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Geochemical and isotopic anomalies preceding K/T boundary in the Cauvery basin, South India: Implications for end Cretaceous events

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The Upper Cretaceous–Lower Tertiary deposits of the Cauvery basin show prominent geochemical and isotopic anomalies preceding the K/T boundary. Analyses of stratigraphic variations of whole-rock elemental concentrations and stable isotopic compositions in the light of sedimentation history, petrography and mineralogy of the rocks reveal that these anomalies may be due to increased detrital influx caused by sea-level and climatic changes, Deccan volcanism and release of volatile gases from buried hydrocarbons, presumably gas hydrates. Comparison of these interpretations with that of K/T sites located in Guatemala, New Mexico and Israel revealed that these interpretations are in conformity with records on gradually increasing environmental stress during Upper Cretaceous that culminated with two major catastrophic events such as bolide impact and Deccan Trap volcanism. Thus this communication provides additional support to the growing acknowledgement of the theory that higher faunal turnover across the K/T boundary the world over might have been the result of gradual environmental deterioration rather than a sudden impact in the global scale.

THE close of the Mesozoic era marked the beginning of an eventful phase in the geologic history in terms of global climatic deterioration that left imprints on faunal and floral distribution and on sedimentary deposits[1], based on which it is established that an abrupt boundary separates the Cretaceous from the Tertiary virtually everywhere in the global stratigraphic record[2]. Review of the scenarios for the Cretaceous/Tertiary boundary event revealed[3] that the oceans were already stressed by the end of the Late Cretaceous as a result of the long-term drop in atmospheric CO_2, long-term drop in sea-level and the frequent development of oceanic anoxia. An increasing body of evidence points to the presence of abrupt $\delta^{18}O$ and $\delta^{13}C$ changes associated with the K/T boundary[4–6]. At a number of localities, however, $\delta^{18}O$ and $\delta^{13}C$ changes have been found to precede the K/T boundary[7]. Many researchers[7–11] recorded anomalies of the Platinum group and other geochemical elements far below the K/T boundary. The anomalies that predate the

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K/T boundary raise questions on the relative timing of biotic and isotopic events near the K/T boundary[12]. In resonance with these studies, we record the occurrence of geochemical and isotopic anomalies preceding the K/T boundary in the Cauvery basin based on whole-rock samples and discuss their causes and implications.

Among NE–SW trending, Late Jurassic–Early Cretaceous rift basins of the Indian peninsular shield, the Cauvery basin is the southernmost[13]. Almost a complete Upper Cretaceous–Palaeocene succession is exposed in the Ariyalur–Pondicherry depression of this basin[14]. Maastrichtian–Danian boundary in this basin is represented by a disconformity surface across which faunal and lithological characteristics of the strata are highly different making the Cretaceous–Tertiary boundary recognizable[14–16]. Figure 1 presents the location of the study area, lithological characteristics and inferred geological events of Maastrichtian–Danian strata[16,17].

Sedimentation of the lowermost deposits of the studied section, the Kallankurichchi Formation, commenced[18,19] at about 75.5 Ma with transgression during the Latest Campanian–Early Maastrichtian[20]. Towards the top, the deposits show reduction in size and proportion of siliciclastics that were increasingly replaced by gryphean colonies. In due course, the gryphean bank shifted towards shallower regions and the locations previously occupied by coastal conglomerate have become middle shelf, wherein typical *inoceramus* limestone started developing. Change in depositional conditions of *inoceramus* limestone was associated with regression of sea-level resulting in erosion of shell banks and middle shelf deposits and their redeposition into biostromal deposits. Again, the sea-level rose to create marine flooding surface as a result of which gryphean shell banks started developing more widely than before. This marine flooding surface had been dated by earlier reports[19,21], which indicated that commencement of this gryphean bank development was coincidental with sea-level rise since 70.45 Ma. Towards the top, shell fragments and minor amounts of siliciclastics are observed indicating onset of regression and higher energy conditions. Occurrence of non-depositional surface at the top of this formation and deposition of shallow marine siliciclastics (Ottakoil Formation) immediately over the carbonates and conformable offlap of much younger fluvial sand deposits (Kallamedu Formation) are all suggestive of gradual regression associated with establishment of fluvial system during end Cretaceous. Data from published chronostratigraphic charts[18,19]

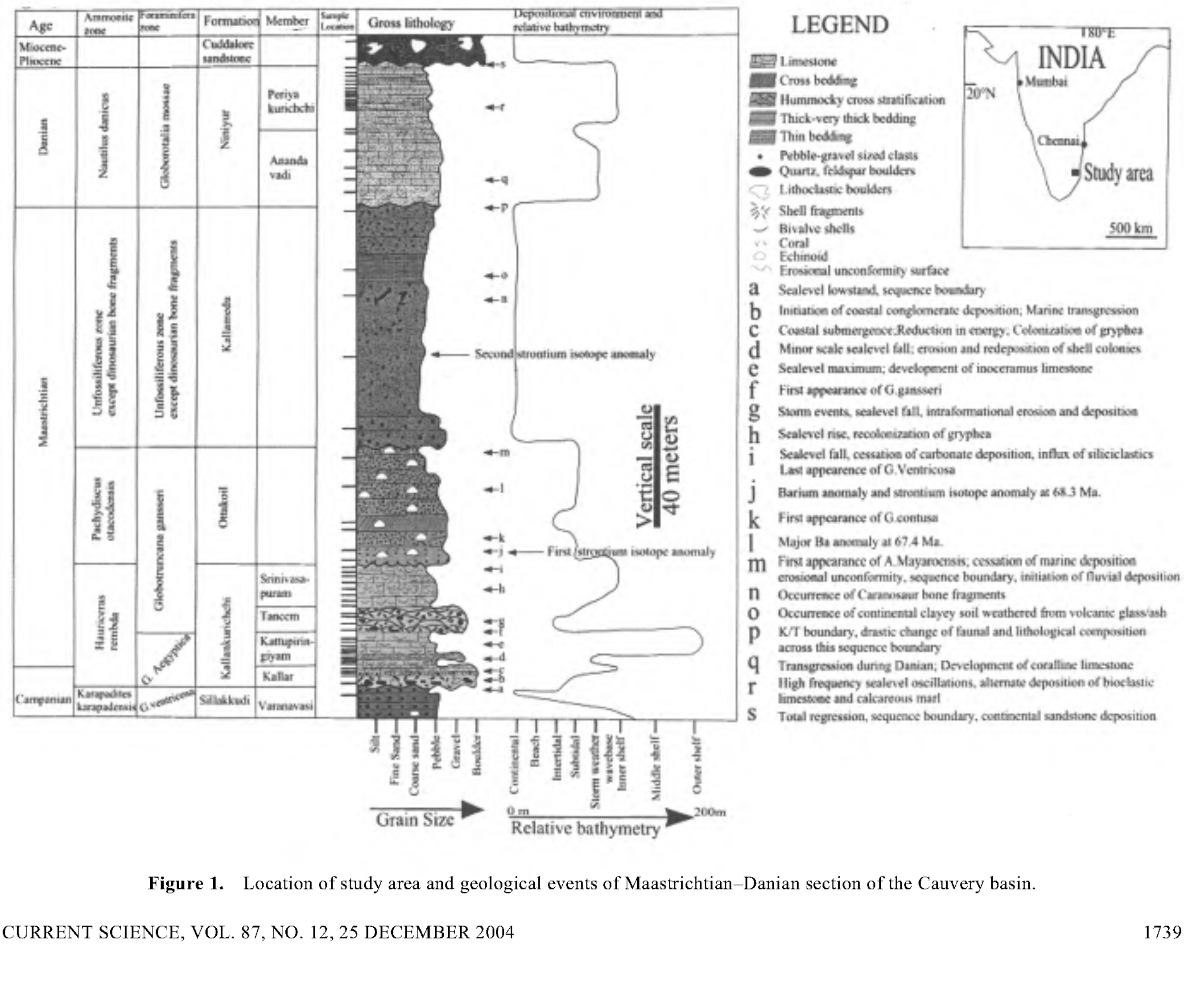

Figure 1. Location of study area and geological events of Maastrichtian–Danian section of the Cauvery basin.

indicate commencement of deposition of Kallamedu Formation at about 67.1 Ma. Towards the top of the Kallamedu Formation, palaeosols (soils formed under subaerial conditions during deposition of end the Cretaceous fluvial sediments) are recorded implying abandonment of river system and restoration of continental conditions at the end of Cretaceous period. At the beginning of the Danian, transgression took place that covered only the eastern part of the Kallamedu Formation. Presence of disconformable contact between the Anandavadi member and the Kallamedu Formation and initiation of carbonate deposition from the beginning of the Danian are indicative of the absence of fluvial sediment supply and tectonic activity at this time. Another sea-level rise during 64.4 Ma led to the deposition of the Periyakurichchi member under shallow, wide shelf with open circulation conditions[18,19,21,22]. At the top, this member has distinct erosional unconformity, which in turn, when interpreted along with the presence of huge thickness of continental sandstone (>4000 m thick Cuddalore Sandstone Formation), indicates restoration of continental conditions in this basin. The global sea-level peaks[18,19] during 73 Ma (± 1; Late Campanian), 69.4 Ma (Early to Late Maastrichtian) and 63 Ma (± 0.5; Early to Middle Danian) are observed[19–22] to occur (Figures 1 and 2) in this basin.

Systematic field mapping in the scale of 1 : 50,000 was conducted to collect data on lithology, sedimentary and tectonic structures and faunal association (mega and ichno) from natural exposures, well and mine sections. Following the revised lithostratigraphy[17], a composite stratigraphic profile representing continuous stratigraphic record of Maastrichtian–Danian strata was constructed (Figure 1). In addition to the occurrence of global sea-level peaks in the Cauvery basin and their stratigraphic locations in the studied section, data after Thompson[18] have provided additional datum lines of 75.5, 70.45, 68.5, 67.1 and 64.4 Ma, that are traceable in the studied composite stratigraphic section through the documentations of several investigations concerning Indian sedimentary basins in general and Cauvery basin in particular[14,16,17–24].

Based on these chronostratigraphic and datum lines, 47 representative whole-rock samples were selected for petrography and trace elemental study. Among these, 24 samples were analysed for strontium isotopes, stable isotopes, major elements and clay mineralogy. The sample selection was such that at first samples were selected at chrono, bio and lithostratigraphic boundaries and also at known datum lines such as sea-level lows and highs, at which age data of these samples are well constrained. Furthermore, based on the characteristics of the stratigraphic section such as monotony of lithology, absence of hiatus and thickness of individual beds, samples were collected at equal spacing between known and constrained datum lines as mentioned above. This method of sampling had allowed representation of strata in a continuous profile, linear extrapolation of the age value for samples collected between known boundaries and datum lines. The classic statement[23] that the Maastrichtian–Danian section of the Cauvery basin is one of the continuous stratigraphic records of the world shows[16,24] the absence of significant unconformity surfaces between the studied lithostratigraphic formations/members, which in turn suggests the sampling strategy followed could well represent a continuous geochemical profile of the Maastrichtian–Danian section of the Cauvery basin[26]. Trace and major elemental analyses were performed by XRF following the procedures discussed elsewhere[7–11]. Stable isotopes and C_{org} were analysed against laboratory standards, details of which have been discussed earlier[9–11]. Strontium isotopic analyses were made following standard procedures[27–29]. Here we discuss the anomalies of strontium isotope and Ba concentrations while other geochemical, stable isotopic trends and sedimentological data were utilized in supportive role only.

Geochemical profiles (Figure 2) of selected major and trace elements and stable and strontium isotope compositions of the Maastrichtian–Danian strata reveal that there are many positive and negative excursions of different elements and isotopic ratios from mean values (as indicated by linear trendline), but most of those anomalies occur below the K/T boundary. Among all these profiles, double-peaked nature of $^{87}Sr/^{86}Sr$, Ba and Si, located below the K/T boundary is predominant and except the anomalies, the profiles show featureless trends.

From a broad perspective, variations in strontium isotopic compositions reflect principally the waxing and waning of Sr input from rivers (continental influx) versus the input from the submarine hydrothermal systems[30]. As local processes do not affect $^{87}Sr/^{86}Sr$ of sea water, which is global in nature and also as the strata under study were adjudged to be of epicontinental shallow marine deposits, and have had little or no hydrothermal activity in the vicinity[17,24,26,31,32] during and after deposition, influence of hydrothermal activity on these anomalies could be ruled out and hence variations in sea-level and continental influx were examined. Comparison of sea-level curve and geochemical profiles of the studied section show that the positive anomalies of $^{87}Sr/^{86}Sr$ form part of sea-level retreats. As deposition in this basin represents a major oscillating carbonate–siliciclastic system coinciding with sea-level high–low respectively, the periods of sea-level low represent advancing of continental river systems that brought in higher terrigenous influx, the positive anomalies could be interpreted as a direct result of clastic input. Occurrence of positive excursions of $^{87}Sr/^{86}Sr$ during sea-level lows confirms the established views[33,34] that periods of glaciations (*sensu stricto* sea-level lows) influence higher erosion in continents and increased terrigenous sediment deposition. This inference is ascertained by higher mean value of $^{87}Sr/^{86}Sr$ of the Cauvery basin strata (0.7120) than the world average of 0.7080 since Cambrian[35]. Higher $^{87}Sr/^{86}Sr$ value indicates increased continental weathering[35] and enhanced riverine influx[30]. Whitford *et al.*[36] stated that $^{87}Sr/^{86}Sr$ in rocks that received riverine source material centres around a mean of 0.7117,

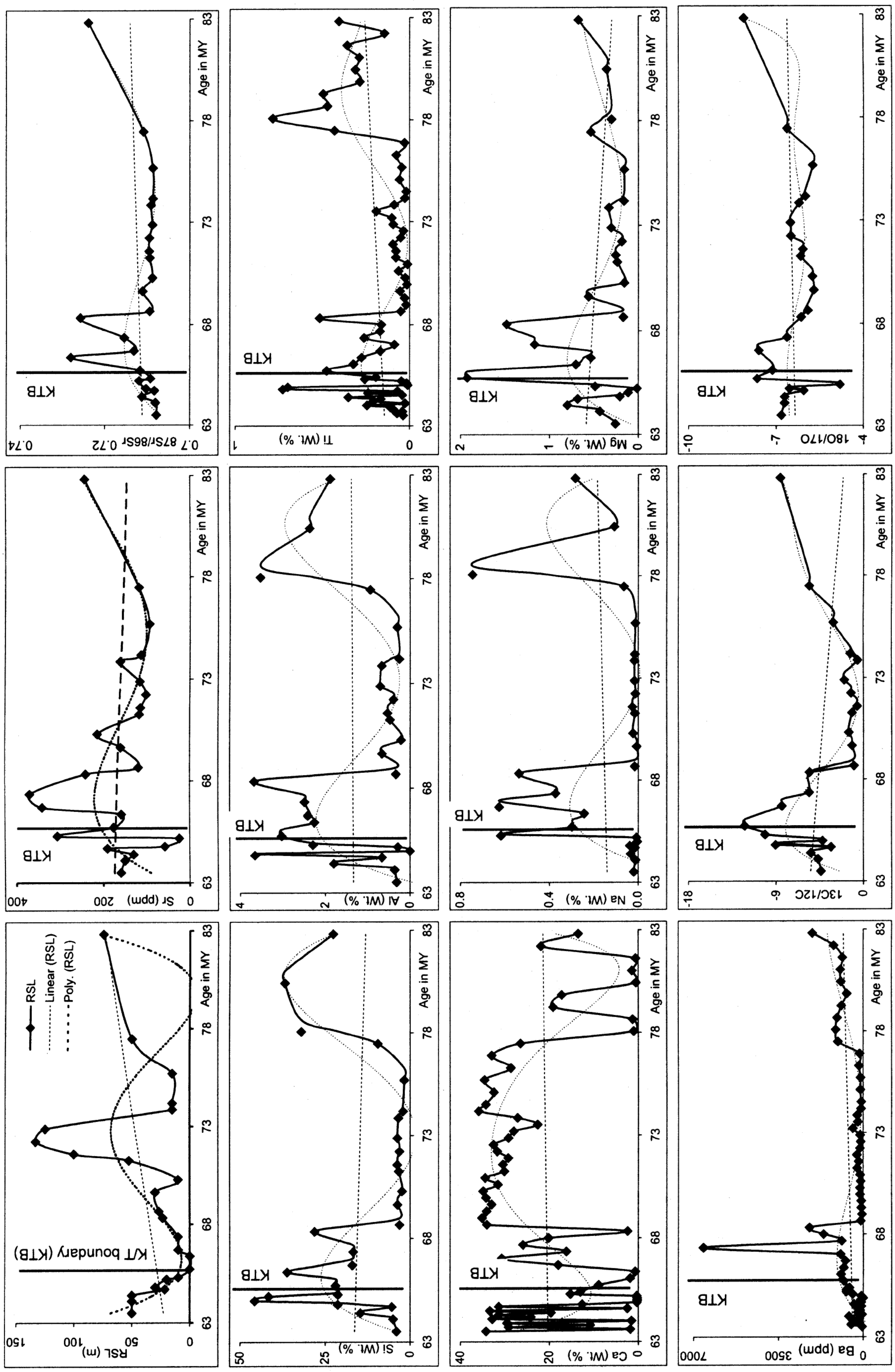

Figure 2. Profiles of relative sea level, elemental and isotopic conce ntrations across K/T boundary.

whereas a hydrothermal source would record a mean value of 0.703. According to these estimates also, higher continental weathering and enhanced riverine influx that have dominated deposition in the Cretaceous–Tertiary deposits of the Cauvery basin could be inferred. This inference is supported by the occurrences of inverse relationships between trendlines (linear and polynomial) of relative sea-level and terrigenous elements Sr, Si, Al and Ti. As the elemental concentration of Sr shows a broad peak covering the two positive anomalies of the $^{87}Sr/^{86}Sr$ curve, coeval with positive excursions of terrigenous elements such as Si and Ti, these observations gain importance. As could be observed elsewhere, increased siliciclastic deposition affected carbonate deposition in this basin and thus the Ca and other carbonate-hosted elements such as Na and Mg show negative anomalies (Figure 2) coeval with positive excursions of terrigenous elements. As observed by other researchers[37] in K/T sections located elsewhere, the smoothed trendline (polynomial trendline generated through sixth order polynomial function that explains maximum variance of the raw data) shows a broad positive anomaly across the K/T boundary in the Cauvery basin. These authors termed this phenomenon as a consequence of rapid influx of radiogenic Sr to the ocean during deposition of these rocks. They have also explained that weathering of volcanic ash/rocks following Deccan volcanism (that took place during and immediately after the K/T boundary) probably contributed to declining Sr isotopic values in the early Cenozoic and the same is evident from the Figure 2.

Having established the link between sea-level retreats, enhanced continental weathering, clastic input and positive excursions of $^{87}Sr/^{86}Sr$, the probable causes that produced two positive anomalies of strontium isotope away from the K/T boundary are examined. As such, the positive $^{87}Sr/^{86}Sr$ anomalies are short-lived and record significant change from background values. These can be linked with major retreat of sea-level, which in turn indicates concomitant cooling of global atmosphere. Among global climatic reversals, cooling trends tend to be gradual while warming trends are abrupt[38,39] as evident from the profiles of carbon and oxygen isotopes (Figure 2). Palaeotemperature data imply a significant warming from the Aptian to Albian, a period of extreme warmth extending from the Albian to the Santonian, followed by a general cooling trend during the Campanian to the Maastrichtian[33,36]. Cooling during the late Cretaceous was followed by warming during the early Tertiary with a sudden increase in temperature at the K/T boundary[40], which in turn is in conformity with the stable isotopic data (Figure 2).

Except two positive excursions preceding the K/T boundary, Ba does not show any significant shifts either from linear trend (Figure 2) or mean value of the entire section (497.67 ppm) or Maastrichtian average value (672.89 ppm) or Danian average value (261.78 ppm) indicating that the positive excursions of Ba are abnormal from the background values. Computation of excess Ba content in the sediments according to the formula of Murray and Leinen[41,42] with reference to PAAS (Post-Archaen Average Australian Shale)[43] has also indicated overwhelming availability of Ba between 68.3 and 67.4 Ma, confirming Ba deficiency during the entire stratigraphic record except these positive excursions. These abnormalities record 4–10 times higher concentration with reference to average shale[43] (~650 ppm) in these rocks. Further, the linear trend (Figure 2) shows that the general Ba concentration of these rocks is more or less equal or falls below the value of average shale. The Ba-peaks occur in the Ottakoil Formation, represented by shallow marine siliciclastics deposited under slowly waning sea. The first peak (Figures 1 and 2) was found at the cross-bedded, fining upward sequence, while the second and major peak occurs at the well-sorted sandstones. The rocks contain abundant and uniform distribution of *Stigmatophygus elatus*, a stenohaline, shallow marine echinoid and an ichnofauna, namely *Ophiomorpha*[16,25,32] which is also typical of shallow marine regions[25]. McManus *et al.*[44] suggested that preservation potential (of Ba) in the nearshore regions is lower than in the continental margin and further offshore regions. In this context, occurrence of Ba peaks in shallow marine deposits is itself an intriguing feature.

Occurrence of Ba-peaks in monotonously uniform featured sandstones implies absence of lithological influence. If the presence of Ba-orthoclase in these sandstones (as indicated by X-ray diffractograms) is to be reasoned for Ba anomaly, the Kallar member of the Kallankurichchi Formation, wherein boulder–pebble sized clasts of fresh Ba-orthoclase are reported[32], does not show any significant Ba-anomaly. In addition, the Ba-orthoclase clasts occur in negligible to minor proportions in the Ottakoil Formation. Petrographic observations show stratigraphically uniform distribution of feldspathic grains in Ottakoil Formation, in which case, had the Ba-orthoclase served as the source of Ba anomaly, the positive excursions of Ba should have had a span covering the entire Ottakoil Formation. In the absence of such a feature, influence of Ba-orthoclase could be ruled out.

Ba has a tendency to adhere onto clay mineral surfaces[45] in which case, sudden influx of clay should be accounted. However, clay admixture in the sandstones of Ottakoil Formation seldom exceeds 5% and its stratigraphic distribution is more or less uniform. If adherence of Ba in all the clay present in the sandstones is presumed, the presumption signifies availability of free Ba during deposition of specific rock slices that show these two peaks. If weathering of Ba-orthoclase in the continental regions to form clay, and their transport and deposition in the marine basin to cause Ba anomaly were considered, occurrence of fresh Ba-orthoclase clasts in the sediments (in Kallar member of Kallankurichchi Formation and feldspathic sandstone in Ottokoil Formation) defies such possibility. Recent studies[26,46] interpreted that detrital influx in this basin was influenced by sea-level lowstands. As the Ottakoil Formation was deposited in a regressive sea, slow but steady increase in the quantum of detrital influx could be expected. Under this scenario, sudden spurt of Ba concentration does not match steady increase in detrital influx. Comparison of gross lithology and sea-level curve of the Cauvery basin had shown[18–20,26,46–48] that the periods of carbonate deposition in this basin occurred during sea-level highstands when owing to the basin configuration and hinterland topography, no chemical weathering was prevalent, depriving siliciclastics in the basin. Few of these studies[26,46–48] also stated that physical weathering dominated the entire depositional history of the basin owing to the climatological characteristics and basin configuration. These observations also point to the fact that if Ba adhered onto clay mineral[49], its contribution should have been minimal, if not insignificant.

The profiles of Si, Al, Na and Mg show distinct peaks during 68.3 Ma indicating significant detrital influx coeval with the first Ba peak. They could have been brought to the depocentre together, in the form of Ba-orthoclase and/or albite or clays (weathered from these feldspars). However, these elements show multiple peaks away from major Ba peaks also. If the primary source of Ba was considered to be detrital and its influx in the form of Ba-orthoclase or its weathered derivatives (clay and Ba adsorbed onto such clay), all these elements should show coeval peaks. Absence of such coeval peaks of Ba except at 68.3 Ma indicates either Ba was not drawn from detrital sources or Ba has got terrestrial source only during 68.3 Ma and there might have been widespread weathering and transport of terrestrial material during 68.3 Ma. The cause of the other Ba-peak has to be accounted for; but neither environmental conditions nor lithological or faunal changes are observed to support this assumption. Furthermore, the magnitudes of peaks of Si, Al, Na and Mg are at subdued levels during 67.4 Ma and the peak of detrital trace element Ti is very high during 68.3 Ma and low during 67.4 Ma, indicating that had there been prime detrital source for Ba, then the major Ba anomaly should have been at 68.3 Ma instead of 67.4 Ma. These observations could be interpreted as dual source for Ba[50]. If so, the cause of major Ba anomaly at 67.4 Ma has to be unravelled and absence of influx of Ba-orthoclase during other periods of detrital influx, as reflected in profiles of Si, Al, Mg and Na has to be explained.

The sea-level curve of the Maastrichtian–Danian strata shows a gradual reduction of depositional bathymetry that culminates at total regression (Figure 1), during the course of which the Ottakoil Formation was deposited. The shift of sea-level from maximum flooding (Srinivasapuram member of Kallankurichchi Formation) to sea-level fall (Ottakoil Formation) records a change in lithology from carbonates to siliciclastics, and this pattern of shift in gross lithology is in line with the general depositional pattern of the basin[16,17,19,21,22,24,26]. Sea-level rise in this basin was always associated with higher organic carbon accumulation and preservation[26], and fall in sea-level resulted in reduction of organic carbon concentration. The carbon budget is of primary importance towards understanding climatic change on all timescales. On a glacial–interglacial timescale, terrestrial vegetation, a reactive carbon reservoir, is destroyed when ice sheets override it. Since $\delta^{13}C$ of terrestrial biomass is low[51] compared to the mean ocean value[52], $\delta^{13}C$ of mean ocean water is affected by the transfer of carbon between the terrestrial biosphere and the ocean[53]. Growth and destruction of terrestrial vegetation also occur on the continental shelf area as sea-level falls and rises[54]. Thus, if regional and or global-scale climatic cooling had influenced sea-level falls in this basin, it might reflect on the carbon isotopic concentration of the studied samples as well. The carbon isotopic profile records a broad negative excursion covering the peaks of Ba-anomaly and culminates at a sharp turn towards less negative values just at the K/T boundary, indicating a major environmental perturbation. It may presumably be the result of prevalent cooler climate prior to the latter part of end Cretaceous that peaked during the latest Maastrichtian followed by warming at the end of Maastrichtian. Continuance of such warming and resultant sea-level rise is also in conformity with the deposition of carbonates during Danian, as indicated by lithological succession (Figure 1), profiles of Ca, and carbon isotope (Figure 2) as could be observed elsewhere[33,55,56]. Although it seems that the oxygen isotopic data of these samples may have undergone diagenetic reequilibration[9,56,57] (as they covary with $\delta^{13}C$ curve), general cooling and warming trends and an anomaly at the K/T boundary are evident (Figure 2). Absence of clear indications of diagenetic alteration stems from Figure 3 as there is no distinct clustering, no significant correlation (R^2 is very low (0.43), which in statistical terms is insignificant) and also by the non-cemented nature of the rocks[16,25,26] from where the anomalies are reported.

Many researchers have observed negative carbon isotope anomaly far below the K/T boundary and suggested that the shift may be a global phenomenon associated with climatic cooling and fall in productivity[7–12,58–60]. As these climatic trends were coupled with global-scale glacial period, general association of glaciation with high silicate weathering and terrigenous sedimentation[9,33] should also be considered, which in turn is in accordance with lithological succession (Figure 1) of the study area. Furthermore, periods of sea-level lowstands promote carbonate weathering and

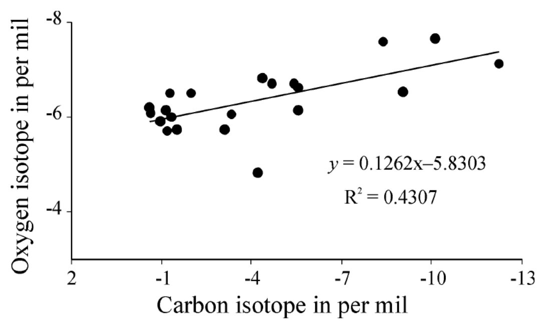

Figure 3. Plot of $\delta^{13}C$ vs $\delta^{18}O$.

thus stimulate CO_2 sink, which in turn, in a long term, increases atmospheric temperature and sea-level, promoting carbonate deposition. At this juncture, it is also inferred that coeval Deccan volcanism might have compensated the CO_2 sink if not overridden it, as weathering of carbonate rocks is influenced by volcanic CO_2 production, exposure of carbonate rocks and susceptibility of silicate rocks to weathering[33].

Change in relative bathymetry of the depocentre during Maastrichtian in this basin from outer–inner shelf (150–200 m) to shallow marine intertidal regions and subsequently total regression as reflected in lithological and faunal composition of the strata, in addition to the presence of higher quantum of C_{org} in rocks of Kallankurichchi Formation and sudden change to non-accumulation of C_{org}, indicate environmental change that might have influenced and/or aggravated the environmental conditions prevalent. It may also be due to the release of volatile materials from buried hydrocarbons and/or clathrate hydrates of gas (gas hydrates). These are crystalline solids composed of gas and water that are stable at high pressure, low temperature and high gas concentration, conditions that are met in the upper few hundred meters of sediment on many continental margins and slopes[61–63]. In most of the cases, the dominant gas in the solid phase is methane, produced through the bacterial decomposition of organic matter. Conducive milieu for entrapment of hydrocarbons/gas hydrates in continental shelf regions prevails during times of sea-level highs. Owing to their unstable nature during sea-level fall, the trapped hydrocarbons release enormous quantities of methane to the sediment–water interface[64] or to the atmosphere. Destabilization of buried hydrocarbons/gas hydrates during the earth's colder intervals (that normally coincide with sea-level falls) is considered to be an important mechanism in the carbon cycle[65]. Occurrences of hydrocarbon residues were reported from the rocks of the Kallankurichchi Formation[32], which support the possibility of accumulation of organic carbon in this formation followed by maturation of organic carbon into hydrocarbons and finally destabilization and release of volatile materials due to subsequent sea-level fall, leaving only non-volatile residues to be preserved in the sediments. Recent studies have indicated that oxidation of sapropel materials promotes enrichment of Ba in overlying sediments[63,66–68]. It is also suggested[65,69,70] that destabilization of hydrocarbons/gas hydrates and release of volatile methane gas into the atmosphere might have been a widespread phenomenon during earth's history and could be traced by negative excursions of $\delta^{13}C$ in sedimentary records. The $\delta^{13}C$ profile of the study area also shows a consistently featureless nature from 75 to 68.7 Ma and a sudden and progressive negative excursion of carbon isotope between 68.7 and 65 Ma, thus adding support to the presumption of emission of methane gas from the study area that might have promoted availability of free Ba to get preserved at specific interval(s) generating Ba-anomalies.

Notwithstanding the causes, the occurrences of double-peaked positive anomalies of $^{87}Sr/^{86}Sr$ and Ba preceding the K/T boundary support the emerging view that the K/T boundary event could not have been caused by an isolated and sudden environmental deteriorating agent; instead the environmental factors that were already under stress got aggravated by meteoritic impact (in and around Chicxulub in the Yucantan Peninsula) and the Deccan Trap (on a global scale)[3,37]. Occurrence of *Caranosaur* bone fragments followed by clayey sandstones (Figure 1) in the study area, presumably derived from weathering of volcanic glass in rocks above the second strontium anomaly, signifies the influence of Deccan volcanism in the deposition of the Cauvery basin during the terminal Cretaceous period. Barium anomalies of the Cauvery basin have indicated deterioration of environment during end Cretaceous, besides suggesting yet another cause, viz. emission of methane gas into the atmosphere preceding the K/T boundary.

Recent researches on the K/T boundary sites, in addition to re-evaluation of previously published data increasingly point to a scenario, namely a more progressive and multi-causal mass extinction as a result of the confluence of environmental and climatic factors during the latest Maastrichtian including rapid climate warming followed by rapid cooling[71]. This would have led to highly stressful conditions for marine biota, vulnerable to environmental changes[2,3,7,38,72]. Furthermore, studies[3,7,9,11] have also indicated unequivocal presence of multiple events that predate the K/T boundary. Kaiho *et al.*[73] also have concluded that although significant biotic turnover took place across the K/T boundary, the timing and sequence of key environmental changes caused by catastrophic and non-catastrophic events are not exactly coeval. The stable isotopic, strontium isotopic and geochemical data from the Cauvery basin also point towards this newly emerging consensus among workers of the K/T boundary sites spread the world over.

The inference of multiple, non-catastrophic events is further substantiated by the presence of Ba-anomalies in Maastrichtian–Danian stratigraphic sections of Israel, NE Mexico and Guatemala[26]. They represent an expanded, well-preserved lithological sequence of the terminal Maastrichtian and the K/T-boundary, including impact-induced spherule layers as well as Ir-anomalies. Detailed biostratigraphic, lithological and geochemical characteristics of these sections have been presented[7–11,26,71,74,75]. During the Maastrichtian, these sections were parts of shallow to moderately deep water shelf-slope regions. The profiles of NE Mexico record single or juxtaposed double-peaked Ba-anomalies preceding the K/T boundary, and the expanded section from Israel records a double-peaked Ba-anomaly similar to the Cauvery basin section. The Guatemala section also records a Ba-anomaly, but during the Danian. The Ba-anomalies are not influenced by lithology or any other similar cause. Furthermore, except for the first Ba-anomaly in the Israel section, no other coeval trace elemental anomalies could be observed. Together, these observations affirm that the occurrence of Ba-anomaly is geographically and chronologically widespread, the causes of which may be local or regional. In addition, they also indicate the prevalence of non-catastrophic events, predating the K/T boundary that released Ba into the sedimentary system.

Occurrence of $^{87}Sr/^{86}Sr$ anomaly in the Cretaceous–Tertiary deposits of the Cauvery basin preceding the K/T boundary, indicates a drastic change in $^{87}Sr/^{86}Sr$ composition of sediments deposited during end Cretaceous, but far below the K/T boundary. Inferences drawn based on relative sea-level and elemental concentrations support the view that the $^{87}Sr/^{86}Sr$ composition of the Cretaceous–Tertiary deposits depended on detrital influx. Record of positive $^{87}Sr/^{86}Sr$ anomalies before the K/T boundary is in conformity with the views that much of the environmental deterioration commenced before the K/T boundary that led to the culmination of higher faunal turnover across the boundary[3,7–9]. It was stated that one of the factors that influenced higher faunal turnover could have been sea-level change as a result of global climate change, which in turn could have been influenced by Deccan volcanism. Although the scale and magnitude of such influences could have varying degrees, the present study broadly follows their inferences.

The Ba-anomaly in the Cauvery basin may have resulted due to two different causes. First, the detrital influx that had produced earliest Ba positive excursion due to short-lived higher energy and higher fluvial influx. As the continental source rocks contain Ba-orthoclase, the ensuing sedimentary record shows higher background values of Ba. It is also to be noted that owing to the absence of chemical weathering in the continental regions, enforced by prevalent cooler climate, the sediments were buried without much chemical alteration. The second cause is related to the sudden availability of free Ba influenced by release of methane gas from destabilization of previously accumulated hydrocarbons (gas hydrates?) in underlying sediments (carbonates of Kallankurichchi Formation deposited during sea-level highstand that promoted higher primary productivity followed by bacterial decomposition of organic matter)[17,26] due to sea-level fall and introduction of newer set of depositional environmental conditions[17,26,32]. Even if only bacterial decomposition of organic matter is considered, it might have also produced microenvironmental barite[76]. It is also observed that global-scale climatic reversals were the causes that triggered sea-level fluctuations, which in turn initiated destabilization of hydrocarbons/gas hydrates in the study area. The Ba anomalies form part of a major trend of general cooling (as indicated by carbon isotope excursions); sea-level fall, subsequent release of methane gas and upsetting of carbon reservoir equilibrium, followed by increasing palaeotemperature may be as the result of a greenhouse effect, triggered by released methane gas. These events were either followed by and or in part coincided with Deccan volcanism and associated environmental changes.

It is to be noted that the results of this study are based on whole-rock analyses of carbonates and unconsolidated loose sands of the Maastrichtian–Danian section of the Cauvery basin exposed in and around Ariyalur, South India. In addition, better chronological control is also required to exactly pin-point the sample locations. However, considering the scarcity of chronological control, except major boundaries such as Campanian–Maastrichtian and Maastrichtian–Danian besides datum lines identified in rock records, such as known sea-level lows and highs and their absolute age as reported from the Cauvery basin and other sedimentary basins of India and the world over[18,19], better chronological control is required. Hence, the results of this study have to be considered together with these two limitations. However, analysis of whole rock chemistry and stable isotopes and comparing them with analytical data generated from foraminiferal tests[77] had shown no significant change between these two datasets, except magnitudes of trendlines. This observation[77] together with our observation on chemostratigraphic trends[26,46–48] of Barremian–Danian strata of the Cauvery basin, which stated that the rocks of the basin indeed preserve primary signals adds support to the conclusions drawn from the present study. Notwithstanding this limitation, additional data are being generated from individual shells and tests of fossils, which may be published elsewhere. Furthermore, efforts are on to collect short borehole cores from the exposed portion of the Cauvery basin with an aim to generate geochemical and isotopic data on centimetre scale samples, which in turn would shed light on the presumptions here.

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Clay as indicator of sediment plume movement in deep-sea environment

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Future polymetallic nodules mining in the Central Indian Basin (CIB) will disturb not only the deep-sea sediments but also the benthic environment. Generation of voluminous sediment plume due to mining activity is unavoidable, even if the miner would screen the nodules just above the sea floor. The released sediments on the sea floor would migrate in the direction of the bottom water currents and affect the benthic community. It would be more hazardous when the sediment are discharged at the sea surface, as they would affect the entire water column, including light transmission, photosynthesis and productivity. The sediment plume generated by any mining system would cause long-term effects in the deep-sea environment. In order to predict the potential impact on benthic environment, it is necessary to estimate the quantity of plume to be generated, direction in which the plume would move, and how much distance the plume would travel. For this, the surface sediments in the CIB (5230 m depth) were artificially disturbed and resuspended 5 m above the seabed in 1997 during the Indian Deep-Sea Experiment. Initial studies have shown that the clay content during monitoring-1 phase significantly increased compared to post-disturbance, by 15 and 24% in the disturbed zone (DZ); 3 and 20% at the ends of the DZ; 9 and 18% north of the DZ, and 10 and 17% south of the DZ. Here, it is shown that the clay particles can be successfully used as an indicator of the plume direction as well as to estimate the distance travelled by the plume.

DISTURBANCE on the sea floor can change the physical characteristics of the deep-sea sediments. For example, artificial disturbance due to deep-sea mining of polymetallic nodules would induce resuspension and transportation of sediments from one place to another. Such changes would also affect the benthic biota[1,2] as the sediment plume is likely to migrate in the direction of bottom water currents[3]. In fact, it would affect the entire water column in many ways, including light transmission, photosynthesis and productivity[4–6], if the sediments after separating from the nodules were discharged at the surface. According to one estimate, the nodule mining in the Central Indian Basin (CIB) would mobilize 57,602 tonnes of sea floor sediment per day or 14.4×10^6 tonnes annually. In other words, 3369.6 (wet) tonnes of nodules recovered per day would resuspend about 57,602 tonnes of sediment per day (Valsangkar, in preparation). It is expected that the sediment plume created due to disturbance on the sea floor by any nodule mining system will have long-term effects in the deep-sea environment. Therefore, the deep-sea sedimentological studies have an important role in deep-sea nodule mining activity.

Earlier studies on impact assessment of nodule mining were limited to the Pacific Ocean, whose results and findings can be summarized as follows. A German environmental group conducted Disturbance and Re-colonization (DISCOL) experiment in 1988–98 in the Peru Basin, Pacific Ocean, which was followed by post-disturbance studies after a gap of 6 months, and monitoring studies after 3 and 7 years. The results showed re-colonization of specific benthic organisms with decreased faunal density than the original undisturbed one[7]. The benthic impact experiment during 1991–94 by the National Oceanographic and Atmospheric Administration (NOAA), USA in the Clarion Clipperton Fracture Zone (CCFZ), Pacific Ocean, observed decrease in abundance of meiobenthos and increase in macrobenthos immediately after the disturbance[8]. Japan's deep-sea impact experiment (JET, 1994–97) showed similar results and it was interpreted that certain groups are more susceptible in adopting to the changed conditions due to disturbance on the sea floor, than the others[2]. Similarly, a benthic impact experiment (IOM–BIE) by the InterOcean Metal (IOM) Joint Organization in CCFZ, Pacific Ocean (1995), showed alteration in meiobenthos assemblages and indicated variable effects on the composition of faunal density[9].

In the Indian Ocean, Environmental Impact Assessment studies were initiated in 1996 in the CIB. This was a multidisciplinary approach and apart from other aspects, the studies were also aimed to find out the (a) distribution of sediment sizes in the selected test and reference areas, (b) major composition of sediment plume generated due to artificial disturbance on the sea floor, and (c) distance and direction in which the plume movement took place.

For this purpose, an artificial disturbance was created on experimental basis (Indian Deep Sea Experiment, INDEX) in 1997 at 5300 m water depth in the selected 3000×200 m narrow strip in the CIB[10]. The disturbance forced resuspension of ~6000 m^3 wet sediments (~580 tonnes of dry sediment) in the waters at 5 m above the sea floor. Prior to the

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