Physical, chemical and biological changes at geological boundaries : causes, consequences and clues based on the study of Indian sections

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Significant and abrupt biological changes are known to occur at the geologic boundaries and are invariably accompanied by some specific physical and chemical changes in the sedimentary deposits. At the Cretaceous-Tertiary Boundary (KTB), for example, shocked minerals, nickel-rich spinels, anomalously high iridium concentration and a variety of other physical and chemical markers have been found. It is generally believed that the biological changes are a consequence of physico-chemical processes which are triggered by some high energy, physical events such as a bolide impact, supernova explosion in the vicinity of the Earth or volcanic episodes. To understand the cause and nature of these physico-chemical processes, a high resolution stratigraphic analysis of physical, chemical, geological, environmental and biological markers of stratigraphic boundaries has been made over the past few decades.

In this article, we summarise the main features of some important bioevent horizons based on typical stratigraphic sequences and then dwell upon various processes which could possibly be responsible for them. The Cretaceous-Tertiary and Permian-Triassic boundaries are discussed in some detail. The clues obtained from the study of stratigraphic sections from India are used to build possible scenarios prevailing at these bioevents.

Key-words — Mass extinction, Iridium anomaly, Deccan Volcanism, Siberian Volcanism, Asteroidal impact, Cometary impacts, Cretaceous-Tertiary Boundary, Permian-Triassic Boundary.

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सारांश

भूस्तरिक सीमाओं में भौतिक, रासायनिक एवं जैविक परिवर्तन : भारतीय खंडों के अध्ययन पर आधारित परिणाम

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भूस्तरिक सीमाओं पर महत्वपूर्ण और आकस्मिक जैविक परिवर्तन पाए गए हैं जिनका सम्बन्ध अवसादी निक्षेपों में कुछ विशिष्ट भौतिक एवं रासायनिक परिवर्तनों से है, उदाहरणार्थ क्रीटेश्यस टर्शियरी सीमा पर प्रघात खनिजकण, निकल-समृद्ध स्पिनेल, असामान्य उच्च इरिडियम सान्द्रण और अन्य भौतिक एवं रासायनिक सूचक-चिन्ह पाए गए हैं। जैविक परिवर्तनों के बारे में यह माना जाता है कि ये उन प्रक्रियाओं के परिणाम हैं जो बोलाइड संघट्ट, सुपरनोवा एवं ज्वालामुखी विस्फोट जैसी उच्च ऊर्जीय भौतिक घटनाओं के कारण होते हैं। इन भौतिक-रासायनिक प्रक्रियाओं के कारणों को समझने हेतु पिछले कुछ दशकों में स्तरिक सीमाओं के भौतिक, रासायनिक, भूवैज्ञानिक, पर्यावरणीय और जैविक अवशेषों के उच्च विभेदीय विश्लेषण किए गए हैं।

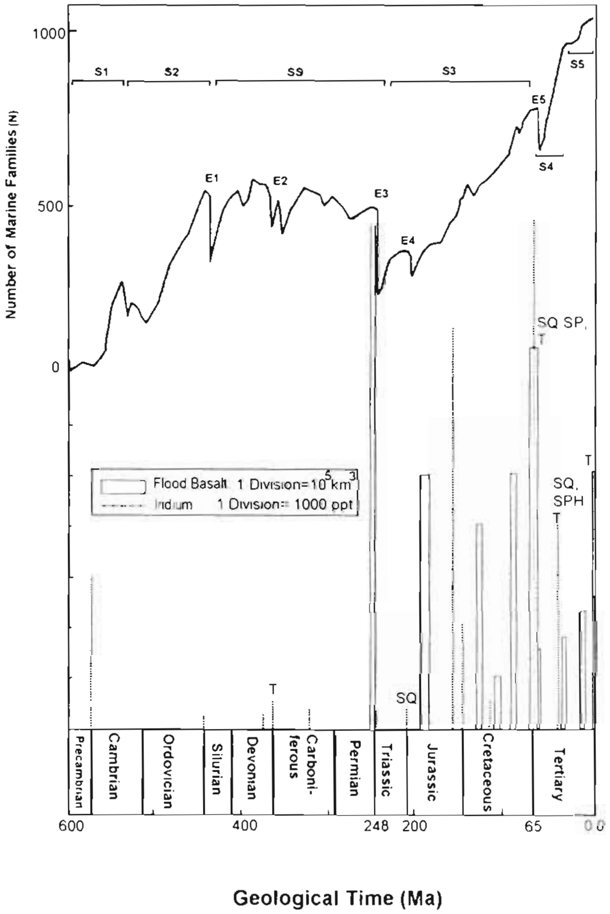
इस शोध-पत्र में हमने कुछेक ऐसी सीमाओं पर घटित विभिन्न परिवर्तनों को संक्षेप में उद्धृत किया है और उन प्रक्रियाओं की चर्चा की है जो उनके लिए उत्तरदायी हो सकती हैं। क्रीटेश्यस-टर्शियरी और पर्मियन-ट्रायेसिक सीमाओं का वर्णन कुछ विस्तार से किया गया है। भारत के समकालीन स्तरिक खंडों से प्राप्त संकेतों से इस जैविक विनाश के समय संभावित घटनाओं को दृश्यान्वित करने का भी प्रयास किया गया है।

SPECIATION and diversification of species is a complex process controlled by their inherent capacity to survive and evolve. The environmental factors, through continuous variation, provide interactive forces, both negative and positive, over the geologic history of the Earth. Extinction is the fate of all species; they become extinct when the rate of adaptation is not able to match the rate of environmental stress. Such extinction records are preserved in the sedimentary deposits on the earth and provide invaluable information on evolution, radiation and extinction of species.

RECORDS OF PALAEOBIODIVERSITY

Fossil records in marine and non-marine sediments show the evolutionary pattern of various species on the Earth. Sepkoski (1992) has compiled the data on initiation, speciation, diversification and extinction of various species. The biodiversity curves constructed from these data have been a subject of intense analysis and discussion over the past few decades. In Text-figure 1, we reproduce the biodiversity curve during the Phanerozoic for marine families as given by Sepkoski (1992).

Several features of these curves are striking. The sudden explosion of species at Precambrian-Cambrian boundary followed by an exponential rise and then a near steady state persistence for nearly 190 Ma, followed again by a steep exponential rise, each punctuated by a number of sudden catastrophic decreases or mass extinctions (Table 1) are clearly seen in Text-figure 1. Some of these features have been widely discussed (Van Valen, 1984). Valentine and Moores (1970) proposed that the empirical curve of taxonomic diversity through time is literally a "map" of continental positions (Raup, 1972) and the diversity change is related to the available extent of the coast line. In this paper, we first bring out some of the intriguing features of biodiversity curve (Text-figure 1) and then discuss the physical causes and chemical clues concerning the processes leading to mass extinctions.



Text-figure 1 — Diversity curve for marine families over geological times (adopted from Sepkoski, 1993). S1, S2, S3, S4, S5 represent epochs of rapid speciation and E1, E2, E3, E4 and E5 represent events of mass extinction. SS denotes era of near steady state in biodiversity. Histogram shows the volume (10^5 km^3) of lava emanating in major volcanic flood basalt episodes (after Rampino & Caldeira, 1993) and the iridium concentration (pg/g) at some horizons where high iridium anomaly has been found. Horizons where shocked quartz (SQ), microtektites (T), meteoric spinels (SP) and spherules (SPH) have been found are marked. Source of data are given in the text.

The exponential rise in number of faunal and floral families is quite consistent with evolutionary trends expected of multiplicative processes (Van Valen, 1984). While the exponents of the curves (Part S1, S2, S3, S4 and S5) reflect congeniality of the ambient life supporting conditions, the physical factors responsible for the rapid rise which govern the speciation and diversification during various epochs (S1 to S5) are not well understood and have not been quantitatively related to the observed rates of growth.

The most intriguing part is the steady state persistence (rate of change being nearly zero) defined by part SS of the curve covering 440 to 250 Ma period. Such a state prevailed for a long period spanning nearly 190 Ma in spite of severe perturbations in form of several catastrophic extinctions. Such a steady state is *unnatural* in a sense that it is not exhibited even by any physical or chemical system, much less sensitive or less dynamic than biological systems. This equilibrium or steady state level can not be explained by simple prey-predator models or continuation of "cosy" environmental conditions.

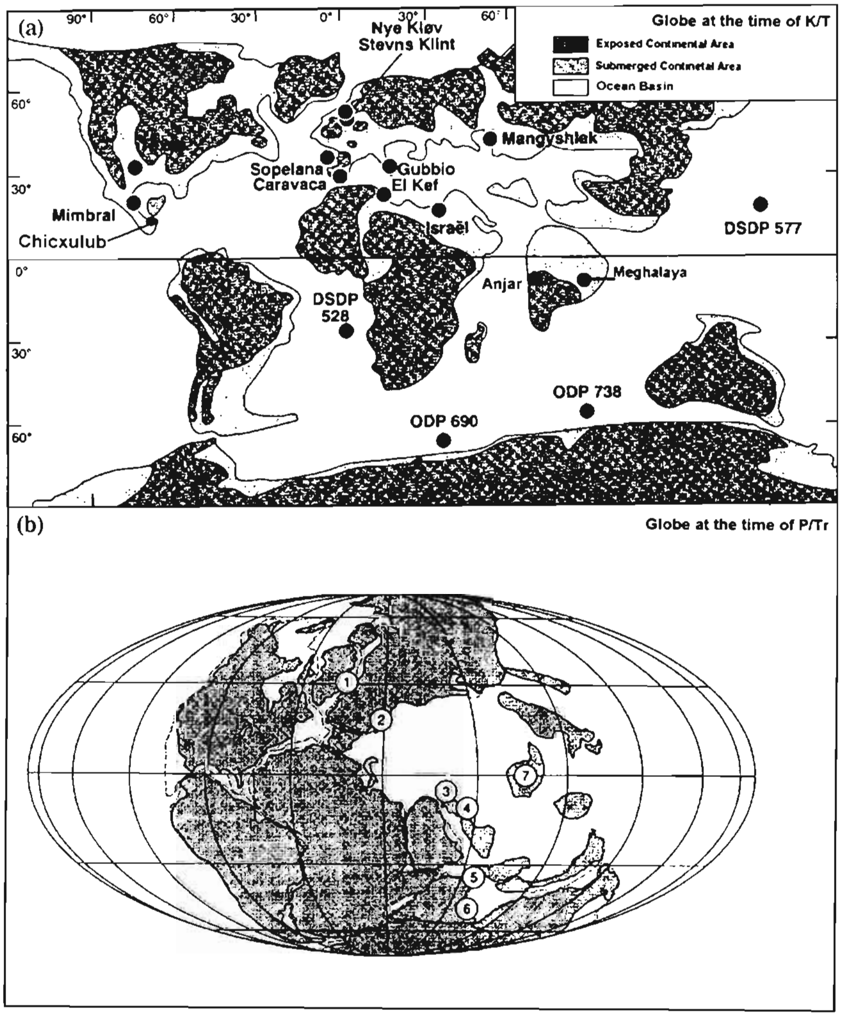
The major catastrophic extinctions which occurred at least five times during the Phanerozoic, i.e., during Late Ordovician, Late Devonian, Late Permian, Late Triassic and Late Cretaceous (Table 1b), in addition to a mid-Carboniferous event, are characterised by sudden onset and slow recovery. But the causative factors responsible for a more vigorous diversification following these catastrophes, surpassing the pre-catastrophic index of growth (dN/dt), have not been identified.

Doubts have been raised about extinctions being sudden and simultaneous for a large number of species at the same point of time since statistical biases exist due to sampling and preservation in sedimentary records (Signor & Lipps, 1982). The true nature of extinction and recovery phases needs to be established by high resolution and statistically significant data but it is clear that the extinctions are, geologically speaking, quite sudden. Selectivity of extinction could also provide vital clues concerning the agencies responsible for them.

Based on the physical, biological, chemical and sedimentary characteristics at various extinction boundaries, a number of hypotheses for mass extinction have been proposed. We shall discuss these observations later in this article. Here we concentrate on the observations related to K/T and P/T boundaries as changes at these boundaries have been the most severe and have been studied in detail. The positions of the continents on the globe at K/T and P/T times are shown in Text-figure 2. To start with, we briefly describe various hypotheses proposed for these extinctions.

Extinction Mechanisms

All the proposed mechanisms for extinctions can be grouped into two categories: terrestrial and extra-terrestrial. The terrestrial causes include massive flood basalt volcanism and sea-level changes, which through climatic stress, can result in mass extinction.



Text-figure 2 — Location of various continents around K/T times (a) and P/T times (b). The locations of major K/T sites and continents and their submerged areas are shown in (a). The numbers in P/T reconstruction of the globe (b) shows approximate locations of various sites studied: (1) Greenland, (2) Southern Alps, (3) Iran-Armenia border, (4) Central Iran, (5) Salt Range, Pakistan, (6) Guryul Ravine and Spiti, India, (7) Meishan and other sections in South China. See Erwin (1994a) and Sweet *et al.* (1992) for more details. This figure is modified from Courtillot (1995).

The energy released in major volcanic flood basalt episodes is ~10^{33} ergs, and is sufficiently energetic, i.e., 10^6 times the annual internal energy release from the Earth, and occurs over long periods of time (million years or more), so that it can produce a cumulative stress to eventually result in mass mortality. The dust and gases released in volcanic episodes can significantly alter both the land and marine environment.The timing, intensity and location of major volcanic provinces on the Earth are shown in Text-figures 1 and 3. The synchroneity of volcanic episodes and extinction events (Text-figure 1) suggests a causal relation between them. The chain of physico-chemical processes triggered by volcanism is schematically shown in a simplified way in Text-figure 4a.

One of the extra-terrestrial hypotheses (Alvarez *et al*., 1980) envisages a large size asteroidal impact (10 km or bigger bolide). Impacts this magnitude are sufficiently energetic (10^{31} ergs) and moreover the energy is released instantaneously (seconds) to have far reaching consequences on the atmosphere and ecology. Other extra-terrestrial phenomena like a supernova explosion (within 10 kpc of the Earth) have also been discussed. One of the mechanisms suggested is that its intense radiation destroys the protective ozone layer thereby exposing both the marine and terrestrial organisms to the potentially lethal solar ultraviolet radiation (Ellis & Schramm, 1995; Van Den Bergh, 1994), ultimately damaging the fibre of life on the Earth. Other extra-terrestrial hypotheses include accumulation of dark matter which, in turn, can give rise to continental flood basalt volcanism by periodically generating heat inside the earth (Abbas & Abbas, 1996) and effect of thermal neutrons (Yayanos, 1983). Any of the mechanisms discussed above is capable of producing severe stress on life depending on its intensity but probably a combination of many of these mechanisms occurring together is required to culminate into an extinction event. We confine to the two most prominent processes : catastrophes by collisions of large interplanetary bodies with Earth and violence by volcanoes. The physico-chemical processes triggered by volcanism and impact are schematically shown in Text-figure 4a and 4b, respectively.

Table 1 — (a) Major periods of speciation and their rates of increase (Text-figure 1)

Epochs of Growth	Period (Ma)	Rate of change, dN/dt
Mean		+4.1
S-5	38-0	+1.04
S-4	65-38	+8.51
S-3	208-98	+2.64
S-2	505-438	+3.96
S-1	565-537	+3.75

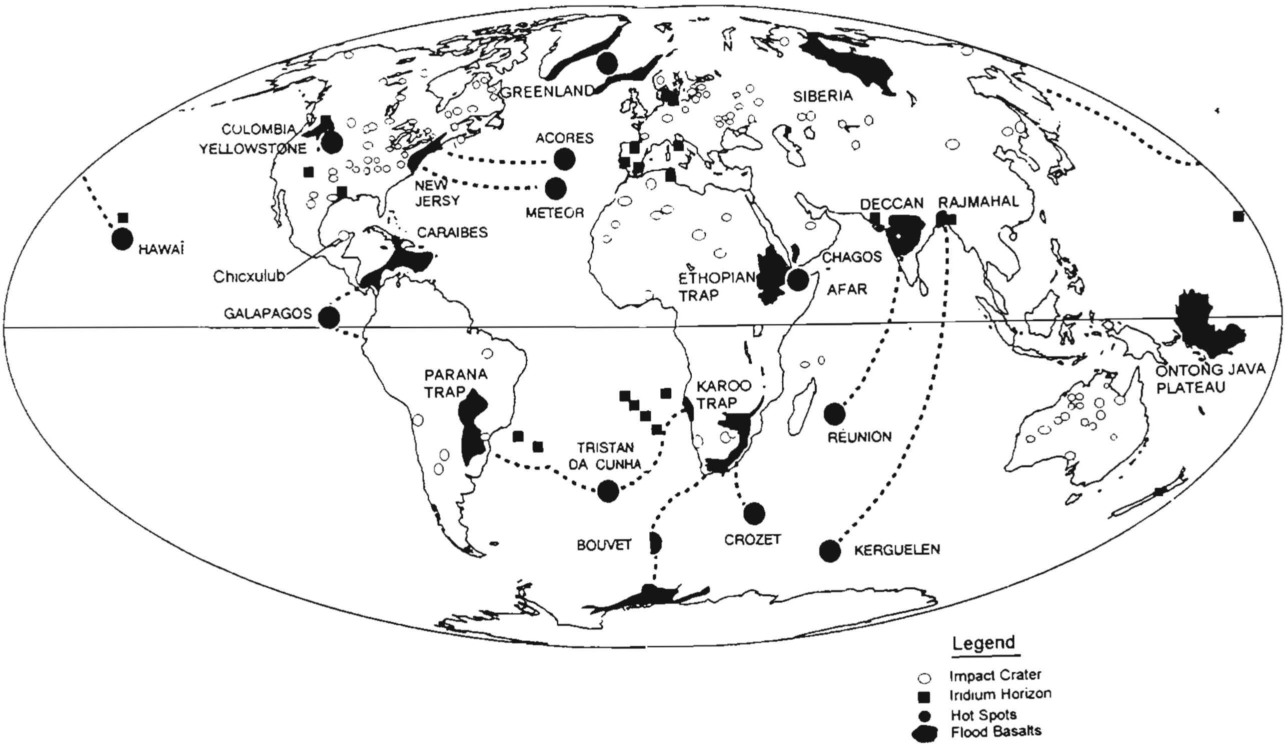
(b) Major events of extinction and their nature

Extinction events	Time (Ma)	Boundary	Extinction	Recovery
E5	65	Cretaceous-Tertiary	Abrupt	Gradual
E4	208	Triassic-Jurassic	Gradual	Gradual
E3	250	Permian-Triassic	Abrupt	Gradual
E2	360	Devonian-Carboniferous	Gradual	Gradual
E1	438	Ordovician-Silurian	Abrupt	Gradual

(c) Major period of steady state

SS	440-250=190 Ma

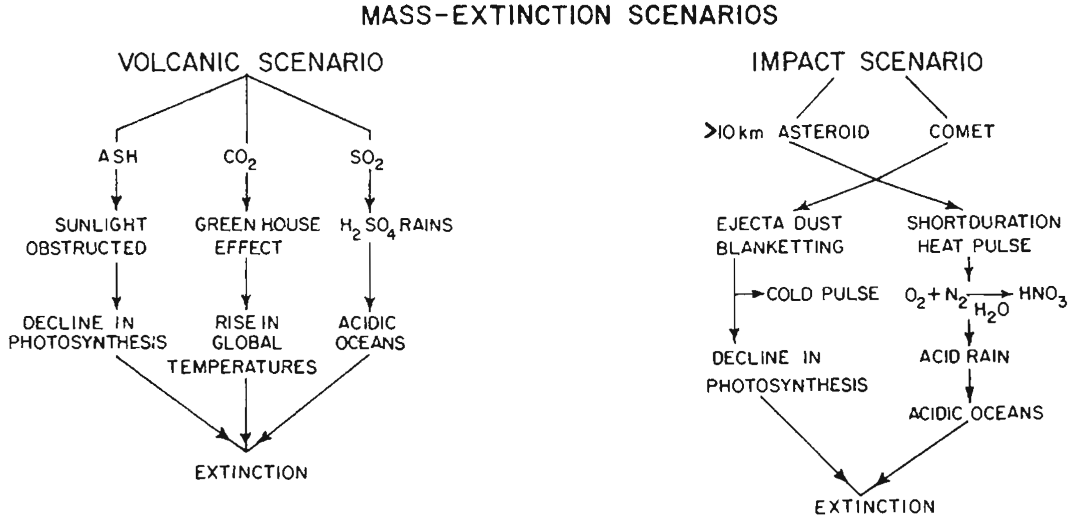
Dynamically, impacts due to stray extra-terrestrial bodies appear to be plausible as we can see from their remnants on the surfaces of the Earth, Mercury or Moon. Several Earth-crossing asteroids (Atens) and comets (Apollo, Amors) (Wetherill & Shoemaker, 1982; Weissman, 1982) and meteor streams are known to exist through which the Earth passes every year. Over a hundred impact craters on the Earth have been identified (Grieve, 1991) and their locations are shown in Text-figure 3. Impacts due to comets are more probable than asteroids (Wetherill & Shoemaker, 1982; Weissman, 1982). As the solar system goes through different regions of space, it encounters different bodies which may tear off the Oort's belt (containing ~10^{12} comets) and deflect a few of them (~10^5) to the inner solar system. A small fraction of them may acquire an Earth-crossing orbit resulting in a cometary shower impacting the Earth. The four main mechanisms which have been proposed for creating gravitational perturbation of the Oort's belt are due to (a) Planet X, (b) Nemesis, (c) Passing stars, and (d) Molecular clouds. In addition, the galactic debris, as the solar system passes through the galactic arms, can also give rise to certain phenomena on the Earth which can, through a series of physico-chemical processes result in mass extinction (Clube & Napier, 1986; Davis *et al.*, 1984; Hills, 1981). Some of these processes are briefly discussed here.



Text-figure 3 — Global distribution of impact craters, volcanic flood basalt provinces, hot spots and high Ir concentration in K/T boundary horizons.

Deflection of comets to the Inner Solar System

1. *Planet X*—Models of planetary formation suggest that the accretion of the outer planets may have left a residual disk of comets or icy planetesimals in the Uranus-Neptune region. Kuiper (1951) suggested that comet-like masses of 10^{17}-10^{18}g between 35-50 AU, perhaps 10^{11} in number, may have formed in this region. There is a small residual discrepancy in the motion of Uranus, Neptune and Pluto (Hoyt, 1980) which can be explained if a planet X exists at 50 to 100 AU with appropriate eccentricity (0.3) and inclination (45°) and a mass between 1 and 5 M_o (Matese & Whitmire, 1986). The planet X will, due to precession of its perihelion and aphelion, deflect periodically ~10^5 comets from this comet belt, to



Text-figure 4 —A simplified chain of physico-chemical processes following volcanism (a) and impact of a large bolide (b), leading to mass extinction.

the inner solar system, giving rise to short period comets, at least 73 of which are known with periods ranging between 3.3 and 13 years. The mean life of the short period comets is about 1,400 years and a small fraction of them can attain earth-crossing orbit to occasionally give rise to a comet shower on the Earth.

2. *Solar Companion Star (Nemesis)* — Another mechanism proposed for deflecting comets from the Oort's belt is due to a (hypothetical) low mass solar companion star Nemesis (Mass 0.05 to 0.3 M_o, an eccentric orbit with a = 90, 000 AU, period = 27 Ma, perihelion distance 10 to 2000 AU). When it passes close enough to the Sun, it would rattle the dense inner cloud of Oort's comet belt. The number of comets perturbed into earth-crossing orbit may be $2x10^9$ (Davis *et al.*, 1984).

3. *Passing Stars* — Hills (1986) has discussed that over the history of the solar system about 2.3 x 10^4 stars are expected to pass within 1 pc of the Sun and these might deflect comets from the Oort's cloud to the inner solar system. These may result in occasional comet showers impacting the Earth, but this phenomena will not be periodic.

4. *Giant cloud fragmentation model* — It is estimated that over 2/3 of the interstellar gas in the inner galaxy is in molecular form existing as giant molecular clouds (GMC) with mass ranging between 10^5 to 4 x $10^6 M_o$ Clube and Napier (1986) have worked out a detailed model for cometary deflection resulting from penetrating encounters of GMC with the solar system. It is estimated that during its life time, the Sun had close (<20 pc) encounters with 56 GMC's having $M \leq 3$ x $10^3 M_o$ and 8 encounters with GMC's having $M \leq 10^5 M_o$ (Napier, 1985). Oort's cloud is thus disturbed quasi-periodically and the deflected comets arrive in the circum-terrestrial space and disintegrate into short-lived Apollo asteroids. The material goes through the processes

Table 2— Physical, chemical and isotope markers at various boundary horizons (from Bhandari, 1991; Rampino & Haggerty, 1996)

Boundary	Age (Ma)	Mortality	Iridium range (ng/g)	$\delta^{13}C$	$\delta^{18}O$
Near Pliocene-Pleistocene	2.3	Insignificant	One minor peak (0.11-4.7)	----	----
Eocene-Oligocene	36	Four sudden minor events	Iridium peak (0.10-4.1)	---	---
Cretaceous-Tertiary (K-T)	65	Severe	One sharp peak (5-180) on a broad hump and some minor peaks	Sudden decrease	Sudden decrease
Cenomanian-Turonian	94	Insignificant	0.56		
Jurassic-Cretaceous	144		7.8		
Callovian-Oxfordian			1		
Middle-Late Jurassic			3.2		
Triassic-Jurassic (T-J)	205	Major	Small peak (0.4)	Decrease	Decrease
Permian-Triassic (P-T)	250	Sudden and severe	(0.003-0.23)	Sharp decrease	--
Lower Mississiplan	33	--	(0.02-0.56)	--	--
Devonian-Carboniferous (D-C)	360	--	Four minor Iridium peaks (0.02-0.56)	--	--
Frasnian-Famennian (F-F)	367	Sudden and significant	Small Iridium peaks (0.08-0.3)	Decrease	Decrease
Late Ordovician	440?	Sudden	Weak Iridium anomaly (0.06-0.23)	--	--
Precambrian-Cambrian (PC-C).	~ 570	--	(0.002-2.9)	Decrease	Decrease

1. In addition to the main peak, some smaller peaks have been found (0.08 to 0.[illegible]) which may be due to variation in carbonate content or perturbations of the main peak.

Table 3—Major observations at Cretaceous-Tertiary Boundary

Biological signatures	
1.	*Global extinction of a large number of marine and land species (Sepkoski, 1992)*: About 50% of genera and ~ 15% of families are believed to have become extinct. In severity, the K/T extinction is only next to P/T extinction. The extinction is gradual, step-wise or sudden is still debated.
2.	*Extinction is believed to be selective*: Studies of Kaiho (1994) shows difference between extinction of planktonic and benthic foraminifera. It has been suggested that extinction was mainly confined to tropics and had some latitudinal dependence (Keller, 1994).
3.	*Near disappearance of pollen and plants*: At the base of the KTB *Micula murus* zone has been identified.
Geological signatures	
1.	*Deccan flood basalts, timing and duration*: Available $^{40}Ar/^{39}Ar$ ages of these basalt flows range between 63 Ma to 68 Ma {large scale ($10^6 km^3$) flood volcanism in central and western India}. It has been suggested that bulk of the basalts erupted within a short interval of time of less than 1 Ma around KTB (Courtillot *et al.*, 1996). However, Venkatesan *et al.* (1993) point out that major peak of Deccan eruptions predated KTB by more than 1 Ma and its duration was not less than 3 Ma.
2.	*Chicxulub Crater*: (a) Chicxulub crater (diameter ~200 km) in the Yucatan peninsula has been identified as the crater formed at the KTB (Sharpton *et al.*, 1996). (b) The age of melt crater rocks at 64.98±0.05 Ma (Swisher *et al.*, 1992) is the same as the age of tektites from Haitian KTB site (Izett *et al.*, 1991). (c) Apart from the 65 Ma resetting age, the zircons from various K/T sites (Colorado, Beloc and Sakatchewan) also give ages of ~545 Ma similar to the age of Chicxulub platform, indicating that it is the only large impact crater at KTB (Bohor *et al*, 1993; Krogh *et al.*, 1993; Kamo & Krogh, 1995). (d) The geometry of the crater and the ejecta indicates that the bolide hit from southeast direction at a low angle (20 to 30°)and the ejecta was thrown in a northwesterly direction.
3.	*Sea-level changes*: Sea-level changes causing regression and transgression are believed to be the main factors in causing extinctions at KTB (Hallam, 1992). A sharp drop of 100 m prior to KTB and an equally rapid rise thereafter have been observed for various sections (Haq *et al.*, 1987; Holser & Magaritz, 1992; Schmitz *et al.*, 1992). It has been argued that these fluctuations would affect even the terrestrial reptiles because of lowering of water tables.
Chemical and isotopic signatures	
1.	Global occurrence of enhanced level of iridium with orders of magnitude higher concentration above the background. In some sections, the Ir peak is superimposed on a broad hump whereas a few sections show multiple Ir peaks (Graup & Spettel, 1989; Bhandari *et al.*, 1995).
2.	Presence of amino acids (-amino isobutyric acid), probably of extraterrestrial origin below and above the KTB but not at KTB (Zhao & Bada, 1989). It has been suggested that these amino acids are derived from cometary sources (Zahne & Grinspoon, 1970).
3.	A sharp decrease in $\delta^{13}C$ at and above the K/T boundary (Hsu & McKenzie, 1990) attributed to planktonic extinction, indicative of strangelove ocean, followed by planktonic boom (Hollander *et al.*, 1993).
4.	Excursions in $\delta^{18}O$ values indicating changes in sea water temperature of several degrees before and after the K/T event (Sarkar et al., 1992). A slow cold wave is followed by a sudden warm epoch.
5.	An increase in strontium isotopic ratio ($^{87}Sr/^{86}Sr$) attributed to enhanced weathering due to impact induced acid rain (Martin & macDougall, 1991). However, Nelson *et al.*,. (1991) suggest an increase in this ratio prior to KTB also.
6.	Enrichment in N and S isotopic ratios ($^{15}N/^{14}N$, $^{34}S/^{32}S$) attributed to interaction of acid rain with organic matter in case of N (Gardner et al., 1992) and an anoxic event in case of S (Kajiwara & Kaiho, 1992).
7.	Fullerenes (C_{60}, C_{70}) have been detected at various KTB sites with estimated mean global C^{60} concentration at the KTB to be 1.4ng/cm^2 (Heymann *et al.*, 1996).
8.	$^{187}Os/^{186}Os$ ratio is found to be ~ 1 in the K/T clay, similar to the value in meteorites or the Earth's mantle whereas the crustal value for this ratio is ~10 (Luck & Turekian, 1983).
9.	A 2.5 mm fragment separated from the K/T clay horizon of a mid-Pacific core shows high concentration of Fe, Cr and Ir, characteristic of chondrites and is suspected to be the fragment of the bolide responsible for K/T impact (Kyte, 1996). Schuraytz *et al.* (1996) have detected almost pure micron size iridium nuggets from Chicxulub impact melt.
Mineralogical and other features	
1.	Presence of shocked mineral grains such as shocked quartz, zircons and chromites (Bohor *et al.*, 1984; Bohor, 1990; Bostwick & Kyte, 1996). This is a strong evidence in favour of impact hypothesis.
2.	Spherules and microtektites have been reported from K/T sites. These include sanidine spherules (Smit & Klaver, 1981) and others having composition of potassium feldspar, glauconite, pyrite, etc. (Montanari *et al.*, 1983; Smit & Kyte, 1984; Brooks *et al.*, 1985). Glasses with shapes resembling those of microtektites have been found from Beloc section near Haiti (Hildebrand *et al.*, 1991; Kring & Boynton, 1991, 1993) which have been dated to be 65.01 ±0.08 Ma (Izett *et al.*, 1991).
3.	Discovery of nanometer sized diamonds favour impact hypothesis (Carlise, 1992, 1995). The authors found the Ir to nanometer size diamond ratio to be similar as observed in case of C2 type chondrites and further noticed that carbon isotopic ratio did not favour a terrestrial origin. The horizon containing the diamonds had fiftyone amino acids out of which 18 are found in carbonaceous chondrites only. Based on C and N isotopic ratio in diamonds, Gilmour *et al.* (1992) suggest an impact or plasma origin for these diamonds.
4.	Meteoric spinels (usually 2-10 microns), rich in nickel have been found at the KTB showing a prominent peak where the iridium enhancement is observed (Robin *et al.*, 1992). These are believed to be produced in the atmosphere during the entry of the bolide.
5.	Presence of soot in the boundary clay provides an evidence of large scale forest fires (Wolbach *et al.*, 1985, 1990; Ivany & Salawitch, 1993) which could have contributed to the loss of sunlight.
Environmental signatures	
1.	A severe temperature fluctuation; a slow cold wave (-6°c) followed by a severe heat pulse (+10°c). The cold wave is believed to be due to blanketing of sun light by soot, dust and sulphuric acid aerosols and the heat wave is due to green house effect resulting from release of large amounts of CO_2 as a consequence of impact on carbonate rocks (O'Keefe & Ahrens, 1989). Based on analysis of paleosol carbonates, it has been found that the $C0_2$ concentration of the atmosphere at the time of KTB was about 800-1200 ppm (Ghosh *et al.*, 1995; Berner, 1992)

of progressive fragmentation and destruction as it evolves through the phases of meteor streams to zodiacal cloud and is eventually blown away by the solar wind. The model predicts bombardment episodes of 10^4 - 10^5 year duration, separated by 10^5 - 10^6 year intervals, spread over a few millions years.

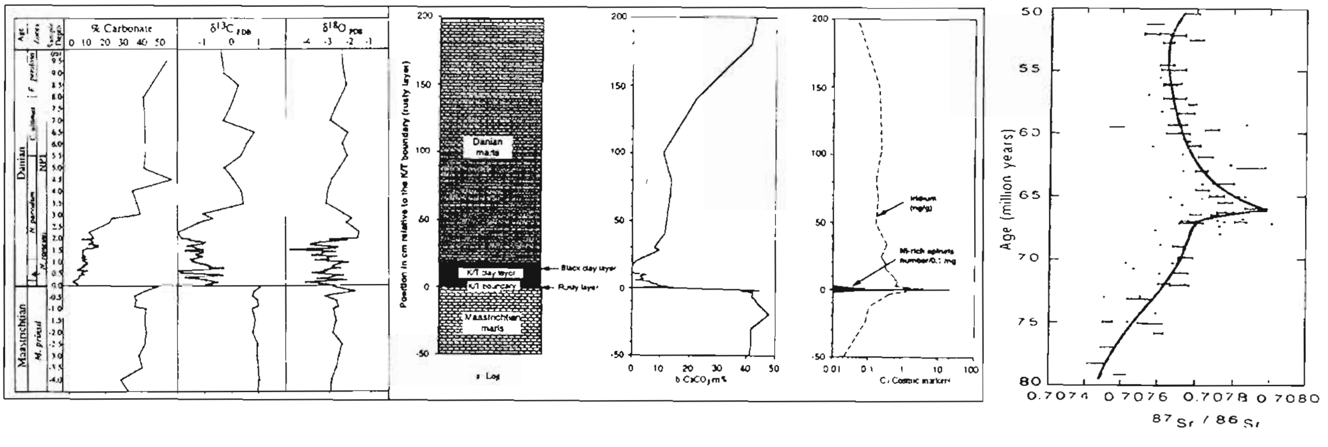
The spectacular celestial event of capture of the comet Shoemaker Levy 9 in circum- Jovian orbit, its breakup in orbit due to tidal forces and subsequent crash on Jupiter, witnessed in July 1994, has given much insight into the phenomenon of cometary impact on planets. Likelihood of a comet in circum-terrestrial orbit is negligibly small. However, there is evidence in form of crater chains (catenae) on satellites of Jupiter, e.g., Callisto and Ganymede and on Earth as well. Two terrestrial catenae have been identified recently. One is the American chain having a string of 8 or possibly 9 craters, identified from NASA's imaging radar space shuttle, ranging in size from 3 to 17 km and extending over a distance of 700 km (from southern Illinois to eastern Kansas), formed about 320 Ma ago. The other is the African chain having three craters including Aoroungan (12.7 km diameter) in northern Chad with two or three more companions, stretching over a 100 km, formed about 360 Ma ago (Rampino & Volk, 1996).

To test various mechanisms discussed above, two principal alternative scenarios depicting cometary impacts can be distinguished using terrestrial sedimentary and cratering records: (i) Impacts which are mainly stochastic in nature and occur due to occasional short-lived but intense comet showers, and (ii) impacts which are episodic and occur at regular intervals. Periodicity (26 Ma) of cratering and mass extinction events has been discussed but it appears that they are not statistically correlated in a significant way.

We first look at the sedimentary records and evidences which may allow us to identify processes responsible for extinctions.

Evidence from extinction horizons

Over ten geological boundaries have been studied for various physical and chemical markers such as the presence of tektites, shocked quartz, anomalously high concentration of platinum group and other diagnostic elements, isotopic changes of $\delta^{13}C$ and $\delta^{18}O$, etc. (Table 2). For understanding the physico-chemical processes responsible for extinction, it is important to distinguish between global and local effects. The results, briefly summarised in Table 2 indicates that every extinction is unique and the imprints of these markers at different boundaries are not identical. There are large craters formed on Earth without accompanying mass extinctions, and there are extinctions where it has not been possible to identify a crater of large enough size, responsible for the extinction. Kyte (1988) has mentioned that six



Text-figure 5—Profiles of some important physical and chemical indices, listed in Table 3, (carbonate content, $\delta^{13}C$, $\delta^{18}O$, occurring at and near the KTB horizon of the El Kef section and magnified profiles (between -50 and 200 cm of the KTB rusty layer) of carbonate and cosmic markers (iridium and nickel rich meteoric spinels) alongwith the litholog of the El Kef section are shown (compiled from Rocchia *et al.*, 1996 and Pospichal, 1996). The figure at the extreme right shows the profile of $^{87}Sr/^{86}Sr$ between 50 to 80 Ma (from Javoy & Courtillot, 1989).

stratigraphic boundaries (Cenomanian-Turonian, Callovian-Oxfordian, Early-Mid-Jurassic, Permian-Triassic, Frasnian-Famennian and Proterozoic-Cambrian) may possibly be of impact origin, whereas there are other boundaries where signatures of impact exists with negligible or no indication of extinction. Among the known (~130) impact craters listed by Grieve (1991) there are nine big craters (including Chicxulub) with their sizes ranging from 55 km to 200 km and ages varying between 36 to 1970 Ma. Among the 24 well-defined extinction peaks in the genus-level data (Sepkoski, 1992), impact signatures are found in case of five extinction boundaries (Pliocene, 2.3 Ma; Late Eocene, 36 Ma; K/T, 65 Ma; Triassic/Jurassic, 205 Ma and Frasnian/Famennian, 367 Ma) only (Rampino & Haggerty, 1996). Thus it is clear that large impacts are not responsible for all the observed extinctions. Similarly there are volcanic episodes accompanying extinctions and extinctions without concomitant volcanic activity. It is, therefore, unlikely that there is a general theory of extinction; rather it appears that there are several mechanisms capable of producing stress on life and some time they work in collusion to result in mass extinctions. The KTB is the most extensively studied horizon and large number of processes which occurred at this time have been documented. We therefore discuss the K/T event in detail.

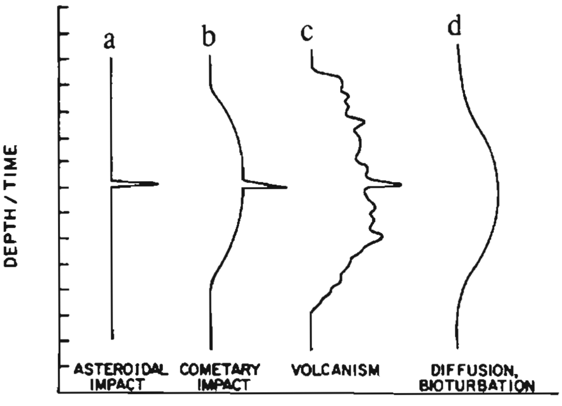
CRETACEOUS-TERTIARY BOUNDARY

Biological, geological, chemical, isotopic mineralogical and environmental signatures observed at the KTB are shown in Table 3. It is clear from this table that there is an overwhelming evidence that an impact took place at or close to the KTB while volcanism in Deccan was active. Krogh *et al*. (1993) on the basis of zircon ages from the KTB, showed that not only the Chicxulub crater was formed at the KTB but this was the only crater formed at the KTB. The argument is based on the bimodal distribution of ages of zircons collected from some KTB sections which have the 65 Ma age of KTB, superimposed upon the 545 Ma age of the Chicxulub platform, on which the impact occurred. The locations where high iridium has been observed is shown in Text-figure 2, indicating global distribution of iridium.

The questions which are now being debated in an impact scenario relate to (i) whether the bolide was a comet or an asteroid, and (ii) the role of impact on extinction. The answer rests on the evidence of extinction being in a single stage and sudden (years) or in multiple stages and gradual over prolonged period of time (million years). A sudden extinction will indicate an asteroidal impact and it would have played a dominant role in extinction. On the other hand, if the extinction is gradual or in several stages, then multiple impacts of cometary nuclei would be favoured. These alternatives and their bearings on tracer profile such as that of iridium are shown schematically in Text-figure 6. We therefore first investigate the nature of the iridium profile observed at KTB.

The Alvarez hypothesis (Alvarez *et al*., 1980), that an extra-terrestrial object of the size ~10 km hit the Earth which caused the mass extinction at the Cretaceous-Tertiary boundary, was proposed to explain the presence of anomalously high concentration of iridium at the KTB. To settle the questions posed above, a high resolution study of KTB is required. Observed variations of some of the diagnostic markers of KTB, e.g., carbonate abundances, $\delta^{18}O$, $\delta^{13}C$, iridium concentration, population of meteoric spinels and change in $^{87}Sr/^{86}Sr$ are shown in Text-figure 5 for the El Kef section in Tunisia, considered to be the best preserved and stratotype section (Keller *et al*., 1995). Kyte and Wasson (1986) looked for signatures of multiple cometary impacts in a marine sediment core but found only one peak of iridium and concluded that there were no impacts of a cometary shower on the Earth. The possibility of resolving multiple impacts, if they have occurred, depends on rates of sedimentation and time interval between different impacts. The fossil data on suddenness of extinction are controversial and favour step-wise extinction (Hut *et al*., 1987). At the same time, role of other causes of extinction, such as multiple volcanic episodes, which is consistent with the iridium profile as well as fossil data can not be ruled out. If volcanism had a major role in gradual or step-wise extinction, then the suddenness of the final extinction may indicate that impact may be the last straw on camel's back.

A series of physico-chemical processes are triggered by the impact. These include aerosol loading of the atmosphere, blocking of Sun light, cessation of photosynthesis, significant temperature excursions, acid rain, destruction of O_3 layer, etc.



Text-figure 6—The expected depth profile of a tracer (e.g., Ir) in an asteroidal (a), cometary (b) and volcanic scenario (c). (d) shows effect of mixing of sediments based on plausible values of deposition and mixing in marine sediments on tracer profile from two sources, volcanic and asteroidal (Bhandari *et al.*, 1994).

which finally lead to mass extinction. The role of acid rain in bringing about extinction is very significant (Prinn & Fegley, 1987; Sigurdsson *et al.*, 1992). Firstly, during the impact, O_2 and N_2 in the atmosphere would combine to give rise to oxides of nitrogen which will be ultimately converted into nitric acid. The production of nitric acid is estimated to be over 1 g/cm^2. Over and above this devastating amount, it has been pointed out that the platform on which the impact occurred at Chicxulub was dominantly anhydrite and the impact would release a lot of sulphate ions in the atmosphere, which ultimately get converted into sulphuric acid. Combination of nitric and sulphuric acids can be even more fatal; Montanari has called it. *Acqua Morta*. If indeed it is the acid which killed the life, then it is difficult to distinguish between volcanism and impact, because both of them produce a lot of acid; volcanism through emission of SO_2 and CO_2, which are eventually converted into acids, and impact through the processes outlined above.

The role of aerosol loading can also be devastating. The Sun light, cut off by the ejecta debris of impact or through dust emanated in volcanism may lead to a dark Earth for at least a few years after the event. This would result in cessation of photosynthesis, leading to loss of the biosphere and consequently the life which depend on it, by mass starvation and other implied effects. The aerosol loading will result in a decrease in temperature over the globe by several degrees. The oxygen isotopic ratios ($\delta^{18}O$), which is a temperature indicator, bear a witness to this sudden cooling by several degrees (Text-figure 5). The green house gases released in impact on carbonate, particularly CO_2 (O'Keefe & Ahrens, 1989) released in volcanism will give rise to a heat wave shortly after the initial cold wave due to aerosol loading as observed. This increase is also expected to be several degrees, and may be another important factor in accelerating mass extinction.

Over and above the various processes mentioned above, there are some additional consequences like forest fires, whose evidence has been found in terms of fine soot at the KTB, which may further amplify the stress.

In summary, there are several evidences which favour impact at KTB (Table 3). Physical evidence for the impact exists in the form of shocked quartz (Bohor, 1990), meteoric spinels (Robin *et al.*, 1992), in addition to identification of the crater at Chicxulub, breccias and quickly quenched spheres around the impact site in the Yucatan peninsula. Chicxulub is a giant crater (diameter ~200 km) and has been dated at 64.98 ± 0.05 Ma, same as the KTB. From the geometry, magnetic and gravity anomalies and distribution of ejecta it has been inferred that the bolide came from south-east and ejecta cloud settled in north Pacific. Several cores raised from this region have provided definitive proof of the impact event (Kyte *et al.*, 1996). Although the processes following a large impact may be very effective in causing severe stress on life (Text-figure 4), its role in causing extinction still remains to be quantitatively established.

RESULTS FROM THE INDIAN SECTIONS

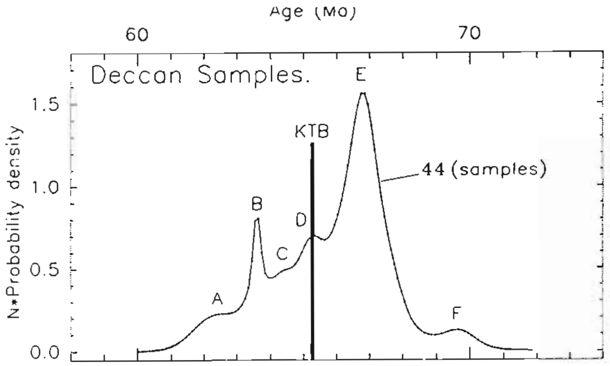
There are several evidences to show (Table 3) that an impact did take place ~65Ma ago at Chicxulub and around the same time, Deccan volcanism in central and western India was also active. However, the precise timing of initiation, peaking and duration of the volcanic episodes is still not established. It has been suggested that voluminous lava flow (<~10^{6}km^3) erupted in a short span of time (<~0.5 or 1 Ma) coinciding with the KTB age (Courtillot *et al.*, 1986; Vandamme *et al.*, 1991). Further, it has been suggested (Courtillot *et al.*, 1986) that the mantle material rich in Ir can emanate during volcanic episodes resulting in Ir rich layer at KTB, similar to those observed in air-borne particles emanating from Hawaiian (Olmez *et al.*, 1986) and Kamchataka (Felitzyn & Vaganov,

1988) volcanoes. Venkatesan *et al.* (1993) dated ($^{40}Ar/^{39}Ar$) stratigraphically controlled samples from 2.5 km section of Mahabaleshwar sequence belonging to the western margin of the Deccan basalts and found that Deccan volcanism pre-dated KTB by at least 1 Ma and emplacement of the whole section lasted at least 3 Ma. Distribution of all available ages of Deccan basalts, compiled by K. Pande (pers. commn., 1996) show a major peak in volcanic episodes at 67 Ma and only a minor one at 65 Ma (Text-figure 7).

To explain the near simultaneity of both impact and volcanic events it was suggested that Deccan volcanism was induced by an impact through pressure relief melting in the asthenosphere, as is believed to have occurred on the Moon which generated the lunar mare (Alt *et al.*, 1988; Rampino & Caldeira, 1993). In this context, it was realised that K/T sections from Indian subcontinent should provide useful clues in understanding the role of Deccan volcanism as its effects would be more pronounced in its proximity. Several intertrappean (IT) samples (lava ash, clay, marl, etc.), from various localities in the Deccan province, were therefore analysed to ascertain the Ir levels in these samples (Bhandari *et al.*, 1993a; Bhandari *et al.*, 1993b. The Ir levels in these samples, except for Anjar, discussed below are low and range from 8 pg/g to a maximum of 120 pg/g (Table 4). These values are short by several orders of magnitude to account for the high concentration of Ir observed at various KTB horizons (e.g., 5 ng/g to 187 ng/g Ir in Marine KTB sites) all over the globe. Further, the intertrappean samples do not show other chemical characteristics observed in case of Hawaiian volcanic particulates, for instance enhanced chalcophile element (Se, As, Sb, etc.) concentrations. If Deccan volcanism was contributing Ir and other elements similar to Hawaiian volcanic emissions, then these elements ought to be enriched in many IT samples contrary to our observation. Significant contribution of Deccan volcanism in giving rise to chemical anomalies seen at KTB can therefore be ruled out.

Anjar Intertrappean Section

The volcano-sedimentary sequence in coastal land section near Anjar, Kutch (Bhandari *et al.*, 1995, 1996; Hofmann *et al.*, 1997) is an exception to the low iridium concentration and shows three well-separated Ir-rich layers. These layers lie within the third intertrappean overlying three lava flows as shown in Text-figure 9. The flows above and below the Ir layer have been dated recently using $^{40}Ar/^{39}Ar$ method (Venkatesan *et al.*, 1996). The plateau ages of the two flows (FIII and FII) underlying the IT containing Ir-rich layer are found to be 65.2 ± 0.6 Ma and 64.9± 0.8 Ma, respectively whereas the overlying flow (FIV) gives a plateau-like age of 65.7 ± 0.1 Ma. These ages are similar to the age of KTB obtained from dating microtektites found in marine KTB sediments (Izett *et al.*, 1991) and 64.98 ± 0.1 Ma obtained by dating melt glass from Chicxulub (Swisher *et al.*, 1992). Furthermore, the flows IV, V, VI and VII all show reverse magnetic polarity (Kusumgar, pers. commn., 1996; Hofmann *et al.*, 1997), whereas the secondary magnetic imprints on FI, II and III are too intense to provide a reliable primary magnetic polarity of these lower flows. Considering the chronology of magnetic polarity, we place flows IV, V and VI in magnetic chron 29R, during which the KTB layer is known to have been emplaced. Whether Flows II and III also fall in this chron or not can only be decided when better data on remnant magnetism are available. FI appears to belong to the narrow reversed period of chron 30R. The three layers in the third intertrappean beds have an enhanced level of Ir and Os, the maximum values being 1.27 ng/g and 1.41 ng/g, respectively (Text-figure 9a), similar to those observed in case of various other continental K/T sections. The integrated amount of iridium in the Anjar section is comparable and not higher than fallout at any other place on the globe. Thus if the Ir-rich layer is taken to represent the KTB layer, then in



Text-figure 7—Probability density of ages of Deccan flows (K. Pande, pers. com.) based on Ar-Ar plateau ages . The distribution shows a peak at 67 Ma, 2 Ma before the KTB age of 65 Ma. A, B, C, D, E represent regions from where samples were dated and their locations are shown in Text-figure 8.

Table 4—Estimates of atmospheric loading (g) at K/T and P/T boundaries

Source	CO_2	SO_4	HCI	NO	Soot from forest fires	Ejecta dust
a) K/T boundary						
Impact Platform	$2.7\text{-}9x10^{18}$ (1)	$0.38\text{-}3x10^{19}$ (2)	-	$3.15x10^{18}$ (3)	10^{17}	10^{19}
Bolide	$1.4x10^{17}$ (4)	$3\text{-}300x10^{14}$ (5)		$2.7x10^{15}$ (4)		
Deccan volcanism	$2.2x\ 10^{19}$ (6)	$1.7\ x10^{19}$ (6)	$2.7x10^{17}$ (6)			
Total	$2.65x10^{19}$	$4.25x10^{19}$	$2.7x10^{17}$	$3.15x10^{19}$	10^{17}	10^{19}
g/cm 2	5.2	8.3	0.05	0.62	0.014	2
b) P/Tr boundary						
Siberian volcanism 8	$2.93x10^{19}$	$2.26x10^{19}$ --	?	$3.6x10^{19}$	?	

1. O'Keefe and Ahrens (1989) gave estimates for platform thickness of 1 and 4 km indicated by the range.
2. Sigurdsson *et al.* (1992).
3. Prinn and Fegley (1987).
4. The CO_2 and SO_2 values have been estimated assuming a 10 km C2 type of bolide (C=2.48%; N=802 ppm). The choice of C2 type bolide is based on similarity of amino acids found in KTB sections and C_2 meteorites (see Table 3).
5. Kring *et al.* (1996).
6. Caldeira and Rampino (1990).
7. Fires will also provide 10^{18}g CO, 10^{17}g CH_4, 10^{16}g N_2O etc. besides CO_2 and the atmosphere ozone layer will be depleted. This may have more devastating effect on life support system (Wolbach, Gilmour & Anders, 1990; Rampino & Haggerty, 1996; and other references therein).
8. Basaltic lava volume from Siberian volcanic episodes is estimated to be $2x10^6$ km^3. The aerosol estimates are scaled from Deccan which had a volume of $1.5x10^6$km^3 .

the light of observations summarised above, some conclusions can be drawn about relation between KTB and Deccan. Firstly, the results show that Deccan volcanism was active before, during and after the KTB transition. Secondly, the extra-terrestrial impact did not trigger Deccan volcanism. The location of the KTB layer within the Anjar intertrappeans provides a high resolution time sequence because of fast sedimentation rate, free from the uncertainties in absolute chronology and contradicts the models of impact induced volcanism proposed by Alt *et al.* (1988) as well as simultaneity of impact and Deccan volcanism (Rampino & Caldeira, 1993).

The Anjar section also provides important criteria to test some other hypotheses. Chatterjee (1990, 1992) proposed that there was another impact on the Earth at the KTB time near the Indo-Seychelles border. The slightly oval-shaped structure, named Shiva Crater, after the Indian God of Destruction, is about km in 600x450x12 km in size and the bolide which created it is estimated to be 40 km in diameter, much bigger than the Chicxulub impactor. The impact which occurred at India-Seychelles border created the Carlsberg Ridge and triggered the rifting of the Indian Plate. The Carlsberg Ridge splitted the crater into two halves which drifted away from each other. At present the boundary of the western half of the crater is identified as the Amirante Arc and the eastern half is concealed under Deccan lava but discernible in the Panvel flexure. From the shape of the crater, Chatterjee (1990, 1992) suggested that the bolide came from south-west. If it is indeed so, Anjar, being not far from the point of impact, and placed in the immediate ejecta fallout zone, should have some evidence of the impact debris. We have not found any evidence of breccias, or other ejecta debris at Anjar, as has been found around Chicxulub crater or in the Pacific sediments where the Chicxulub ejecta cloud settle. If the sediments around the iridium layers at Anjar were deposited at the KTB time, as appears likely, than absence of these markers at Anjar rules out another impact of a larger magnitude at the proposed site of the Shiva crater. The same argument can be extended to the crater near Bombay high, proposed by Negi *et al.* (1993) based on a gravitational anomaly, although its dimensions are much smaller and thus large ejecta debris is not expected.

Table 5 — Ir concentration (pg/g) in Deccan basalts and in K-T boundary sections, India

I.		**Deccan basalts**	
	1	Takli	≤ 0.027
	2	Lonar Crater	0.004-0.006*
	3	Anjar FIII	<0.01
II.		**Continental K-T sections**	
A.		Takli section, Nagpur	
	1	Volcanic ash	0.05-0.12
	2	Marl	0.032-0.067
	3	Green clay	0.041-0.099
	4	Lower contact with trap	0.081
B.		Lameta Section, Jabalpur	
	1	Brown layer, Chui Hill	0.026
	2	Coal Seam, Padwar	0.015
C.		Bargi Canal section	
	1	Clay	0.008-0.015
D.		Jirabad	
	1	Trap contact	
E.		Mahabaleshwar section	<0.2
F.		Anjar	
	1	Boundary clay	0.69 -1..33
	2	Below and above boundary clay	0.1
III.		**Marine K-T sections**	
A.		Um Sohryngkew River section	
	1	Boundary clay	7.8
	2	Brown separate	12.1
	3	Cretaceous shales (-70 cm)	0.019
	4	Tertiary shales (+50 cm)	0.04
B.		Gongma section	<0.2

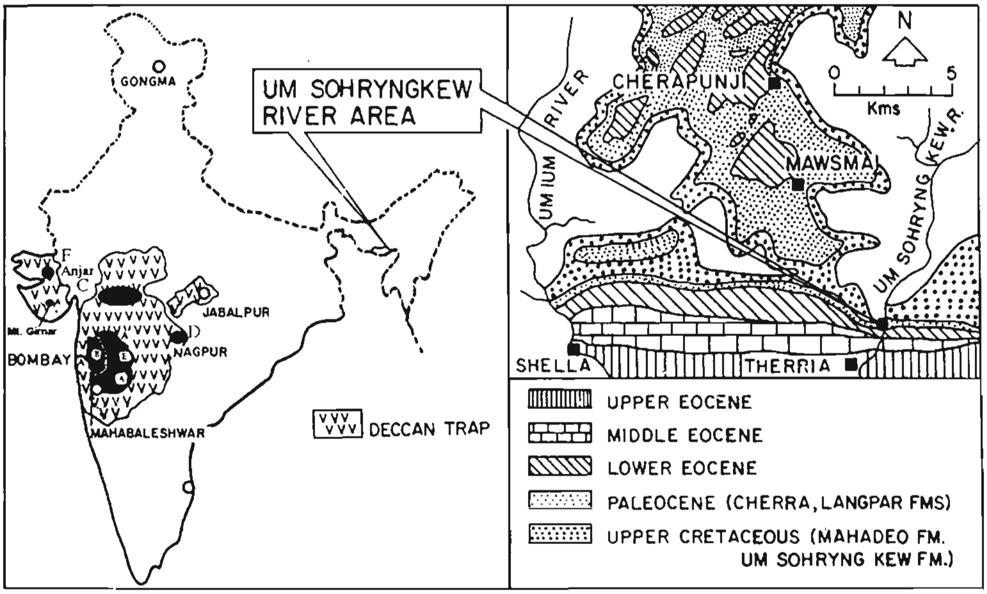
*Morgan (1978)

Um Sohryngkew River Section

A marine K/T section was studied from Um Sohryngkew River Basin, Meghalaya in eastern India (Text-figure 9) where the Maastrichtian-Danian sequence is continuous and a 1.5 cm thick limonitic layer enriched in Ir, Os and the other siderophile elements, characteristic of the KTB, is observed (Bhandari *et al.*, 1994 and references therein). The Ir profile in this section (Text-figure 9) shows a broad (30 to 70 cm) band on modest Ir concentration (~100pg/g), ten times higher than the background levels (10 pg/g) both below and above the KTB. The main sharp Ir peak (1200 pg/g) coincident with KTB is superimposed on this broad band.

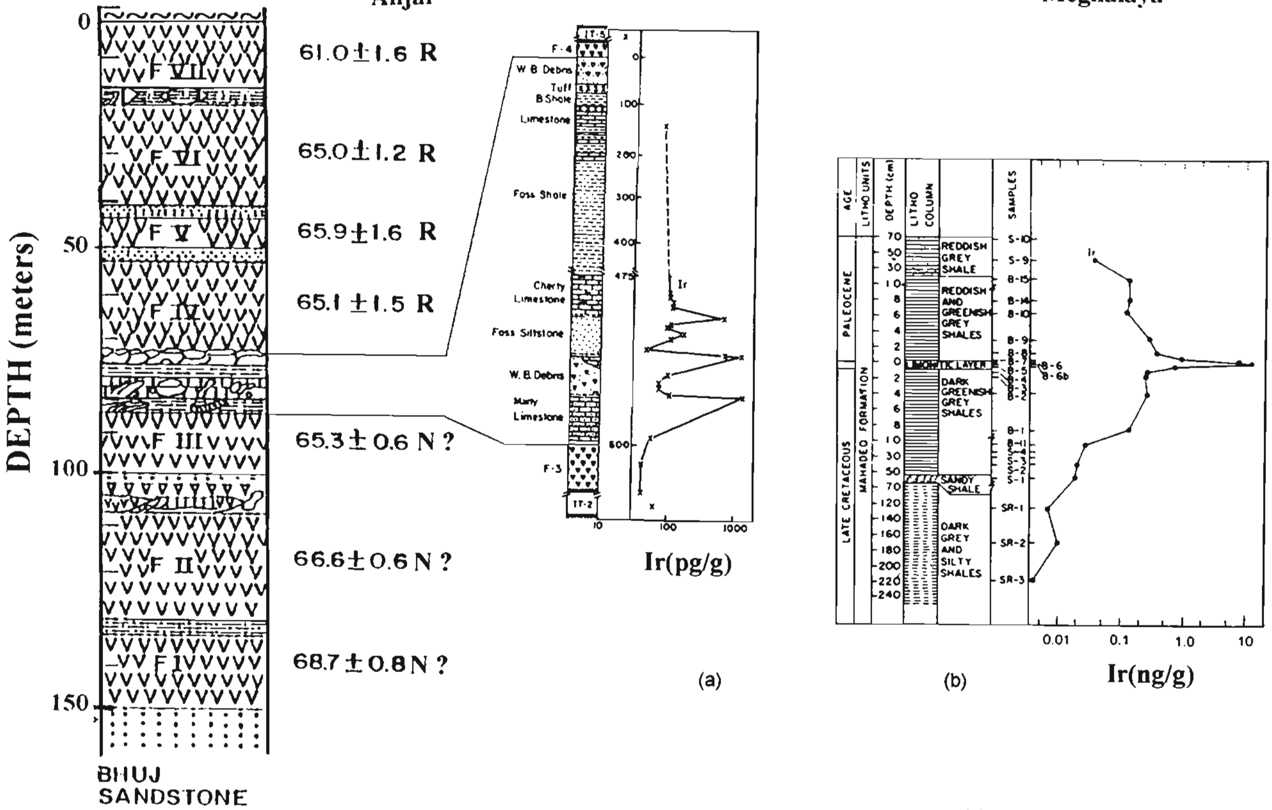
The extended Ir profile of Meghalaya section may be compared with Ir profiles in other marine KTB sections, e.g., Stevens Klint; El Kef, Caravaca; Hole 761 shown in Text-figure10. In all these sections, the main Ir peak at KTB is situated on a broad hump although the shape of the profile which depends on sedimentation rate is quite different in each of them. The broadening of the profiles is usually dismissed as due to post-depositional migration of Ir and other elements (Colodner *et al.*, 1992) although, at least in Meghalaya there is absence of significant bioturbation, mixing and post-depositional movement (Bhandari *et al.*, 1994). If this indeed is the case then it should be possible to test various hypotheses, i.e., volcanic, an asteroidal and multiple cometary impacts. It can be seen that Ir profile in a single asteroidal impact (Text-figure 6a) does not match with the observed Ir profiles in various sections (Text-figures 9, 10). Also a single asteroidal impact hypothesis does not explain the step-wise extinction pattern observed around the KTB (Hut *et al.*, 1987). The best match is obtained with tracer profiles shown in Text-figure 6b, or with combination of different profiles.

The other two scenarios, viz., volcanic eruptions and multiple cometary collisions are essentially episodic in nature and are also consistent with the observed gradual or step-wise extinction pattern. In case a comet fragments into a number of km-sized nuclei and a large amount of debris in a heliocentric earth-crossing orbit, all of it may eventually fall on the Earth, preceding and succeeding the impact of various nuclei. This scenario is shown in Text-figure11. In this model the main Ir peak could be due to the impacts of different nuclei as observed at Anjar, whereas the hump structure in the elevated Ir profile could be due to smaller debris. Similarly, in a volcanic scenario one could observe multiple Ir peaks corresponding to each volcanic episode. Graup and Spettel (1989) have reported three Ir enriched layers in the Lattengebirge section from Bavarian Alps and suggested volcanism as a cause for these enhancements. In this section, Ir resides in sulphide phases and is accompanied by enrichment in chalcophile trace elements as well. As mentioned earlier, Ir and chalcophile trace element enrichment in particulates from Hawaiian volcanoes also favour such a scenario. However, our extensive measurements of intertrappean sediments at various Deccan localities (Table 5) neither show adequate level of Ir nor there is any enrichment of chalcophile elements (Bhandari *et al.*, 1993a, 1993b, 1995, 1996).



Text-figure 8—Sites of Indian K/T boundary sections and the Deccan Plateau showing regions A, B, C, D, E and F for which the distribution of ages is shown in Text-figure 7. Anjar intertrappean (IT III) in Kutch and Um Sohryngkew River section in Meghalaya shows anomalously high iridium concentration.

In conclusion, there is mounting evidence summarised earlier (Table 3) that Deccan volcanism was active around the K/T time and that a large impact took place ~65 Ma ago. Some authors (Alt *et al.*, 1988; Rampino & Caldeira, 1993) argue that a bolide impact triggered volcanism whereas others opine that impact and volcanic eruptions at KTB are independent events with no causal link, having



Text-figure 9—Ir profiles observed in two Indian K/T sections. Anjar is a continental section from Kutch (a) and Um Sohryngkew River section is a marine section from Meghalaya (b). The composite section of Anjar volcano-sedimentary sequence is shown on the left some sample locations are marked.

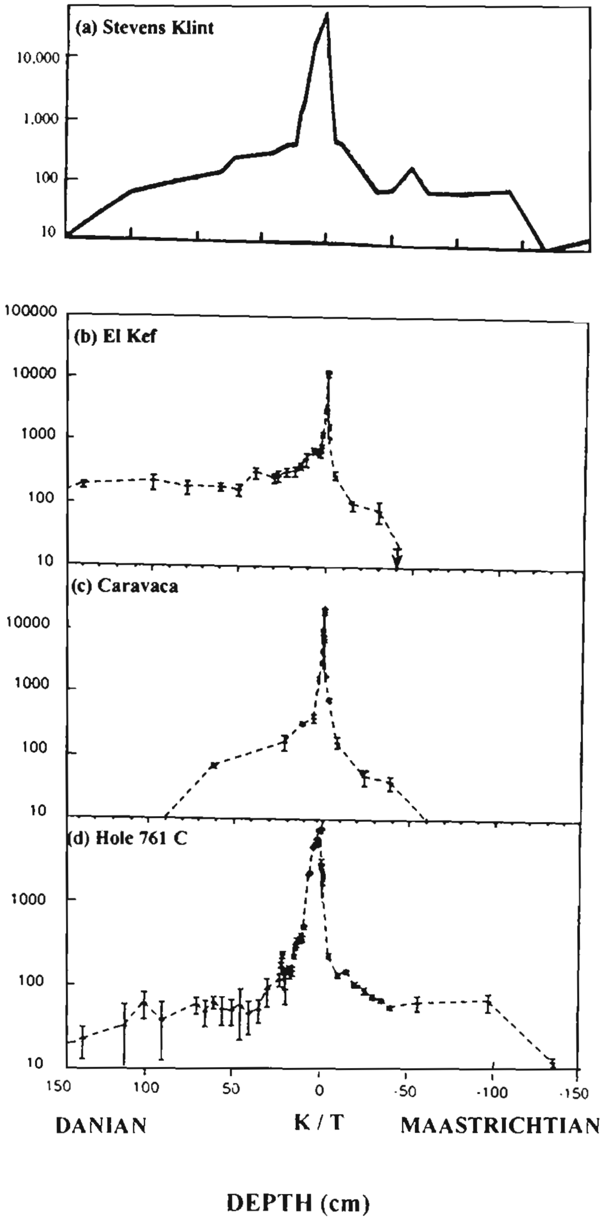
Table 6— Major observations at Permo-Triassic boundary

Biological signatures	
1.	**Global extinction of about 90% of marine fauna and 70% of terrestrial vertebrates (Sepkoski, 1992):** This is the most severe extinction event in the Phanerozoic.
2.	**Near disappearance of Permian flora (Retallack, 1995)**
Geological signatures	
1.	**Siberian flood basalts, timing and duration:** $^{40}Ar/^{39}Ar$ ages range between 253 Ma to 247 Ma. The volume is estimated to be ($2x10^6$ km^3). It has been suggested that bulk of the basalts erupted within a short interval of time of less than 1 Ma around P/TB (Renne & Basu, 1991).
2.	Pyroclastic volcanism in south China (1000 to 4000 km^3)
3.	**Sea level changes:** Rapid regression and transgression. About 280 m fall in sea level is estimated. The scenario envisages two regressions followed by a rapid transgression in the Early Triassic.
Chemical and isotopic signatures	
1.	Two small peaks of iridium (≤ 120 pg/g) have been found at several locations (Holser *et al.*, 1989; Bhandari *et al.*, 1992)
2.	A positive europium anomaly has been found in Lalung and Guling sections in Spiti India (Bhandari *et al.*, 1992)
3.	A sharp decrease in $\delta^{13}C$ at and above the P/TB
4.	Excursions in $\delta^{18}O$ values indicating changes in sea water temperature of several degrees before and after the P/T event.
5.	Enrichment in S isotopic ratios ($^{34}S/^{32}S$) attributed to an anoxic event.
6.	A marked shift in Sr isotopes.
7.	Strong anoxia in the world oceans, both at high and low palaeolatitudes in the Late Permian (Erwin 1996; Wignell and Twichett, 1996). Records from the deep sea sections indicate a totally stratific ocean for a period of about 20 Ma which included a 12 Ma super anoxic period (Isozaki, 1997).
Mineralogical and other features	
1	Presence of quartz with planar deformation features in Australia and Antarctica P/TB sections (Retallack, 1996)

occurred by chance at the same time (Sutherland, 1994). The results on the Anjar and Meghalaya sections support the latter view as discussed above. Both of these events are highly energetic and their relative roles in mass extinction remains to be quantitatively evaluated.

The presence of excess Ir in the limonitic layer in the Um Sohryngkew River section in Meghalaya led Bhandari *et al.* (1994) to conclude that this layer represents the KTB. Further work on this section has been controversial in spite of the reported presence of the characteristic faunal break (Pandey, 1978, 1980) concomitant with iridium enrichment (12.1 ng/g) in the limonitic layer, by more than an order of magnitude (Bhandari *et al.*, 1987) above the normal level. Lahiri *et al.* (1988) reported absence of such a faunal break and contended that the KTB is about 30 m above the iridium rich limonitic layer. Subsequently, Jafar and Singh (1992) reported that latest Maastrichtian planktonic foraminifer and nannoplankton assemblages are absent in this section and argued that this section might be incomplete and without KTB. On the other hand, evidence for presence of KTB within this layer has come from a detailed study of foraminifera (Pandey, 1978, 1990) and from the occurrence of the diagnostic calcareous nannoplankton assemblages containing *Micula prinsii* just below the iridium layer (Garg & Jain, 1995). As it is important to ascertain if the KTB indeed occurs in this section, a search for meteoric spinels in the limonitic clay was made. Ni-rich spinels are believed to provide an unequivocal imprint of a cosmic bolide (Robin *et al.*, 1992). Simultaneous occurrence of Ni-rich spinels and high Ir concentration in the Meghalaya section (Robin *et al.*, 1997) has now settled this controversy and confirmed the existence of KTB in this section.

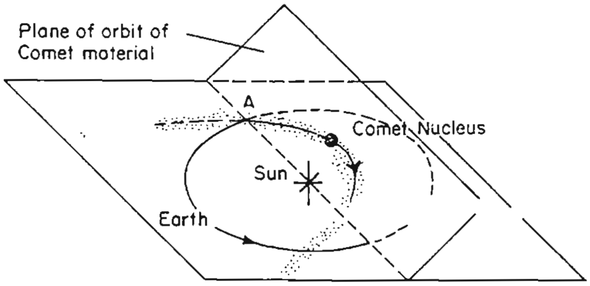
Recently, Alvarez (1996) modelled the fallout ejecta debris from the geometry of impact (angle, velocity, palaeogeographic locations) and concluded that impact ejecta did not reach India, which was located in the "forbidden zone". Although iridium and meteoric spinels have been found in Meghalaya section, there is as yet no evidence of the presence of shocked quartz which is a physical marker of the ejecta debris. Their presence in Anjar or Um Sohryngkew River sections may provide a test of the models of distribution of ejecta material.



Text-figure 10—Ir profile in some selected K/T boundary sections (Stevns Klint, El Kef, Caravaca and Hole 761C). Occurrence of a major Ir peak located on a broad extended hump above and below KTB, can be seen.

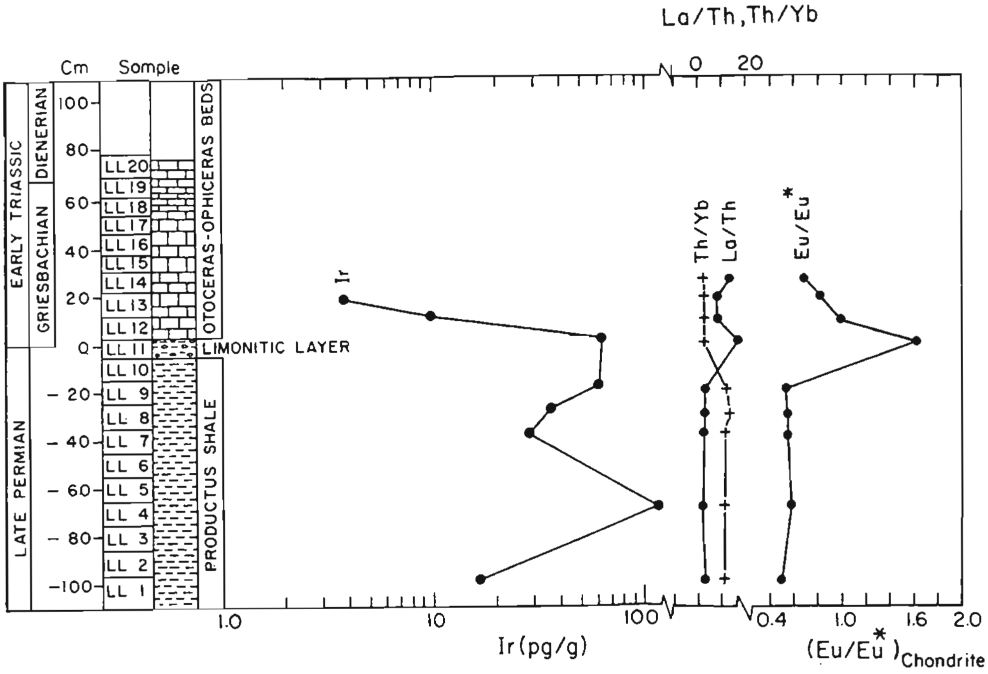
PERMIAN-TRIASSIC BOUNDARY

The Permian-Triassic (P-T) mass extinction was the most catastrophic in the geological record where as many as 90 per cent of the marine fauna and 70 per cent of the terrestrial vertebrates became extinct (Raup & Şepkoski, 1986; Erwin, 1994a, 1994b). Significant floral extinctions are also observed around this boundary (Retallack, 1995). The PTB is quite complex and palaeontological controls as well as preservation of evidence is relatively poor. Several P/T sections have been studied, but in most of them some horizons are missing (Sweet *et al.,* 1992; Kapoor, 1992). Some of these sections are shown in Text-figure14. Claystone, mudstone or pyrite bands have been found at the PTB at many locations (Nakazawa *et al.,* 1992). Geochemical, isotopic and palaeontological studies have been carried out on Carnic Alps section in Austria (Holser *et al.*, 1989); China (Clark *et al.,* 1986; Zhou & Kyte, 1988), India (Bhandari *et al.*, 1992); Italy (Wignall & Twitchett, 1996); Russia (Alekseev *et al.*, 1983), etc. Although earlier reports indicated that P-T extinctions took place over about 8 to 10 million years (Stanley, 1987; Teichert, 1990), a recent re-examination of the palaeontological data by Erwin (1994a, 1994b,1996) suggests a shorter duration, about 2 Ma or less, for this extinction. Important biological, geological, chemical and isotopic signatures found at PTB are summarised in Table 6. Search of a chemical marker having a global nature has not yielded any definitive clues. The range of Ir values observed across the boundary in various sections range from a few pg/g to hundreds of pg/g as listed in Table 6. In their detailed study of Gartnerkofel section in Carnic Alps Holser *et al.* (1989) found two minor Ir peaks, one occurring at the base of a pyrite zone at the boundary and the other about 40 m above it. Both the Ir peaks are associated with $\delta^{13}C$ minima. Though the peak Ir concentrations at the boundary are marginally higher than the background values, these minor Ir enhancements could result from some terrestrial processes (Colodner *et al.,* 1992).



Text-figure 11—Schematic diagram showing orbits of cometary debris and the earth-crossing each other which may explain the iridium profiles observed in KTB sections shown in Text-figures 9 and 10.

Before we discuss the scenario emerging for P/T transition, the results obtained from Indian sections (Bhandari *et al.*, 1992) are briefly described here. In view of the geographical proximity of these sections



Text-figure 12—Ir and Eu profiles in a P/T section from Lalung, Spiti, showing a large positive europium anomaly in the limonitic layer. Th/Yb and La/Th profiles are also shown which indicate basaltic volcanic contribution above the limonitic layer (Bhandari *et al.*, 1992).

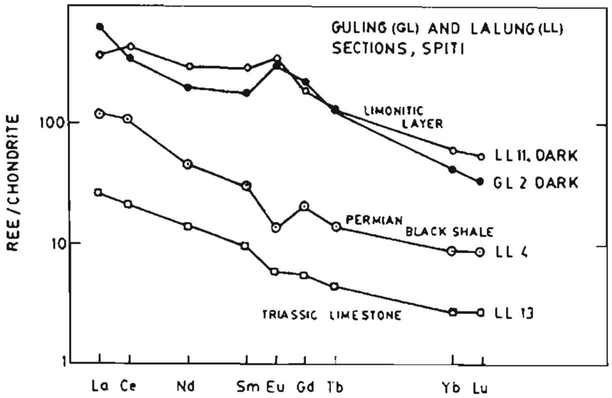
to Siberian volcanic region (Text-figure 2) during the end-Permian period, it can only be expected that the large volcanic episode will overwhelm the chemistry of sedimentary deposits at that time. If indeed there was another event of global significance, such as an impact, its signatures can best be seen far away from the volcanic regime.

CLUES FROM THE INDIAN SECTIONS AT GULING AND LALUNG, SPITI VALLEY

During the Permian-Triassic time Australia, Antarctica and India were located in the southern hemisphere (Text-figure 2b). Chemical analysis of Lalung and Guling sections in Spiti by Bhandari *et al.* (1992), where a limonitic layer exists at the Permian-Triassic interface, shows a small Ir enhancement at the boundary (70 pg/g) and another minor Ir peak (~114 pg/g) about 70 cm below the boundary (Text-figure 12). These Ir levels are similar to those observed in Carnic Alps by Holser *et al.* (1989) and in Chinese sections by Zhou and Kyte (1988), both located in the northern hemisphere (Text-figure 2b). However, the boundary sample of the limonitic layer at Spiti shows a very high Eu concentration and the chondrite normalised REE patterns (Text-figure 13) shows a positive Eu anomaly of $(Eu/Eu^*)_{max}$ equal to 1.9 (Eu^* is the interpolated concentration based on its neighbouring elements Sm and Gd). The Eu anomaly is also associated with high value of Sb and Zn. Some of these geochemical features like high Fe, Zn and Sb are also observed in boundary samples from Meishan section in China (Zhou & Kyte, 1988). Bhandari *et al.* (1992) have discussed various terrestrial and extra-terrestrial causes which can give rise to the positive Eu anomaly observed at the PTB. Among the terrestrial sources, it has been pointed out that volcanogenic sediments and interaction of hydrothermal solutions with felsic volcanic rocks could give rise to a positive Eu anomaly. Among the extra-terrestrial objects, differentiated meteorites like eucrites and lunar anorthosites exhibit high positive Eu anomaly and have very low Ir values. Thus if an impact were responsible for the P/T event, the observations would be consistent with a bolide of a differentiated achondritic body.

Recently, Retallack (1996) found some quartz grains having planar deformation features (PDF) in the P/T section near Sydney, Australia which can possibly be due to impact. Similar damaged quartz were found in the P/T section of Victorialand, Antarctica. These PDF quartz are associated with $\delta^{13}C$ anomaly indicative of P/T extinction. The search for shocked quartz at PTB in sections located in the northern hemisphere has not yielded positive results.

If an impact occurred in the southern hemisphere, some northern hemisphere sections may be excluded from the ejecta debris and this may explain their absence in Chinese and European sections. Whether an impact occurred or not at the PTB the extinction may be a result of cumulative stress created by several physico-chemical processes. Some of these are schematically shown in Text-figure 14 (after Erwin, 1996) and these possibilities are briefly discussed below.



Text-figure 13 — Chondrite normalized REE patterns from Guling and Lalung PTB sections, Spiti. A positive Eu anomaly is observed at the boundary (Bhandari *et al.*, 1992).

EFFECT OF SIBERIAN VOLCANISM

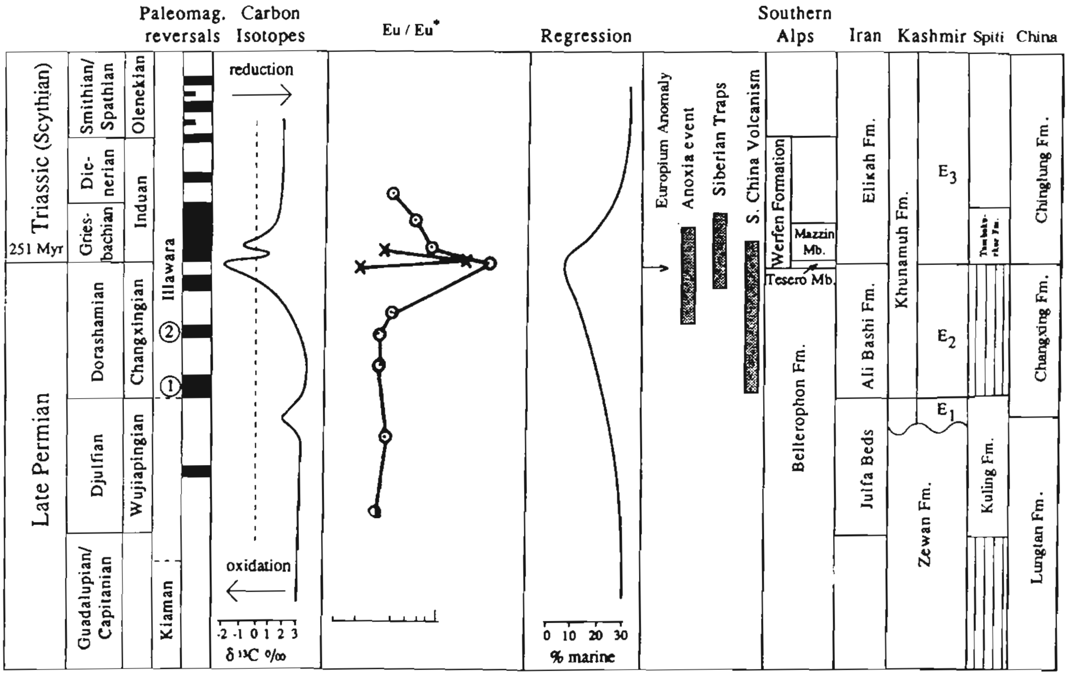
The available geochronological data on Siberian traps suggest that it was synchronous with the P-T extinction. Renne *et al.* (1995) estimated the age of the PTB by dating two tuff samples from southern Chinese sections, Shangsi and Meishan, located just above and below the boundary. The plateau ages 249.91±0.51 Ma (Meishan, Sanidine sample) and 250.04±0.36 Ma (Shangsi, Plagioclase sample) are indistinguishable from each other. The mean value of 249.98±0.2 Ma is comparable to the PTB age of 251.2±3.4 Ma obtained by U-Pb analysis of zircons from the Meishan section (Cloue-Long *et al.*, 1991).

The best estimate of initiation time of the Siberian trap volcanism as indicated by main stage of the tholeiitic magma is 250.0±1.6 Ma (Renne *et al.*, 1995) same as the estimated age of the PTB. The volcanism lasted for a short duration, ~1Ma (Renne & Basu, 1991; Renne *et al.*, 1995; Basu *et al.* 1995; Venkatesan *et al.*, 1997). Prior to this main pulse of tholeiitic magma, an alkaline volcanism from the north eastern part of the Siberian flood basalt province has been observed by Basu *et al.* (1995) around 253.3±2.6 Ma. Siberian flood basalts have the largest subaerial exposure of ~$3x10^6$ km^3 in the Phanerozoic and are associated with mafic intrusions which contain sulphide ores. The eruptions were both explosive and sulphur rich which would have injected large amount of SO_2 and volcanic dust in the atmosphere causing acid rain and global cooling. The estimated sulphate loading of the atmosphere is given in Table 4. Campbell *et al.* (1992) mention several features of Siberian volcanism which could bring about global cooling through SO_2 emissions and have argued in favour of Siberian volcanism as the main cause of P-T extinction through climatic stress. This scenario is supported by Courtillot *et al.* (1996) who also believes Siberian volcanism to be dominantly responsible for the P-T extinction. The isotopic and geochemical studies of Alpine and the Chinese sections (Holser *et al.*, 1989; Clark *et al.*, 1986; Zhou & Kyte, 1988) suggest a strong regression-transgression event occurring with mass extinction at the PTB and also favour a volcanic scenario based on geochemical arguments.

In the scenario that is emerging, various observations could be visualized as follows. Siberian traps produced sufficient sulphate aerosols in the stratosphere which resulted in rapid cooling. This initiated ice cap accumulation causing a marine regression leading to sub-aerial exposure of the continental shelves. It also explains the observed excursions in C, S and Sr isotopes. Mantle derived CO_2 and SO_2 being light in C and S contributed to the negative anomalies in $\delta^{13}C$ and $\delta^{34}S$. When the Siberian volcanism ceased, a rapid transgression followed and climate recovery took place due to green house effect of volcanic gases like CO_2. Thus anoxia, volcanism and sea level regression, all three may have played an important role in P/T extinction as shown in Text-figure 14. Search of impact signature and a detailed study of claystones, mudstones, pyrite bands and limonitic layers found at various P/T boundaries may provide some clues to other significant processes occurring at the PTB.

SUMMARY

We have described the main features of the two most severe extinction events in the geologic history of the Earth. The debate between impact and volcanic



Text-figure 14 — Schematic scenario for extinction at the PTB (modified from Erwin, 1994a, 1994b, 1996). Periods of global anoxia, Siberian volcanism and south Chinese volcanism are shown together with the event of positive europium anomaly, observed in Spiti. Palaeomagnetic polarity, carbon isotope and Europium (Eu/Eu*) profiles and sea level changes are shown. Some of the P/T sections (Southern Alps, Iran, Kashmir, Spiti and China) are shown at the right.

hypotheses is far from resolved. From the evidences summarised in this article, it is clear that there are very few similarities in physical, chemical and biological markers observed at P/T and K/T boundaries. The situation is even more exclusive when other boundaries are taken into consideration. It therefore appears unlikely that there is a single mechanism which could explain the extinctions. Hypotheses involving multiple causes, therefore, appear more plausible although McLaren and Goodfellow (1990) and Rampino and Haggerty (1996) have argued for an impact theory of extinction whereas Courtillot *et al.* (1986) and McLean (1985) have advanced the volcanic hypothesis. It may be that sometimes volcanism and impact occur together increasing the severity of climatic stress (Sutherland, 1994). In Text-figure 14, we reproduce a likely scenario, developed by Erwin (1994a, 1994b, 1996), where anoxia, aerosol loading, sea-level regression, etc. can contribute to extinction in some measures. Whatever may be the primary cause that triggered the sequence of event(s) that resulted in mass extinctions, it is clear that at the time of mass extinctions, the days were cold, pitch dark and dry and climate was not conducive for the survival of fauna and flora.

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