hemisphere. However, since the trajectory of the Shiva Crater is from SW to NE, Hartnady's model fails to explain the origin of both the Shiva Crater and the Chicxulub Crater by oblique impact ricochet process. However, the recent crash of 21 fragments of comet Shoemaker-Levy 9 (S-L 9) on Jupiter inspired scientists searching for similar multiple impacts on other bodies in the solar system. Crater chains were soon discovered on Jupiter's satellites and on the Moon (Levy et al., 1995). The cometary fragments of S-L 9 did not collide simultaneously on Jupiter but spread in time over 5 days. If the original KT meteorite broke into several fragments, as in the case of Shoemaker-Levy, and the larger one formed the Shiva Crater, the second impact, almost after 12 hours (or odd multiple thereof), could create the Chicxulub as the Earth rotated anticlockwise around its axis. If the collisions of two fragments were spread over 12 hours, two antipodal craters could be formed by meteorite fragments around a great circle. If so, one can predict that additional KT impact scars, if discovered in future, should lie on this great circle joining the Shiva and the Chicxulub structures. This great circle is named here the *Alvarez Impact Belt* in honor of Luis and Walter Alvarez for their pioneering work (Fig. 8A).

There may be signs of this 'string of pearls' effect along the Alvarez Impact Belt in the form of a crater chain. Various authors have predicted a third KT impact site on the Pacific plate which surprsingly lay along the Alvarez Impact Belt. Frank Kyte (pers. comm.) made a dramatic discovery of a tiny fragment (~ 3mm) of the KT bolide in a drill core from DSDP site 576 in the western North Pacific. The bolide chip held micrometer-size metallic grains that are up to 87% nickel and rich in iridium. From the geochemical signature of the chip, Kyte speculates that the KT projectile is probably an

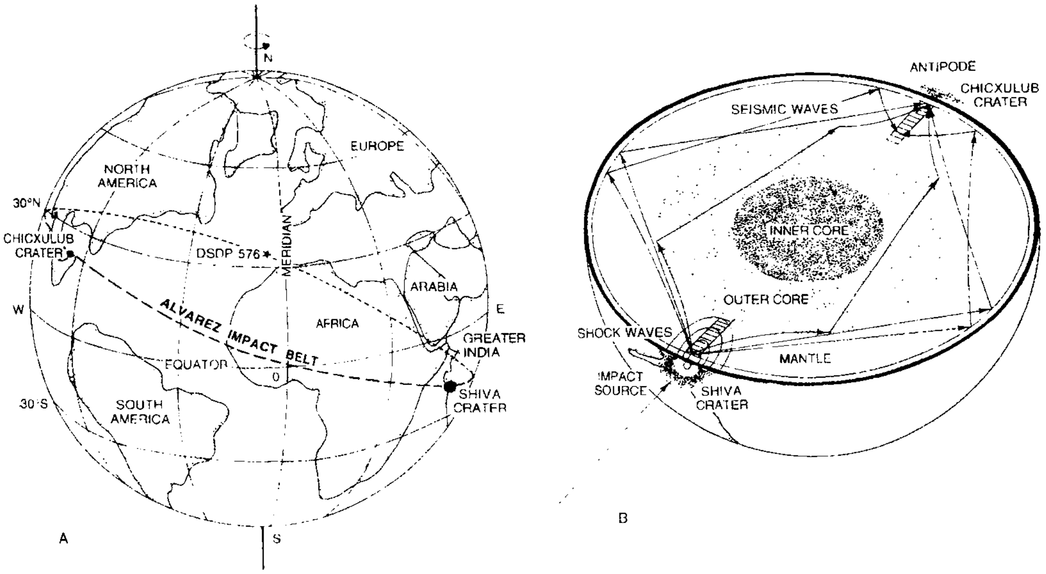

FIG. 8. Possible links between the Shiva and Chicxulub Craters. A, locations of the Chicxulub and the Shiva Craters along the 'Alvarez Impact Belt' at KT boundary time; note, impact debris and extinction events are concentrated along this belt. Both craters may have originated when two fragments from a larger meteorite crashed on a rotating earth over the course of 12 hours. B, near-antipodal positions of the Chicxulub and the Shiva Craters may also indicate alternative scenario that a large impact on one side of the Earth (near India) might have produced a similar signature on the far side (near Mexico) by axial focusing of seismic waves (modelled after Boslough et al., in press).

asteroid, not a comet, that slammed into Earth at a shallow angle. This is the first direct evidence regarding the carrier for iridium. The chip may have broken off of the asteroid before it crashed on the Pacific plate. At 65Ma, the Pacific impact site was located midway between the Chicxulub and the Shiva Craters right on the Alvarez Impact Belt (Fig. 8A). Kyte et al. (1994) also identified additional five KT boundary sites on the Pacific Plate around 576, characterized by an iridium anomaly, spherules and shocked quartz; they all cluster along this DSDP site 576. The point of collision of the KT projectile on the Pacific plate is further supported by other evidence. Robin et al. (1994) concluded from spinel compositions at the KT boundary sites of the Pacific plate that multiple impacts might have occurred from a single disrupted bolide, where the largest objects would have impacted in the Pacific and Indian Ocean. Their spinel distributions and proposed impact site at the Pacific fit nicely with the Alvarez Impact Belt. Finally, all the known localities with an iridium anomaly and shocked quartz related to the KT impact event (see Alvarez & Asaro, 1990) cluster symmetrically on either side of the Alvarez Impact Belt. Distribution of impact-related minerals and trace elements along this belt coincides nicely with biogeographic selectivity of extinction at low latitudes (Keller, 1994). The high latitudes probably served as a refuge for many organisms, especially for plants. If so, the distribution of several impact sites and variation of composition of impact-generated minerals along the Alvarez Impact Belt could be explained by multiple impact events on a rotating Earth, around the equator, rather than by a single large impact. Such a latitudinal gradient, with most extinctions occurring in the tropics, is exactly what is to be expected by a chain of three impact sites in India, Mexico and Pacific plate respectively. These sites were formed when a large parent body broke apart into a string of smaller asteroidal fragments in the inner solar system and crashed into the planet.

Recently, Alvarez et al. (1995) raised three paradoxes in KT boundary sediments which are apparently difficult to reconcile in a single impact hypothesis. 1) In North America the KT boundary reveals the double layer of ejecta: the lower layer consists mainly of iridium spike and altered spherules, whereas the upper contains shocked quartz. 2) Shocked quartz is more abundant and coarser grained at longitudes west than east of the Chicxulub Crater. Various KT boundary sites in Europe, Africa and Asia show little or no evidence of shocked quartz and may represent a 'forbidden zone' for shocked quartz distribution. 3) The proposed impact energy (>100GPa) released by collision of a 10km diameter asteroid at Chicxulub Crater would produce impact melt, not the moderate-pressure shock lamellae. Alvarez et al. linked all these three anomalies to differential timing of emplacement of target rocks. However, we speculate that the double layer ejecta at KT boundary sediments reflects two different sources of impact events: the lower iridium spike and impact spherules layer might have come from the earlier Shiva impact, whereas shocked quartz layer was emplaced during the Chicxulub event. This travel time sorting at two different impact sites may explain stratigraphic superposition of the double layer ejecta in North America and lack of upper layer in the distant areas of Europe, Asia and Africa. We propose that the energy released at the Shiva impact site was hundreds of gigapascals through the collision of a larger bolide fragment that produced mainly impact melt, emplacing it around the crater vicinity. From this impact site, spherules and iridium spikes were emplaced distally and globally. The high impact pressure would explain why we could not detect any shocked quartz grains at the KT boundary sections in India after repeated searches, as well as a general lack of shocked quartz in adjacent landmasses in Asia, Europe and Africa. On the other hand, the impact energy at the Chicxulub site was moderate to the tune of a few tens of gigapascals, producing mainly shocked quartz ejecta that were emplaced on the western side of the crater as the Earth rotated anticlockwise. Occurrence of multiple iridium spikes at some KT boundary sections (Officer et al., 1987) may be attributed to different timing of arrival from separate sources of impact sites.

Antipodal Crater Pairs Model. The antipodal locations of the Chicxulub and Shiva craters at the KT boundary are intriguing and suggest an alternative scenario (Fig. 8B). A hypervelocity impact is now known to have important geomorphic effects at its antipode. For example, Watts et al. (1991) documented unusual surface features such as 'disrupted terrains' antipodal to crater basins on the Moon, Mercury and icy satellites. Similarly, Rampino & Caldeira (1992) proposed that antipodal focusing of impact energy may lead to Deccan volcanism and hotspot activity. Boslough et al. (1994) proposed a new model to explain how energy from a large impact on the Earth's surface would couple to its interior and focus axially at its antipode. However, their model is based on a vertical impact, whereas most impacts occur obliquely (Schultz & Gault, 1990). Because the Shiva Crater is much larger than the Chicxulub, it is likely that the Shiva Crater is the primary impact event at the KT boundary, whereas the Chicxulub may be its antipodal effect (Fig. 8B). The oblique impact may explain the departure of a few hundred kilometers from the true antipodal position. However, the presence of an iridium anomaly at the Chicxulub antipode is difficult to explain by the axial focusing mechanism. Similarly, the Pacific site of collision is anomalous in this model. The multiple-impact model is preferred here because of an unusual concentration of impact deposits and biogeographic selectivity of extinction at low latitudes along the Alvarez Impact Belt.

DID THE SHIVA IMPACT TRIGGER DECCAN VOLCANISM?

DISTRIBUTION AND EXTENT OF DECCAN VOLCANISM. The close of Cretaceous time was marked by the outpouring of the enormous Deccan lava flows, spreading over vast areas of western, central and southern India (Fig. 9). The Deccan Traps cover 800,000km^2 of west-central India and extend seaward along more than 500km of Arabian sea coastline, reaching as far as the continental shelf and beyond (Devey & Lightfoot, 1986). Deccan lava flows also spread across the Seychelles-Saya de Malha Bank, implying that their original extent may be more than 1.5 million km^2 (Krishnan, 1982; Devey & Stephens, 1992). They are extremely flat, with most dips less than 1, and rest mainly on the Precambrian granitic basement. Significant departures from horizontal occur, in particular, in the Western Ghats, west of the Panvel Flexure. Deep-seismic sounding studies reveal that the thickness of the Deccan Traps varies from about 100m in the northeastern part to about 2km along the west coast (Kaila, 1988). Deccan volcanism is considered to be one of the largest continental flood basalt deposits in the Phanerozoic (Courtillot et al., 1986).

STRUCTURAL FEATURES. Four important structural lineaments are associated within the Deccan volcanic province: the east-west trending Narmada Rift (Choubey, 1971); north-south trending Cambay rift (Biswas, 1982); northwest-southeast trending Godavari Rift (Qureshy et al., 1988); and the arcuate Panvel Flexure (Auden, 1949) (Fig. 9). The Narmada, Cambay and Godavari Rifts are older geofractures (Biswas, 1987), and may have influenced the distribution of the Deccan lava basalts. The Panvel Flexure, on the other hand, is syntectonic with the younger flows (Wai subgroup) of the Western Ghats Deccan volcanism (Auden, 1949) and is interpreted here as the faulted outer rim of the Shiva Crater (Chatterjee, 1992). Three volcanic subprovinces are identified within the Deccan associated with these rift systems: the Narmada subprovince, north and south of the Narmada Rift including the outlier of Rajahmundry in the Godavari Basin; the Saurashtra subprovince, covering the Deccan exposures in Saurashtra, west of the Cambay Rift; the Western Ghats subprovince, including the thick volcanic sequence east and west of the Panvel Flexure. The boundary between the Narmada and Western Ghats subprovinces is somewhat diffuse and can be demarcated in the field by mineralogy and the nature of the lava flow. A combination of field mapping with petrochemical and isotopic studies permits division of the thick lava pile of the Western Ghats section into 3 subgroups (Kalsubai, Lonavala & Wai) and 12 formations, with a progressive decrease in age from north to south (Beane et al., 1986; Hooper et al., 1988). Similarly, Subbarao et al. (1988) recognized 3 new formations in the Narmada region (Narmada, Manpur & Mhow), but their relationships with the Western Ghats section is not clear.

TIMING AND DURATION OF DECCAN VOLCANISM. The temporal coincidence of the main pulse of the Deccan volcanism with the KT boundary led many authors to believe that a major asteroid impact might have initiated this massive volcanism (Alvarez et al., 1982; Rampino, 1987; Alt et al, 1988; Negi et al., 1993; Chatterjee & Rudra, 1993). However, critics have pointed out that the Deccan volcanism started at least a million years before the impact event, making the causal relationship less likely (Courtillot, 1990; Sutherland, 1994; Alvarez et al., 1994; Bhandari et al., 1995). The possible link between the KT extinction and the Deccan flood basalts has spurred detailed analyses to determine the timing and duration of Deccan volcanism from radiometric, palaeomagnetic and palaeontologic constraints. We have also sampled various Deccan stratigraphic sections to determine the KT boundary event layer. Here we synthesize all available data to estimate the absolute age and age span of the Deccan volcanism in the context of its origin and subsequent influence on the biotic crisis at the KT boundary.

Geochronology. Because of the altered nature of the Deccan basalt, previous attempts to determine its age by K/Ar method were unsatisfactory, with results ranging from 102 to 30Ma (Alexander, 1981). However, recent $^{40}Ar/^{39}Ar$ dates of the stratigraphically controlled thick sequence of the Western Ghats section cluster around a narrow span of age from 69 to 64Ma, with a major eruptive phase around 65Ma (Duncan & Pyle, 1988; Courtillot et al, 1988; Venkatesan et al., 1993; Baksi, 1994). Although a close temporal correspondence between the main pulse of Deccan volcanism and the KT boundary is indicated by isotope dating, early phases of eruption may have started at least 1Ma before the KT event.

Palaeomagnetism. Recent palaeomagnetic studies indicate that only 3 magnetic chrons (30N, 29R, & 29N) are represented in the thick Deccan lava pile, where the main eruptive phase in the Western Ghats section corresponds with chron 29R (Gallet et al., 1989; Courtillot, 1990; Vandamme & Courtillot, 1992). This normal-reversed-normal (NRN) magnetostratigraphy appears to be a powerful tool in correlating widely separated Deccan basalt provinces. Palaeomagnetic results support a shorter span of Deccan volcanism, from 67 to 64Ma, centered around chron 29R (65Ma). In this case, the whole eruptive history would cover only 1-2Ma.

Palaeontology. Palaeontologic evidence comes from thick fossiliferous sedimentary beds associated with the basaltic flows. These interbeds are traditionally named according to their physical position relative to the basal Deccan flow; they may underlie the flows (infratraps, such as the Lameta Beds) or they may be intercalated within the flows (intertraps). Stratigraphically infratraps are believed to be older than the intertraps (Krishnan, 1982, p. 415). This distinction is not clear-cut in regional biostratigraphic analysis. Local infratrappean beds may appear intertrappean in large-scale mapping. Sahni & Khoshla (1994) proposed a neutral term, 'Deccan basalt volcano-sedimentary sequence' (DBVSS) for these trappean beds. These sedimentary beds occur marginal to the Deccan outcrops in the

Narmada and Saurashtra subprovinces, indicating that these vast thicknesses of lava flows were not extruded all at once; volcanic activity was punctuated periodically. In between the flows are fluvial or lacustrine deposits of trappean beds that contain abundant remains of plants, invertebrates, dinosaurs and their eggs. We made extensive sampling of these trappean beds in search of the iridium anomaly, shocked quartz and tektites to detect the KT boundary layer, but the results were negative, reinforcing the palaeontologic observations that most of these trappean sediments are older than the KT boundary. Palaeontologic evidence drawn from palynoflora *Aquilapollenites*, charophytes, non-marine ostracods, the selachian *Igdabatis*, pelobatid frogs, anguid lizards, booid snakes, pelomedusid turtles, abelisaurid, titanosaurid and ankylosaurid dinosaurs and palaeoryctid mammals indicate a Maastrichtian age for these trappean beds, but the upper limit is unknown (Sahni & Bajpai, 1988; Chatterjee, 1992). More precise data comes from oil-exploration wells in the Godavari Basin, where the Narsapur well has encountered KT boundary flows (Govindan, 1981). Here the lower marine intertrap has yielded the planktonic zone fossil *Abathomphalus mayaroensis* of Late Maastrichtian age, whereas the upper post-trappean bed contains *Globorotalia praecursoria* of the P2 planktonic foraminifera zone of Early Palaeocene age. Palaeontological data define broad limits of Deccan volcanism from 67.5 to 60.5Ma in the Godavari Basin.

Stratigraphic Calibration. A schematic correlation of Deccan Trap sequences between the western Ghats and the Narmada/Saurasthra subprovinces is shown in Fig. 10, combining radiometric, palaeomagnetic and palaeontologic data. The following observations can be made:

1) The volcanism north of the Narmada Rift started somewhat earlier than the southern part. The Lameta beds are restricted to the north of this lineament and provide palaeontological control on the onset of volcanism. So far, only one magnetic chron, 30N, has been identified in this region associated with the infratrap (Sahni & Bajpai, 1988). In the Bara Simla section of Jabalpur, north of the rift zone, the Deccan flow overlying the dinosaur-bearing Lameta Group shows normal polarity (30N). This flow has not yet been dated by the Ar-Ar technique. Dinosaur bones, nesting sites, microvertebrates, palynoflora *Aquilapollenites* and the selachian *Igdabatis* suggest a Maastrichtian age for the Lameta Beds (Chatterjee, 1992; Jaeger et al., 1989; Sahni & Bajpai, 1988; Sahni et al., 1994). Sauropod nesting sites occur in a specific lithotype, a pedogenically modified sandy carbonate that forms a distinct marker bed. This egg-bearing bed can be traced for almost 1,000km, from Balasinor, Dohad and Hathni to Jabalpur in the northern part of the Narmada Rift (Mohabey, 1984, 1987; Srivastava et al., 1986; Sahni et al., 1994).

2) The 670m thick volcanic sequence at Kalghat-Mhow region, north of the Narmada lineament, lacks infratraps but shows three trap formations (Narmada, Manpur and Mhow) with normal (30N) and reverse (29R) chrons (Subbarao et al., 1988; Vandamme & Courtillot, 1992) and can be equated with the Western Ghats section.

3) The Saurashtra subprovince is not well constrained in age by palaeontological and palaeomagnetic analysis. Here the Deccan Traps overlie the 50m marine sequence of Late Cretaceous Wardhan Member and can be correlated with the volcanics of the northern part of the Narmada Rift (Biswas, 1988).

4) South of the Narmada lineament, in the Nagpur-Umrer-Dongargaon intertrappean beds, a thick sequence of reverse polarity (29R) is followed by a normal sequence (29N) (Sahni & Bajpai, 1988). In these intertraps dinosaur bones, fragmentary eggshells and microvertebrates of Late Maastrichtian are common. In Dongargaon the basal flow has yielded a precise Ar-Ar plateau age of 66.4±1.9Ma (Duncan & Pyle, 1988).

5) Vadamme & Courtillot (1992) reported a 29R-29N reversal chron from the Rajahmundry outcrop. Geochronological studies suggest an age of ~64Ma coeval with 29N chron (Baksi et al., 1994). In the Narsapur well, trappean beds can be tied to two foraminiferal zone boundaries in the type KT boundary sections of Italy (Alvarez et al., 1987; Govindan, 1981): the lower, infra-trap bed correlates with the *Abathomphalus mayorensis* zone (Maastrichtian), while the upper, post-trap bed corresponds with the *Globorotalia praecursoria* of P2 zone (Early Palaeocene).

6) The thick flows of Deccan volcanism in the Western Ghats sections show three subgroups (Kalsubai, Lonavla, and Wai) and are well-constrained by radiometric and palaeomagnetic data; volcanic activity was short-lived and reached its major peak of activity during chron 29R (~65Ma), followed by a short interval of chron 29N. Lack of trappean beds makes it impossible to estimate the age of Western Ghat sections by palaeontological methods.

7) A definite KT boundary section with iridium anomaly has been identified recently in the intertrappean beds of Anjar in Kutch, where radiometric ages of the traps cluster around 65Ma (Bhandari et al., 1994). As discussed earlier, we believe this section of alkaline basalt flows is directly related to the impact event.

8) The duration of Deccan volcanism may range from 67.5 to 60.5Ma (palaeontologic constraints), from 69 to 64Ma (geochronologic constraints), or from 67 to 64Ma (palaeomagnetic constraints). Thus the minimum age range of eruption may be around 67Ma to 64Ma, about 3My in duration.

9) Because of the presence of foraminiferal zones and magnetic reversal chrons, the Deccan stratigraphic sequence can be equated with the magnetostratigraphic type section of the KT boundary at Gubbio, Italy (Alvarez et al., 1987).

ORIGIN OF DECCAN VOLCANISM. A cause-and-effect connection between impact and Deccan volcanism has been the subject of extensive discussion and speculation. If the Deccan volcanism started 1Ma before the KT boundary event, and extended over 3Ma, as combined evidence of isotopic dating, magnetic anomalies and palaeontology suggests, then the Shiva impact did not initiate the Deccan volcanism. Deccan volcanism predated the impact event (Courtillot, 1990; Sutherland, 1994; Bhandari et al., 1995). Impact and Deccan volcanism are independent, having occurred by chance at about the same time. Deccan volcanism was already active when when the KT mpact occured near the Bombay coast. However, the impact might have shaken the Earth's mantle violently to enhance the spectacular Deccan outburst precisely at the time of the KT boundary.

The spatial and temporal coincidence of Deccan volcanism with the Carlsberg Rift and the Reunion hotspot activity at the KT boundary sheds critical insights into its origin. The enormous thickness of the lava pile in the Western Ghats sections associated with compound flows and ash beds indicate that the major eruptive source for Deccan volcanism must be located near the Bombay area, where evidence of both hotspot and rift magmatism are present. There has always been controversy as to whether the plume or rifting was the initiating factor for the Deccan volcanism. This conflict can be resolved if we can determine accurately the timing of initial eruption and duration of Deccan volcanism. Morgan (1981) proposed that the Deccan flood basalts were the first manifestation of the Reunion hotspot that subsequently produced the hotspot trails underlying the Laccadive, Maldive and Chagos islands; the Mascarene Plateau; and the youngest volcanic islands of Mauritius and Reunion. Recent DSDP data confirm that the age of the volcanism decreases from north to south, from the Deccan to the Reunion hotspot (Backman et al., 1988). Thus the geometry and the age range of these volcanic provinces, islands and submarine ridges are consistent with the rapid northward motion of the Indian plate over a fixed hotspot (Morgan, 1981; Duncan & Pyle, 1988).

Although the hotspot model is very attractive in explaining the Deccan flood basalt volcanism and linear volcanic chains of the western Indian Ocean, there are distinctions in both trace element and isotope geochemistry between present-day Reunion eruptives and those of the Deccan province; the likely source of the Deccan volcanism is similar to rift volcanism rather than the Reunion hotspot (Mahoney, 1988). Further geochemical and geothermal evidence suggests that Deccan magmas were generated at relatively shallow (35-45km) depth in Mid-Ocean Ridge Basalt (MORB) mantle and rules out the possibility of its origin by a deep mantle plume (Sen, 1988). However geophysical evidence indicates that the continental crust was extremely thin in the Western Ghats section under the plume (Negi et al., 1993). Morever, Ellam (1992) showed convincingly that the thinned lithosphere of Western Ghats is the reason for this trace element discrepancy between the Deccan volcanism and the Reunion hotspot.

Was rifting triggered by doming above the Reunion hotspot? Some workers (White & McKenzie, 1989; Hooper, 1990) argued that the Reunion hotspot actually created the Carlsberg rift along which Deccan volcanism erupted. However, as discussed earlier, the Carlsberg rifting did not start before chron 29R, whereas Deccan volcanism started somewhat earlier around 30N. If the Sarnu-Dandali and Mundawara volcanics of Rajasthan are regarded as the earliest manifestation of the Deccan volcanism in Peninsular India and the initial location of the Deccan-Reunion hotspot (Basu et al., 1993), then the Deccan volcanism must have started 3.5 million years earlier than the timing of the Carlsberg Rift, making the causal link unlikely. Moreover, if the Carlsberg Rift was triggered by the Deccan-Reunion hotspot, its geographic location would be at the center of the Shiva Crater, offshore of the Bombay coast. However, the hotspot track indicates that the Reunion hotspot always lay farther east within the Indian continent, probably near Igatpuri at the KT boundary (Fig. 9). If we consider the Rajasthan volcanics as the earliest and northernmost activity of the Reunion hotspot, it would be at least 500km northeast from the Carlsberg Rift at the time of eruption. Thus the timing of the eruption and the location of the Reunion hotspot do not suggest any close link between plume generation and rifting. On the other hand, at the KT boundary time, the impact had been coincidentally close enough to the Reunion hotspot to activate the major phase of the volcanic outbursts (Figs. 7A, 9). Reviewing all the evidence, the Deccan-Reunion hotspot remains the best model for the origin of Deccan volcanism.

How did the Deccan lava cover such an enormous area of India? The interconnected rift basins may be implicated in the distribution of Deccan lavas. Prior to the onset of Deccan volcanism the palaeodrainage of the Narmada and Godavari Rivers was directed toward the Bay of Bengal (Krishnan, 1982, p. 17). The Cambay Rift basin was tilted northward and westward at that time (Biswas, 1987). This centripetal pattern of drainage system was further accentuated by doming of the Western Ghats section around Igatpuri by the uprising plume (Fig. 9). Lava generated from the Deccan-Reunion hotspot flooded the Narmada, Cambay and Godavari rift basins. These lava rivers traveled many hundreds of kilometers in all directions with occasional flooding in the overbank areas. The main reason these flows could travel such great distances is their unusually large volume and rapid rate of eruption, coupled with their low viscosity. The final distribution of the Deccan Traps may reflect the topography at the time of distribution and the palaeosplope of these interconnected rift basins (Fig. 10). Similar long-distance intercanyon flows are known from the Columbia Plateau basalt of western United States, where the Pomona Member of the Saddle Mountain Basalt flowed down the ancestral Columbia River from north-central Idaho to the Pacific Coast (Hooper, 1992).

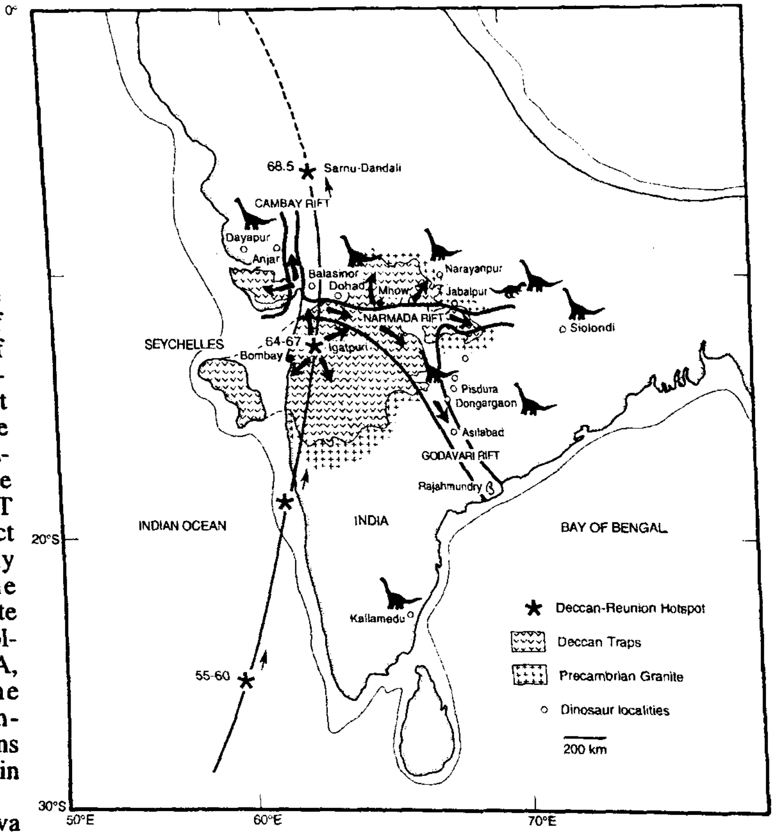

FIG. 9. Sketch map showing the localities of Maastrichtian dinosaurs around the Deccan volcanic province before the impact event; microcontinent Seychelles was adjacent to India; asterisks indicate the Deccan-Reunion hotspot track during the rapid northward drift of India. During Maastrichtian, the Deccan-Reunion hotspot was located near Igatpuri forming a domal structure with centripetal distribution of lavas; bold arrows indicate the possible directions of intercanyon flows of Deccan lavas along the drainage of the Narmada, Godavari and Cambay basins. Intercanyon flows may explain large areal distribution of Deccan Traps.

MAASTRICHTIAN DINOSAURS OF INDIA

Although dinosaur (implying nonavian dinosaur throughout the text) extinction was a

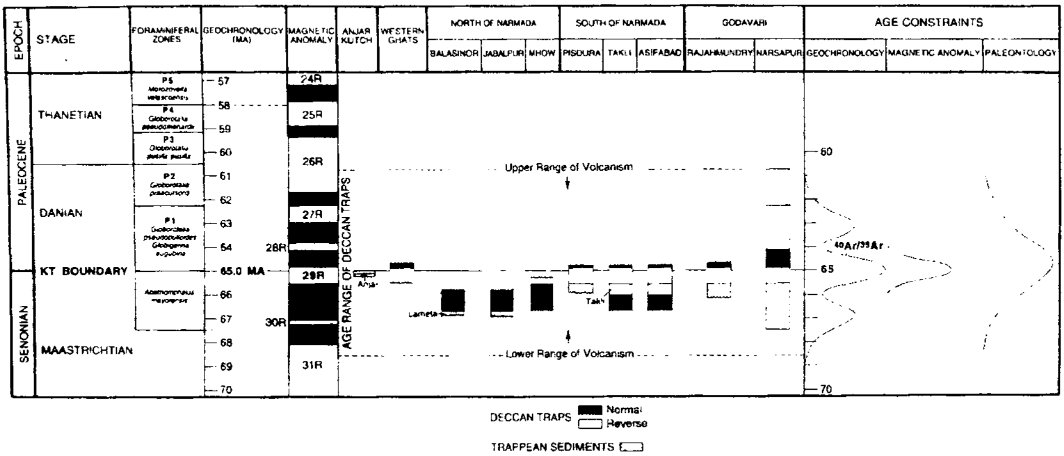

FIG. 10. Stratigraphic correlation of Deccan volcanic provinces in relation to KT boundary by geochronologic, palaeomagnetic and palaeontologic constraints. The minimum age span of Deccan volcanism may range from 67Ma to 64Ma; (data from Vandamme & Courtillot, 1992; Harland et al., 1989; Jaeger et al., 1989; Subbarao et al., 1988; Sahni & Bajpai, 1988; Chatterjee, 1992; and personal observations).

global phenomenon, there are very few places in the world where dinosaur-bearing sediments document the crucial KT boundary events; most of these exposures are known only from western North America (Wyoming, Montana, Alberta, Saskatchewan, Colorado, New Mexico and Texas), Mongolia and India. As a result, the tempo of dinosaur extinction, whether sudden or gradual, has been debated intensely (Clemens, 1982; Sloan et al., 1986; Sheehan et al., 1991). In this context, Indian biostratigraphic evidence may play a crucial role, since most of the dinosaur bones are known almost exclusively from the Deccan volcano sedimentary sequence such as Lameta Group which was deposited close to the KT boundary time. In the KT boundary section of Anjar, Gujrat, the last dinosaur bones occur precisely at the iridium layer. This is probaly a unique biostratigraphic evidence for a sharp truncation of dinosaurs supporting the sudden extinction event.

Maastrichtian dinosaurs from India are extremely rare. Some fragmentary remains of dinosaurs are also known from the Kallamedu Formation of Tamilnadu, South India (Fig. 9). Most of the Lameta dinosaurs came from a single quarry on the western slope of Bara Simla Hill of Jabalpur. This quarry in 1917-19 produced various dinosaurs including titanosaurids, coelurids, ornithomimids, allosaurids and ankylosaurids (Huene & Matley, 1933). Although the fauna from the Lameta Group indicates a moderate diversity of dinosaur community that inhabited India as it collided with Asia near the very end of the Cretaceous, most of these bones are fragmentary limb, girdle and vertebral elements which have few diagnostic characteristics. Furthermore, all of the previous Lameta dinosaur collection, housed at the Geological Survey of India, Calcutta and the Natural History Museum, London, has been missing for the last 50 years. Thus the affinity of Indian Maastrichtian dinosaurs has never been thoroughly investigated in recent time because of lack of material. The only valuable specimen remaining from the early collection is a partial skull of a juvenile theropod *Indosuchus*, now at the American Museum of Natural History (AMNH 1955), collected by Barnum Brown in 1922 and subsequently described by Chatterjee (1978).

During the past thirty years, many attempts had been made to locate this important quarry at Bara Simla Hill without any success. The site was covered with thick vegetation, and no landmarks or quarry maps of the original excavation survive. In 1988, we found this classical site and began exploring. A preliminary excavation has uncovered the original bone beds with sauropod and theropod remains, but most of the new material is yet to be prepared. We collected a partial skeleton of a large titanosaurid associated with limbs, girdles, vertebrae and a beautiful braincase. The large size (femur more than a meter long), undivided cervical neural spine, and strongly procoelous caudal vertebrae establish its titanosaurid affinity. In addition, several cranial fragments of *Indosuchus* were also recovered. In 1995, we discovered a rich graveyard of dinosaur bones in the mudstone facies of the Lameta Group near Raiholi village of Gujrat, western India. The most remarkable discovery from this quarry represents a nearly complete skeleton of a large theropod, about the size of *Allosaurus*. We have also collected various bones of titanosaurs and ankylosaurs from this quarry. Abundant sauropod eggs were also found from adjacent Dohad locality (Fig. 9). Finally, we have traced the missing dinosaur bones from Jabalpur described by Huene & Matley (1933) at the Indian Museum, Calcutta, last year. With this new information, we hope to get a first good look at the last dinosaurs in India. Here we provide a preliminary description of the new finds to evaluate the systematics of Indian Maastrichtian dinosaurs.

SAURISCHIAN DINOSAURS.

Sauropoda: Family Titanosauridae Lydekker, 1885. Titanosaurids were first recognized from the Late Cretaceous of India by Richard Lydekker in 1877 on the basis of their peculiar procoelous caudal vertebrae, and were later found in contemporaneous beds in South America, North America, Africa, Madagascar, Europe and Asia. They were among the largest dinosaurs that ever lived, but their origin and relationships are poorly understood, in part because no good skulls are known. They were the dominant herbivores of Gondwana during the Cretaceous, but radiated into Laurasian continents. The titanosaurids are characterized by vertebral attributes, especially by short cervicals, undivided neural spines in anterior dorsals, 6 sacrals and procoelous caudals (McIntosh, 1990). One of the most intriguing features of titanosaurids is the presence of body armor in the form of bony scutes and knobby dermal bones, known from *Saltasaurus* from Argentina (Bonaparte & Powell, 1980). There is no doubt that the dermal ossicle collected by Barnum Brown (AMNH 1359) from the Bara Simla locality, which was attributed to stegosaurs (Huene & Matley, 1933) and ankylosaurs (Coombs, 1978), actually belongs to titanosaurids.

Huene & Matley (1933) described two titanosaurid genera from the Lameta Group, based on size differences: the gracile-*Titanosaurus indicus*, Lydekker and a new robust species, *Antarctosaurus septentrionalis*. They figured a partial braincase of *Antarctosaurus* which compares well with *A. wichmannianus* of South America. However, the braincase of Indian *Titanosaurus* was unknown at that time. Later, Berman and Jain (1982) described the braincase of a small titanosur from the Lameta Group at Dongargaon and concluded that new braincase is fundamentally different from *Antarctosaurus*. The associated postcranial material collected from the site, especially vertebrae, resembles that of *Titanosaurus indicus* (Jain, 1989). It is likely that the Dongargaon braincase belongs to *T. indicus* (Jain, pers. comm.). Thus, from the braincase morphology and postcranial characteristics, the coexistence of at least two titanosaur genera, *Antarctosaurus* and *Titanosaurus*, in the Lameta Group can be established. This conclusion is further strengthened with the discovery of two additional braincases, one belonging to *Titanosaurus*, the other to *Antarctosaurus*, which are described below. Braincases are conservative which makes them excellent tools for identifying taxa; they are less susceptible to convergences that characterise skeletal features associated with feeding and locomotion. Using braincase morphology as a guide, the distinction between *Titanosaurus* and *Antarctosaurus* appears very clear-cut. In *Titanosaurus* the basipterygoid processes are extremely short, reduced and lie almost at the level of basal tubera; moreover, the parocicipital processes are wide and moderately curved ventrally. In *Antarctosaurus*, the basipterygoid processes are very long, slender and directed considerably ventrally below the level of the basal tubera. The paroccipital processes in this genus are narrow and highly curved downward. In sauropods, the nature of the basipteryoid process is intimately linked to the attitude of the quadrate; the short basipterygoid process is associated with the vertical quadrate, whereas the long basipterygoid process indicates highly slanting quadrate.

Antarctosaurus septentrionalis Huene & Matley, 1933. The new braincase (ISI R 162) recovered from Bara Simla site is beautifully preserved and provides a wealth of anatomical information. All the bones are tightly sutured so demarcation of individual elements is difficult. Although the braincase described by Huene and Matley (1993, Fig. 5) as *Antarctosaurus septentrionalis* is fragmentary, the preserved part shows close resemblance to the new material, especially in the construction of basipterygoid process and paroccipital process. The new specimen probably belonged to a young individual, as it lacks the laterosphenoid, orbitosphenoid and skull roof. In this respect, this specimen is very similar to that of a French

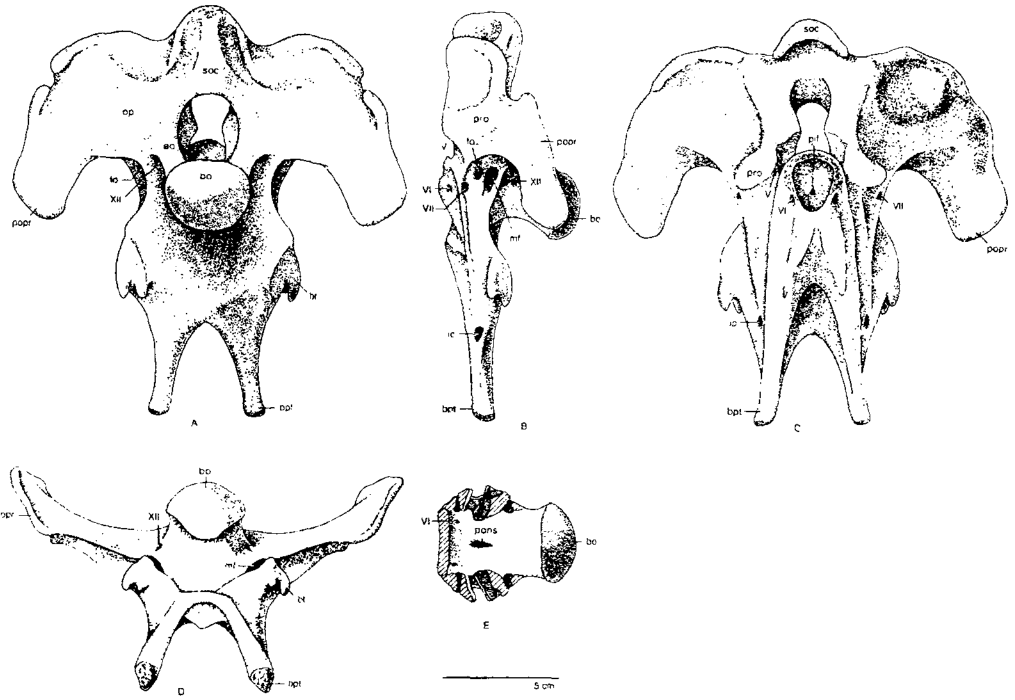

FIG. 11. Braincase of *Antarctosaurus septentrionalis*, a sauropod from the Lameta Group of Jabalpur, based on ISI R 162; A, caudal view; B, lateral view; C, rostral view; D, ventral view; E, dorsal view of basioccipital showing pons varioli. bo=basioccipital, bpt=basipterygoid process, bs=basisphenoid, bt=basal tubera, eo=exoccipital, fo=fenestra ovalis, ic=internal carotid artery, mf=metotic foramen, op=opisthotic, pif=pituitary fossa, popr=paroccipital process, pro=prootic, soc=supraoccipital; foramina for cranial nerves in Roman numerals.

titanosaurid (Loeuff et al., 1989), which also lacks the anterior and dorsal parts.

The braincase is short and extremely deep so that the basioccipital and the basisphenoid are telescoped (Fig. 11). The most outstanding feature is the highly enlarged basipterygoid processes, which are slender and directed downward as in several other titanosaurid genera such as *Amargosaurus*, *Nemegtosaurus* and *Saltasaurus*, (McIntosh, 1990). On the lateral wall of the basipterygoid process, at the level of the basal tubera, the openings for the canals of the internal carotid artery are visible. These tunnel through the bone and emerge at the base of the pituitary fossa through separate openings. The pituitary fossa is deep on the dorsal surface of the basisphenoid. The posterior wall of the fossa, the dorsum sellae, is pierced laterally by a pair of openings for the abducens (VI) nerves. On the lateral wall of the braincase, there are two prominent foramina at the middle ear region: the caudal one, the metotic foramen is very large and transmitted nerves IX-XI and the caudal branch of the jugular vein; the rostral one, the fenestra ovalis, is relatively small to receive the stapes. Rostral to the fenestra ovalis is a small aperture indicating the outlet for the facialis (VII) nerve. Farther rostrally each prootic is notched by the trigeminal foramen (V) which would be enclosed by the laterosphenoid. Both laterosphenoid and orbitosphenoid bones are missing in our specimen. In the occiput, the strong nuchal crest on supraoccipital and obliteration of sutures between the exoccipitals, the supraoccipital and the basioccipital, can be seen. The paroccipital processes are narrow, wing-like structures extending outward and considerably downward. The occipital condyle is large and spherical. Each exoccipital bone near the lower rim of the foramen magnum is pierced by a foramen for the hypoglossal (XII). At the floor of the braincase, the basioccipital shows a median cavity for the pons variolii (Fig. 11).

Titanosaurus indicus Lydekker, 1877. Berman & Jain (1982) described a sauropod braincase (ISI

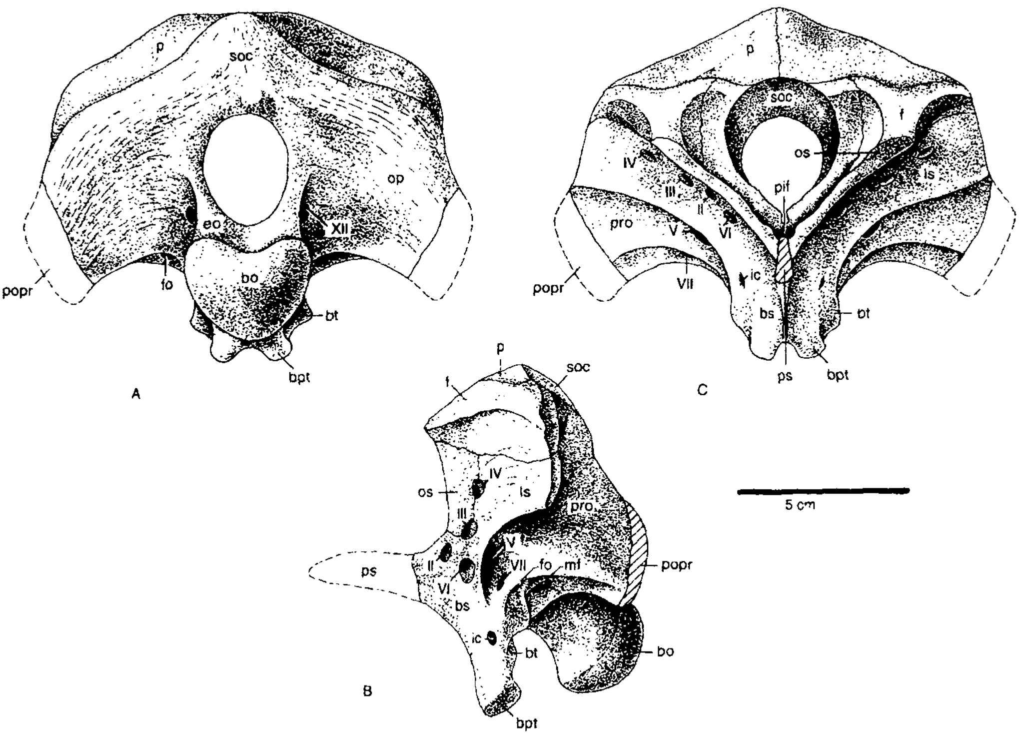

FIG. 12. Braincase of *Titanosaurus indicus*, a sauropod from the Lameta Group of Raiholi, based on ISI R 467. A, caudal view; B, lateral view; C, rostral view. Abbreviations as in Fig. 11; f=frontal, ls=laterosphenoid, os=orbitosphenoid, p=parietal, ps=parasphenoid rostrum.

R 199) from the Dongargon which was later assigned to *Titanosaurus indicus* (Jain, pers. comm.). The specimen is not well-preserved which makes the detailed interpretation somewhat difficult. This deficiency is remedied by the discovery of a better specimen from Raiholi site (ISI R 467). The new specimen is very similar to the Dongargaon specimen in size and morphology (Fig. 12), but fundamentally different from that of *Antarctosaurus*.

As in all sauropods, the braincase is completely ossified. The occipital condyle is hemispherical except for being somewhat concave dorsally to give a kidney-shaped appearance. Ventrally, the basal tubera are subdued and completely fused with the basipterygoid processes. The basipterygoid processes are very small and closely appressed. The foramen magnum is somewhat oval and smaller than the occipital condyle. At the base of the foramen magnum, each exoccipital is pierced by a single canal for cranial nerve XII. In Dongargaon specimen, there is a prominent protuberance on the occipital bone representing the articular facet of proatlas. This feature is lacking in our specimen. The opisthotic is intimately fused with the exoccipital; it is directed laterally and somewhat ventraly as a robust wing of paroccipital process. The supraoccipital is fairly massive and forms the dorsal roof of the foramen magnum. Laterally it is overlapped by a ventral flange of the parietal.

In lateral aspect, the cranial foramina are beautifully preserved. In the middle ear region two foramina are visible; the rostral, smaller one is the fenestra ovalis; the caudal, large one is the metotic foramen for nerves IX-XI. Farther rostrally the large foramen, shared between the prootic and laterosphenoid, is the trigeminal opening for nerve V. Ventral to it, the entrance of the internal carotid artery to the pituitary fossa can be seen at the base of the basipterygoid process. Rostral to trigeminal foramen, three foramina are visible in a vertical row in the laterosphenoid-orbitosphenoid-basisphenoid complex.

The dorsal foramen indicates the exit for nerve IV, the middle one for nerve III and the ventral one for nerve VI. At the base of the parasphenoid rostrum a large opening within the orbitosphenoid indicates the lateral aperture for nerve II. In rostral aspect the fused orbitosphenoid-basisphenoid complex narrows considerably to form a median vertical ridge as seen in a Romanian titanosaurid specimen (Weishampel et al., Fig. 15). Dorsal to the parasphenoid rostrum, the large cavity indicates the pituitary fossa.

Theropoda. Huene & Matley (1933) described two large predatory dinosaurs from the Lameta Group of Jabalpur. *Indosuchus raptorius* and *Indosaurus matleyi* as late survivors of allosaurs. Both taxa are known from partial skull fragments as well as several postcranial elements. The distinction between *Indosuchus* and *Indosaurus* was based on the structure of the fronto-parietal region. In *Indosuchus*, the fronto-parietal region has a narrow crest as seen in tyrannosaurs. The skull roof is flat between the orbits and the postfrontal is smooth. In *Indosaurus*, on the other hand, the parietal is broad, the lower surface of the frontal is wide and the transverse crest lies above and below the orbit. The frontals are concave and decline in front. The supratemporal fossa is short and broad as in allosaurs. Huene & Matley also described a maxilla of *Indosuchus* which is identical to a similar element collected by Barnum Brown in 1922 from the Lameta Group (AMNH, 1955). Later, Chatterjee (1978) described partial jaws of AMNH specimens of *Indosuchus* as a juvenile tyrannosaurid, partly on the basis of narrow fronto-parietal crest, elongated supratemporal fossae, incisiform premaxillary teeth and similar dental formula. He accepted *Indosaurus* as an allosaurid.

The classification of *Indousuchus* and *Indosaurus* has been difficult in the past because of fragmentary material. Despite marked similarities to tyrannosaurs, *Indosuchus* is characterized by the absence of preantorbital fenestrae in the maxilla. Bonaparte & Novas (1985) described a large skull of a new theropod, *Abelisaurus comahuensis*, from the Maastrichtian Allen Formation of Rio Negro, Argentina. Later, Bonapart et al. (1990) described a virtually complete, articulated skeleton of another theropod, *Carnotaurus sastrei*, from the Middle Cretaceous Gorro Frigio Formation of Argentina. *Carnotaurus* shows unusual frontal horns. Its forlimbs are highly reduced, with extremely short radius and ulna. Bonaparte and associates placed *Abelisaurus*, *Carnotaurus* and *Indosuchus* in the same family, Abelisauridae. This family is defined by large infratemporal fenestra, elongated quadrate, posteriorly directed squamosal with a ventral, rod-like process and a small maxillay fenestra near the preorbital opening. Comparison of *Abelisaurus* and *Indosuchus* clearly indicates close similarity between these two genera. *Indosuchus* is not a tyrannosaurid as was supposed earlier, but possibly an abelisaurid. Although abelisaurs were the dominant predators throughout Gondwana during the Cretaceous Period, our knowledge of these enigmatic theropods is still limited. The occurrence of a supposed abelisaur in the Late Cretaceous of France has been recognized recently (Buffetaut et al., 1988). Although abelisaurids superficially resemble large predatory dinosaurs such as allosaurs and tyrannosaurs, they are more primitive, probably a separate lineage evolving from ceratosaurs.

Various small coelurosaurs described from the Bara Simla quarry by Huene & Matley (1933), such as *Jubbulpuria tenuis* and *Laevisuchus indicus* are intriguing. We need additional material to assess their relationships.

Family Abelisauridae Bonaparte & Novas, 1985. Indosuchus raptorius Huene, 1933. The type specimen of *Indosuchus raptorius*, now housed at the Indian Museum, Calcutta is allocated to this species. Some of our recent finds may also belong to this species. For example, we have collected additional cranial bones of *Indosuchus*, such as the lacrimal, jugal and posterior part of the jaw (ISI R 163) from the Bara Simla Hill of Jabalpur. Furthermore, we have unearthed a nearly complete skeleton of *Indosuchus* from Raiholi site of Gujrat. The teeth are compressed laterally and serrated; the tooth crown is extremely low; the ratio of the crown height to rostro-caudal width is 1.5. The vertebrae are amphicoelous but lack pleurocoels. The scapulocoaracoid is narrow with a prominent acromion process. The forelimb is short relative to the hindlimb; the ratio to femoral to humeral length is about 2. Unlike *Carnotaurus* and *Tyrannosaurus*, the forelimbs of *Indosuchus* were as along as in allosaurs. Unfortunately, the postcranial elements of *Abelisaurus* are unknown. The iliac blade of *Indosuchus* has a deep preacetabular and long postacetabulr process; the pubis is expanded distally to form a foot. The hindlimb bones are hollow, thin-walled, stout and resemble the corresponding elements of *Carnotaurus*. The femur has a spherical, inturned

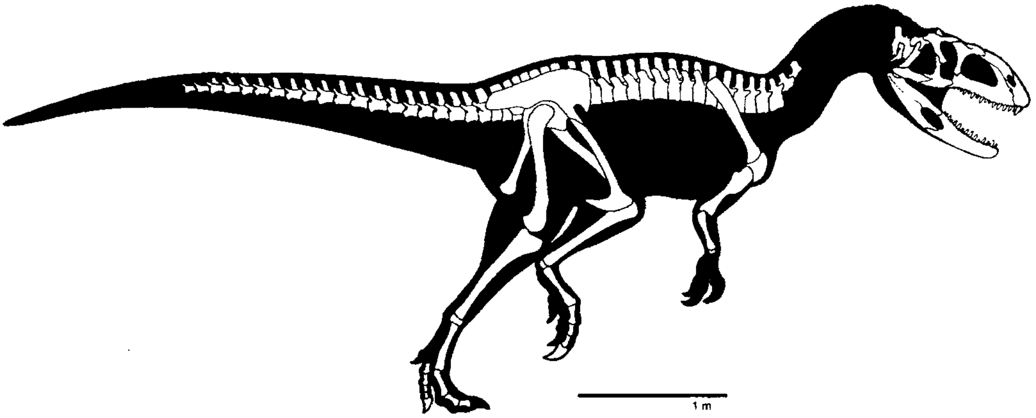

FIG. 13. Skeletal restoration of *Indosuchus raptorius*, a theropod from Raiholi site, showing preserved bones; skull modified from Chatterjee (1978). Restoration is based on disarticulated elements (ISI R 401 - 454).

head with a distinct neck. The lesser trochanter is fairly well-developed but lower than the greater trochanter. The tibia is robust with a distinct cnemial crest; distally it remains unfused with the astragalus. The astragalus is hemicylindrical in form, but its ascending process is relatively short. A preliminary skeletal reconstruction of *Indosuchus* is shown in Fig. 13 and restoration of the skull in Fig. 14.

Indosaurus matleyi Huene 1933. Another theropod partial skull from the Bara Simla quarry, *Indosuchus matleyi*, is generally allied to Allosauridae (Huene & Matley, 1933; Chatterjee, 1978), but Molnar (1990) pointed out some attributes in *Indosaurus* similar to those of *Carnotaurus* of Argentina and allocated it to Abelisauridae. Recently we have collected a *Carnotaurus*-like atlas-axis complex from the Lameta Group of Raiholi area, which strengthens Molnar's assessment.

ORNITHISCHIAN DINOSAURS. Various ornithischian fragments have occasionally been reported from the Late Cretaceous of India, but their identity is dubious except for the ankylosaurian *Lametasaurus*.

Ankylosauria. *Lametasaurus indicus* Matley 1923. *Lametasaurus* is known from the sacrum ilia, tibia, spine and armor (Matley, 1923; Huene & Matley 1933). It is a fossil chimera of mistaken association containing parts of two different dinosaurs: armour fragments often attributed to stegosaurs, nodosaurs (Huene & Matley, 1933), or ankylosaurs (Coombs & Maryanska, 1990), whereas sacrum, ilia and tibia probably belong to theropods (Chakravarti, 1935), such as abelisaurids (Molnar, 1990). Yet Huene & Matley mentioned, but did not figure, two additional types of dermal scutes from the same bed that could be ankylosaurian (Galton, 1981). Recently we have recoverd definite remains of an ankylosaur from the Raiholi site. The new material represents isolated vertebrae, scapulocoracoid, humerus, femur and several pieces of armor such as hollow lateral spikes and solid dorsal scutes, typical of ankylosaurs, which will be described in a separate paper.

Stegosauria nomen dubium. *Dravidosaurus blanfordi* Yadagiri & Ayyasami (1979). A small, late surviving stegosaur was described from the marine Cretaceous *Kossmaticeras theobaldianum* Zone Trichinopoly Group by Yadagiri & Ayyasami (1979). In 1991, we visited the site and found only fragmentary remains of plesiosaurs. We also examined the holotype and could not see anything related to the stegosaurian plates and skull claimed by these authors. Instead, the bones are highly weathered limb and girdle elements and may belong to plesiosaurs.

DISTRIBUTION OF DINOSAURS. It appears from the above discussion that Indian Late Cretaceous dinosaurs remain rather poorly known. Fossil records indicate that they lived around the fringe of the Deccan volcanic province and adapted to the harsh environments (Fig. 9). Yet this distribution reflects an artifact of preservation because of unusual protection of intertrappean beds by the Deccan basalts. Most of the nonmarine Cretaceous deposits in peninsular India were removed by erosion except for the little patch in the Kallamedu area near Madras. As a result, the extent of dinosaur distribution, other than in the Deccan volcanic province, is unknown. Although Masstrichtian dinosaurs have been reported from all Gondwana continents including Antarctica, reasonably complete skeletons have been recovered only from South America. The disjunct distribution of the titanosaurid-abelisaurid assemblage in South America, India and Europe is interesting in the context of drifting continents in Late Cretaceous time. Palaeontologic evidence suggests that the India/Eurasia collision took place during this time, facilitating the migration of northern fauna to India (Chatterjee, 1992; Jaeger et al., 1989; Prasad et al., 1994). Isolation between the northern and southern continents produced dramatically different distributions among dinosaurs. In contrast to the nothern hemisphere, the dominant herbivores in the Late Cretacous of India and South America were titanosaurids rather than ornithischians, whereas the large predators were abelisaurids instead of tyrannosaurs (Fig. 15).

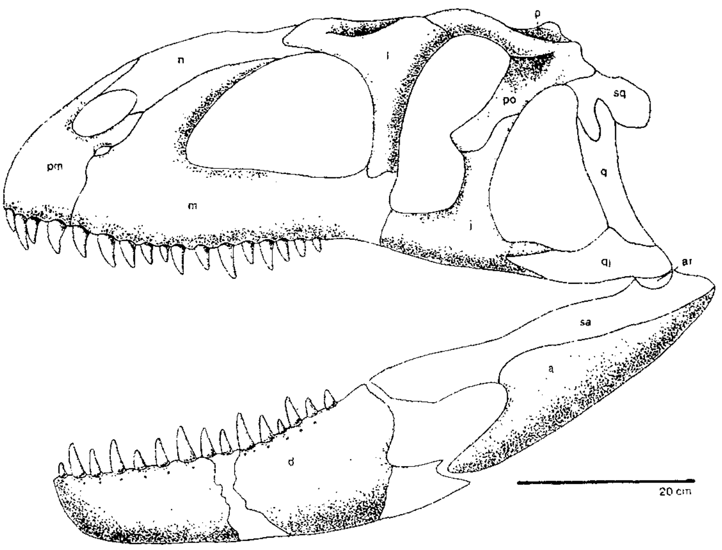

FIG. 14. Composite restoration of the skull of Indosuchus raptorius, an abelisaurid theropod from the Lameta Group; left lateral view; based on AMNH 1753, 1955, 1960 and ISI R 163. a=angular, ar=articular, d=dentary, j=jugal, l=lacrimal, m=maxilla, n=nasal, p=parietal, pm=premaxilla, po =postorbital, q=quadrate, qj=quadratojugal, sa=sarangular (modified from Chatterjee, 1978).

SAUROPOD NESTING SITES. Sauropod nesting sites from the Lameta Group underlying the Deccan volcanics represent one of the most extensive fossil hatcheries in the world (Mohavey & Mathur, 1989; Srivastava et al., 1986; Sahni et al., 1994). They can be traced almost continuously along the north of Narmada Rift from Anjar to Jabalpur for more than 1,000km, wherever the Lameta Group is exposed (Fig. 9). The eggs are particularly restricted to a thin (3-12m), sandy carbonate unit, interpreted as calcretized palaeosoil (Sahni & Khosla, 1994). Several hundred nests with 3-13 eggs and abundant fragmentary eggshells are found in this unit. Most of these eggs belong to titanosaurids. A partial skeleton of a baby titanosaur has been discovered among the nesting grounds in Gujrat (Mohabey, 1987), but Jain (1989) questioned its identity and assigned it to a booid snake. We have collected excellent specimens of titanosaurid eggs from Jabalpur and Dohad areas. The eggs are spherical with an average diameter of 15cm and were laid in linear or circular fashion. Similar titanosaurid eggs are known from France and Spain.

BIOTIC EFFECTS OF THE KT BOUNDARY CATASTROPHIC EVENTS

The Cretaceous Period was rich in biodiversity. Yet by the end of the period, there was an unprecedented ecological crisis leading to extinctions of many groups of organisms, from the giant dinosaurs to microscopic plankton. The abruptness and importance of the KT boundary has been recognized from the birth of stratigraphy, as it was the basis for the demarcation of two geologic eras. Although both impacts and Deccan volcanism coincided with the KT boundary, their relative importance for global climatic instability and disruption of life is still hotly debated. There are three possible ways in which extinctions could have been brought about: 1, an abrupt cataclysm triggered by the impact; 2, a gradual extinction process induced by the prolonged Dec-

FIG. 15. Life restoration of the Masstrichtian Indian dinosaur community. In the foreground are two abelisaurid theropods, *Indosuchus raptorius* confronting a herd of titanosaurid sauropods, *Titanosaurus indicus*.

can volcanism that polluted the atmosphere and changed the world's climate; or 3, the combined effects of both impact and volcanism might have contributed to environmental crisis leading to mass extinction. The fossil record of victims and survivors across the KT boundary have been used by the proponents of both impact and volcanic models to champion their views.

BIOTIC EFFECTS IN INDIA. Since India was ground zero for both impact and Deccan volcanism, this would be an ideal place to search for the evidence of crisis on local biota. Unfortunately, the terrestrial sequence coinciding exactly with the KT boundary is limited in India as in other parts of the world. It is very unlikely that such a singular event would leave dense, multispecific dinosaur bone beds in the area of greatest mass mortality, unless the catastrophic bed is quickly buried and protected. Surprisingly, there is one dramatic event of mass mortality preserved in India which may be tied to the Shiva impact. In the Anjar KT boundary section of Kutch, the dinosaurs died out suddenly at the KT boundary which is defined on the basis of the iridium anomaly and isotopic dating (Bhandari et al., 1994). Here, the KT boundary section is a 1cm thick, pinkish clay layer above a cross-bedded limestone unit which contains associated titanosaurid bones. No dinosaur bones occur above the impact layer. We collected some KT boundary samples and dinosaur bones from this section and sent them to Dr Moses Attrep Jr, of Los Alamos National Laboratory for geochemical analysis. Dr Attrep found a signicant enrichment of iridium (348 parts per trillion) from the clay sample, but could not detect any anomaly in the dinosaur bone (82 ppt) or limestone unit. This is the first unequivocal evidence that the dinosaur extinction occurred precisely at the time of meteoritic impact.

The influence of Deccan volcanism on contemporary biotas can be inferred from the fossil record in the trappean beds. The most obvious local catastrophe posed by Deccan volcanism was the habitat destruction of 800,000km^2 of tropical forest by extensive lava flows — an area of about the size of Texas (Fig. 9). The advancing flow and ash fallout must have destroyed the complex ecosystem for a large number of plant and animal species. The largest land vertebrates, the dinosaurs, were most affected by loss and fragmentation of habitats. The surviving populations of flora and fauna were forced to move out to the restricted space available in peninsular India, where they had to compete for food and resources. However, Deccan volcanism consisted largely of nonexplosive, tholeiitic eruptions similar to Kilauea and Reunion emissions, though on a grander scale. Recurrent eruptions do not disrupt much of the rich biota on the islands of Hawaii and Reunion. Although basaltic flows of relatively low viscosity commonly destroy plants, they move slowly enough that they seldom threaten the lives of the animals. Luxuriant vegetation thrived in the Deccan province as indicated by palaeobotanical evidence. Between the flows are the trappean beds that contain plant remains of fungi, bryophytes, ferns, conifers and angiosperms. This flora, a very extensive one, is decidedly unusual in that it consists of seeds, fruits, leaves, trunks, branches and the like — thousands upon thousands of them. In 1988, we visited the little-known 'National Fossil Park' in Shahpura, about 80km from Jabalpur. This is probably one of the best petrified forests in the world, preserving this magnificient Deccan flora. We believe that these vast floral accumulations may signify recurrent deforestation events induced by Deccan ashfalls. In spite of floral deterioration, no major extinction event has been recorded among the Deccan flora (Lakhanpal, 1970). Within the intertrappeans beds, magnificent fossil accumulations indicate that life was resilient in this hostile environment. Deccan volcanism cannot be the proximate cause of the mass extinction.

The long-term hazard of Deccan volcanism would be several trillion tons of toxic gases pumped into the upper atmosphere, which would result in global climatic perturbations disrupting the ecosystem. Within the trappean beds, especially in the Lameta Group of rocks, the greenhouse effect can be identified, by the climate becoming more severe, with marked seasonal changes and aridity. There were large alkaline playa lakes around the periphery of the Deccan province where dinosaur bones and eggs were preserved in hot, arid conditions (Sahni et al., 1994). These lakes were subjected to alternate wet and dry seasons. Although pollution from the Deccan volcanism might have had some adverse effect on vertebrate populations, Prasad et al. (1994) could not detect any change in the composition or population of biota from infratraps to intertraps, during episodic volcanic activity. They concluded that the Deccan volcanism was not detrimental to life. There is another line of evidence which supports this theory. Midoceanic ridges spewing tholeiitic lava, toxic gases and sulfides, support a rich oasis of life, including tubeworms, polychaetes, crustaceans and mollusks. In fact, submarine vents provide a refuge for many relict forms that might have escaped the KT extinction (Tunnicliffe, 1991). Extrusion of the Deccan flows certainly affected the local flora and fauna by habitat destruction and pollution, but had little direct regarding the major extinctions.

Eggs are generally more sensitive indicators of environmental stress. As mentioned earlier, the world's largest fossil nesting sites have been discovered recently in the northern part of the Narmada lineament around the fringe of the Deccan province stretching for almost 1,000km. These eggs were apparently laid on wet, sandy-limey soils and were later subjected to prolonged intervals of aridity that resulted in considerable dehydration (Sahni et al., 1994). The abundant distribution of eggs suggests that sauropod population was thriving there when Deccan volcano was erupting. Sarkar et al. (1992) reconstructed the palaeoecology of the Lameta titanosaurids from stable isotope (^{18}O and ^{13}C) analysis of their eggs from the Kheda district of Gujrat. They found oxygen isotope data indicating that titanosaurids drank water from rivers and evaporative pools, whereas carbon isotope data suggesting they consumed C3-type plants (small palms, conifers, dicot shrubs, etc.) in a semiarid environment. It is well-known that pathological conditons in living reptiles and birds is caused by hormonal imbalance which can be induced by psychic stress due to overcrowding in a restricted space, or sudden a change in the environment (Erben et al., 1979). Surprisingly, in various nesting sites around the Deccan Province, embryos, hatchlings and juvenile skeletons are almost absent. Did these dinosaur eggs fail to hatch because of halogen poisoning from the Deccan flows? This seems unlikely because dinosaur eggs have been found at the KT boundary section in Anjar (Ghevaria & Srikarni, 1990). Unlike the condition in French and Spanish nesting sites (Erben et al., 1979), we could not detect any pathological abnormality in shell thickness and growth.

Was there any other mechanism of gradual reproductive failure among Indian dinosaurs? Heat from Deccan volcanism could have altered the sex ratio of the local dinosaur population. Paladino et al. (1989) proposed that sex in dinosaurs may be controlled by incubation temperature in the nests as seen among living reptiles such as turtles and crocodiles. They argued that during the Late Maastrichtian, climatic perturbations may have led to unisexual dinosaur populations and eventual extinction. This is an interesting concept but difficult to evaluate from the fossil record. Moreover, if dinosaur physiology was similar to that of birds (Bakker, 1975), temperature during incubation may not have had any role in sex determination. The occurrence of dinosaurs and eggs in the sediments intercalated with with Deccan lava flows indicates that volcanism had little direct effect on their demise. However, the pollution from Deccan volcanism may have some global impact in conjunction with impact.

IMPACT-EXTINCTION MECHANISMS. One of the most important questions about the KT extinctions concerns its timing and duration. The extinction of six groups of marine microfossils — planktic and benthic forams, coccoliths, radiolarians, dinoflagellates and diatoms — took place precisely at the impact horizon and are compatible with this scenario (Smit, 1982; Thierstein, 1982; Alvarez et al., 1984). Brachiopods (Surlyk & Johnson, 1984) and ammonites (Ward et al., 1991) also show a similar abrupt pattern of extinction at the KT boundary. Similarly, pterosaurs, plesiosaurs and mosasaurs in the marine realm became extinct suddenly at the end of the Maastrichtian (Buffetaut, 1990). There is no question that the oceanic food chain collapsed by environmental changes around the KT boundary. In terrestrial communities, the sharp floral event exactly at this boundary strongly suggests a causal link with the impact scenario (Tschudy & Tschudy, 1986). Careful sampling indicates that dinosaurs in Montana died out suddenly at the KT boundary (Sheehan et al., 1991). We see the similar evidence of abrupt disappearance of dinosaurs precisely at the iridium KT boundary layer in Anjar section of Gujrat. Thus, the palaeontological record favors a sudden and simultaneous extinction pattern at the KT boundary among certain groups of organisms.

If, as seems likely, one or more meteorite impacts did play a role in the mass extinction event, what mechanism was involved? How devastating was the collision and how did it affect life? Various models have been proposed in recent times to explain the killing mechanism. A massive impact would generate earthquakes of high magnitude, inject a large volume of dust into the stratosphere, darken the skies, halt photosynthesis, ignite global fires, initiate tsunamis, produce acid rains, decrease ocean surface alkalinity and devastate the biosphere. Millions of organisms would die instantly from the direct effect of the impact — shock heating of the atmosphere by the expanding fireball (Alvarez 1986, 1987; Emiliani et al., 1981; 1987; Melosh et al, 1990). Comet Shoemaker-Levy 9 provided proof that the KT impact ignited global fires. As the ejecta fell back into the atmosphere after 20 minutes of each mpact, they reentered with a release of titanic energy; the heat from this reentry was so intense it was easily detected from Earth (Weissman, 1995). Similarly, when the KT ejecta reentered into Earth's atmosphere, they ignited terrestrial forests and plant covers. The wildfires consumed oxygen and poisoned the atmosphere with CO. This massive impact would generate a 100-million megaton blast — 1000 times more powerful than the explosion of all nuclear arsenals of the world. The impact force would have vaporized not only the meteorite but also melted the target rock. This melt ejecta would spread in large waves, until it had formed a large crater. Huge tsunamis produced by the oceanic impact could destroy coastal habitats across the globe (Sharpton & Ward, 1990).

Available data suggest that the extinction of carbonate-secreting plankton was especially severe at the KT boundary (Smit, 1982; Keller, 1989). Acid trauma is likely a consequence of many biotic crisis in the oceans. Various impact mechanisms have been proposed to produce large volumes of HNO_3 and H_2SO_4 for acidification of surface marine waters. Shock heating of the atmosphere would cause nitrogen and oxygen to combine with steam to form nitric acid (Prinn & Fegley, 1987). The sheer size of the projectile cannot by itself account for the devastation. The unique composition of the crash sites provided additional arsenal. Because the target rock at the Yucatán Peninsula (and western coast of India) has a thick-cover of $CaSO_4$, an impact there could have released as much as a trillion tons of SO_2 (D'Hondt et al., 1994). Release of devolatilized SO_2 would form sulfuric acid aerosols which would contribute to a rapid decline in global surface temperature and halt photosynthesis. The subsequent showers of acid rain must have been agents for decreased ocean alkalinity and destruction of life. All of these events had cascading effects through the terrestrial and marine ecosystems to collapse the food chain.

All the extinction mechanisms cited above are based on a 10km-sized meteorite. If we consider the impact of a 40km meteorite, the devastation would be much more traumatic on the biosphere. One obvious consequence of a larger oceanic impact would be partial vaporization of the photic zone, raising the atmosphere's temperature to hundreds of degrees, and destoying all life in the ocean surface. Thus, a large body impact may explain the marine regression by vaporization of water which is generally associated with the KT event. The impact-induced thermal radiation would ignite global wildfires on land and destroy ecological niches (Melosh et al., 1990).

MECHANISM OF VOLCANIC-EXTINCTION. Many palaeontologists are skeptical about the scenario of impact holocaust. They argue that the KT extinction was neither global, nor instantaneous, but occurred over an extended period of time, because different organisms disappear at different levels at or near the KT boundary. They look for extinction agents that could explain a gradual extinction event and favor terrestrial causes, such as prolonged Deccan volcanism and regression of sea level, as main contributing factors for the biotic crisis (Clemens, 1982; Officer et al., 1987; Hallam, 1987; Stanley, 1987, p. 167; Keller, 1989; Zinsmeister et al., 1989; Courtillot, 1990).

However, the gradual extinction pattern seen among some organisms may be an artifact of preservation and declining sampling quality. Signor & Lipps (1982) showed theoretically how a sudden catastrophic extinction would appear to have been gradual in the fossil record, if the record was not dense. The Signor-Lipps effect weakens the case for a gradual extinction. Furthermore, the instantaneous extinction in both continental and marine organisms is not a necessary corollary of the impact theory (Alvarez et al., 1984). A large impact could trigger environmental crisis, and the latter could, in turn, cause extinctions spread over 10^4 to 10^5 years (Hsu et al., 1982). The most ecologically-sensitive organisms were probably the first victims, with progressively more tolerant groups succumbing in the later stages. The short term physical event may lead to long term biological events.

There are many examples of pre-boundary and post-boundary extinction events (Keller, 1979) which led many palaeontologists to advocate a close relationship between the biotic crisis and Deccan volcanism. There is no doubt that such a massive volcanic outburst over an extended period would have deleterious environmental consequences. Based on data known from the Laki eruption in 1783, the Deccan eruption must have pumped large volumes of SO_2, HCl and ash into the atmosphere to cause global cooling, immense amounts of acid rain, reduction in alkalinity and pH of the surface ocean and ozone layer depletion that might be harmful to both terrestrial and marine organisms (Hallam, 1987). Deccan volcanism must have produced large-scale aerosol clouds of sulphur and CO_2. The reduction in temperatures caused by sulphur aerosols in the stratosphere act in the opposite direction to the greenhouse gases such as carbon dioxide. Emissions of CO_2 from the Deccan volcanism would directly increase the atmospheric and oceanic CO_2, leading to sustained global warming.

SYNTHESIS. Some of the consequences of an asteroid impact and of massive volcanism would be quite similar, such as pollution of the atmosphere, darkness resulting from dust (either ejecta or ash), suppression of photosynthesis, acid rain, global cooling, carbonate crisis in the ocean waters, environmental stress, devastation of ecosystems and the collapse of the food chain. The scenario of extinction by food chain disruption is compatible with both impact and volcanic hypotheses. It is generally believed that the biotic crisis was most severe and sometimes limited to tropical-subtropical regions while high latitude faunas and floras were little affected (Keller, 1994). The geographic locations of two or three impact sites, Deccan volcanism and the distribution of impact deposits along the Alvarez Impact Belt may explain this geographic selection of KT extinction (Fig. 6B). The sudden cooling by H_2SO_4 aerosol and warming by CO_2 would result in chaotic climatic perturbations which would be especially traumatic for global organisms. However massive volcanism would lack some of the titanic lethal features that are generally associated with a large body impact, such as gigantic shock effects leading to vapor plume, global fire, thermal pulse, evaporation of the photic zone and concomitant sea regression, chondritic metal toxicity and volatilization of target rocks. Impacts probably made more dramatic changes to KT environments globally and a more traumatic crisis to the ecosystem than volcanic emissions. Impacts also perturbed the environment so suddenly and catastrophically that most organisms failed to adapt to these changes in such a short time and perished. In contrast, prolonged volcanism allowed enough time for some organisms to adapt, or for others to disappear gradually. Global fire must have decreased the amounts of atmospheric oxygen which would further exacerbate the hostile conditions already developing among terrestrial and marine life. Selectivity and a step-wise extinction pattern can be better explained by the volcanic model. It seems that impact was the proximate cause to the biotic crisis at the KT boundary, whereas long-term volcanism produced harmful changes that enhanced climatic stress and finished off the extinction process.

CONCLUSION

We have outlined two catastrophic events at the KT boundary in India: a giant meteorite impact at the India-Seychelles rift margin and the spectacular volcanic outbursts of Deccan volcanism. These two events were so closely intertwined in space and time that it is difficult to untangle them in proper chronologic order. The subsurface stratigraphy and geophysical data suggest that the Shiva Crater is a potential candidate for the long-sought KT impact scar. Biostratigraphic, geochronologic and palaeomagnetic evidence indicates a KT boundary age.

We speculate that an oblique impact by a 40km asteroid produced the oblong, complex, Shiva Crater on the continental shelf of western India, 600km across and more than 12km deep. Part of the crater rim survives in the Panvel Flexure and the Narmada Fault near western India and in the Amirante Arc south of the Seychelles. The central uplifts are represented by the elevated peaks of the Bombay High, Praslin and Mahe. Between the central peaks and the crater rim lay an annular trough, now preserved as the Surat Basin, the Dahanu-Panna Depression and the Amirante Basin, each containing thick Tertiary sediments (Fig. 5A). The impact melts were emplaced radially downrange of the trajectory and are clustered around the Shiva Crater in the form plugs of alkaline igneous complexes. Radiometric, palaeontologic and palaeomagnetic data suggest that the Shiva Crater was formed at the KT boundary.

We are aware that one serious shortcoming of the Shiva Impact hypothesis is the documentation of shock metamorphism in crater proximity. There are several possible reasons for this deficiency. First, we could not acquire any KT boundary core samples from Oil and Natural Gas Commission of India regarding Bomay High area. These samples are crucial to detect impact signatures such as iridium anomaly, shocked quartz, melt rocks, breccias, suevites and shatter cones. Second, the impact took place in a shallow-marine setting. The tsunami generated by this impact would have been efficient at removing ejecta material. Third, some of the shocked signatures may be preserved in the deeper part of the basin, yet to be penetrated by drilling. Fourth, contemporary Deccan volcanism and impact melt which had filled part of the crater and crater exterior must have consumed or erased other evidence of shocked features such as shatter cones, breccia and ejecta. The thick blanket of Deccan Traps on the western part of India must have concealed most of the crucial evidence of impact signatures. As in the case of Chicxulub, we need more subsurface data to confirm the impact origin of the Shiva structure. An international effort is needed to unravel the morphology of the Shiva Crater.

It is highly coincidental that critical evidence for both the Chicxulub and Shiva Craters came from petroleum prospecting, because the sediments overlying the central peak of a complex crater form a domal structural trap. The Shiva crater now preserves a complicated geological history, as well as valuable economic resources — the largest oil field in India. Thus the Shiva impact had created not only an immense crater and continental rifting, but also affected global climate, the chemistry of the world's ocean, a biotic crisis and perhaps even the production of oil traps.

The near-antipodal positions of the Chicxulub and Shiva structures suggest two possibilities: Either, two large meteorite fragments crashed on a rotating Earth at a short interval, creating two large scars along the Alvarez Impact Belt. Or, a large impact on one side of the Earth produced a similar signature on the far side. The first model finds support from the unusual concentration of impact deposits and biogeographic selectivity of extinction at low latitudes (Keller, 1994) along this Alvarez Impact Belt.

The impact-induced model of Deccan volcanism, though very appealing, is rejected because of conflict of timing. The revised calibration of Deccan volcanism indicates that the eruption began over 1Ma before the KT event and extended for 3Ma. If so, then the Shiva impact did not initiate the Deccan plume activity.

Although both impact and volcanism might have contributed to inhospitable environments and biotic crisis at the KT boundary, the impact must have played a major role in the killing mechanism. Both catastrophes contributed heavily to the breakdown of stable ecological communities and disrupted the biosphere. In the aftermath of the KT extinction, some forms of life, such as bird and mammals rebounded. They formerly played minor roles, but assumed prominence after the extinction. Today, they are abundant in both numbers of species and populations and can be found on every continent occupying virtually all available niches. The selectivity of KT extinction is still puzzling. For example, terrestrial dinosaurs became the victims, but their flying counterparts — birds —

survived the catastrophe. Birds rose like the Phoenix from the funeral pyre of terrestrial dinosaurs with renewed youth and beauty to carry their ancestral heritage into the Cenozoic cycle.

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