phology (Figure 2b). Two analyses conducted on this grain (numbers 7A, B) yielded ages of 3583 ± 25 and 3505 ± 30 Ma respectively. Two more zircons—a prismatic grain and the core region of a sub-rounded grain (numbers 2 and 13; see Figures 2c, d)—have ages of 3538 (mean of analysis numbers 2A, B) and 3628 Ma respectively (Table 1). Two analyses carried out on either side of a longitudinal fracture in another homogeneous, rounded zircon (grain number 3; Figure 2e) yielded ages of 3501 and 3323 Ma respectively; we suspect that one or both of these ages reflect partial Pb-loss from a single domain which crystalized at or before 3501 Ma. Four analyses conducted on three homogeneous zircons (grain numbers 4, 11 and 12) from this sample (e.g., Figure 2f, grain number 11) yielded intermediate ages around 3.4 Ga. Another homogeneous zircon (grain number 1) from this sample has a distinctly lower mean age of 3223 Ma (analysis number 1A, B). We have also estimated the U content of the zircons based on a close system approximation; these values range from a few tens of ppm to a few hundred ppm (Table 1).

The data shown in Table 1 reveal three groupings: greater than 3.5 Ga, 3.43–3.38 Ga and ~3.2 Ga for the analysed zircons. The age of 3.2 Ga for the overgrowth around the 3.55 Ga old detrital core (SB-94/3C, analysis numbers 1A–F) strongly suggests that the 3.2 Ga age reflects a younger metamorphic event affecting the OMG rocks that led to the growth of zircon on an older core. The morphology of this overgrowth (Figure 2a) does not support a detrital origin for the total core-overgrowth assemblage. We note that the 3.2 Ga signature is seen in zircon grains analysed from both the samples.

Two of the zircons belonging to the >3.5 Ga group are clearly of detrital origin as attested to by their sub-rounded shape (Figures 2a, b). Among the three zircons belonging to this age group, two show distinct evidence of rounding of edges with low length/width ratios (Figures 2d,e), while the third one possesses an ambiguous morphology (Figure 2c). We, therefore, conclude that crust of ~3.6 to 3.5 Ga age was a major sialic component within the provenance of the OMG. The four zircons with ages between 3.38 and 3.43 Ga are all homogeneous, subhedral, prismatic grains and do not show obvious detrital characteristics. Unfortunately, the lack of detailed information on possible Pb-loss history of these grains makes it difficult to attribute these ages to specific geologic events. We note that the lower end of this range is only slightly older than a recently reported Sm–Nd age of 3305 ± 60 Ma (2σ) for the OMG amphibolites.

The present study provides several important geochronological constraints on the evolution of the Singhbum Craton. The zircon ages from the OMG metasediments confirm the presence of an Early Archaean crust in this region. Our data suggest that the provenance of the sedimentary precursor contains a significant granitoid component with ages ~3.6–3.5 Ga. Zircon growth, possibly in response to a regional metamorphic overprinting, has been identified at ~3.2 Ga. Our results also provide an older limit of ~3.5 Ga for the age of sediment deposition.


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Significance of the terminal Cretaceous calcareous nannofossil marker *Micula prinsii* at the Cretaceous–Tertiary boundary in the Um Sohryngkew section, Meghalaya, India

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A diagnostic calcareous nannofossil assemblage, representing the terminal Maastrichtian *Micula prinsii* zone, is discovered below the iridium-spike bearing clay-layer in the Um Sohryngkew section, Meghalaya. Its significance for the precise demarcation of the K/T boundary, providing crucial evidence for the presence of the youngest Cretaceous sediments in a continuous, bioturbation-free calcareous shale sequence, is demonstrated.

The Um Sohryngkew section is located on the western bank of the Um Sohryngkew river, about 1 km north-eastwards of the Therria village in the foothills of the Cherrapunjhi Plateau, Meghalaya, northeastern India.
K/T boundary level suggested by Lahiri et al., also disproves their contention. Jafar and Singh\(^5\) considered the Um Sohringkew section to be an incomplete K/T boundary sequence due to the absence of the latest Maastrichtian planktonic foraminifer marker *Abathomphalus mayaroensis* and the calcareous nanofossil *Micula prinsii*, and the reported continuation of bored Cretaceous planktonic foraminifera above the iridium layer. They further substantiated this inference by simply considering reports of the presence of the basal Danian planktonic foraminifer markers *Globigerina fringa* and *G. eugubina* to be 'poor' and 'dubious' without providing any substantial arguments.

Thus, the recording of a characteristic latest Maastrichtian calcareous nanofossil assemblage, belonging to the *Micula prinsii* zone, from immediately below the iridium-rich clay layer, confirms not only the existence of the youngest Maastrichtian in this section but also suggests demarcation of K/T boundary below this layer\(^\text{10}\).

The material for the present study was initially collected during a field trip in February 1987 (in which Jagadish Pandey\(^3\), S. K. Acharyya and M. K. Sen\(^3\) also participated), and subsequently in February 1990, when more closely spaced samples at 5 cm intervals (sample thickness ca. 2–2.5 cm) were collected from a nearly 2 m interval across the clay layer. The studied part of the K/T successsion consists of non-bioturbated, thinly laminated calcareous to fine silty shales which are dark grey to ash grey in lower part, followed by a 1.5 cm thick reddish-brown clay layer, overlain by greyish to yellowish-brown calcareous fine silty shales.

These calcareous shales have lately been included within the Mahadeo Formation\(^1\). However, the authors prefer to group these beds within the overlying Langpar Formation, in accordance with the original lithological criteria\(^11\)–\(^13\). The Langpar Formation, comprising calcareous shale, carbonaceous shale and argillaceous limestone, conformably overlies the Mahadeo Formation, consisting of glauconitic non-calcareous sandstone and sandy shale, becoming calcareous in the upper part. There is a distinct gradational transition from a greenish-grey, sandstone-shale facies of the Mahadeo Formation into the overlying dark to light grey, calcareous shale-limestone facies of the Langpar Formation. The sequence studied immediately overlies these passage beds.

Abundant and diversified Late Cretaceous calcareous nanofossil assemblages have been recovered from samples underlying the iridium-rich clay layer. They contain the terminal Maastrichtian, low latitude zonal marker *Micula prinsii* Perch-Nielsen 1979 along with *M. murus* (Martini) Bukry 1973, *M. decussata* and *Watznaueria barnesae* are the most abundant and consistent species in the studied interval (Figure 3). This assemblage typically represents the *Micula prinsii* zone of the latest Maastrichtian.

\(^1\) Lahiri et al.
\(^2\) Cretaceous–Tertiary boundary in this section has been demarcated on the planktonic foraminiferal evidence\(^\text{1,2}\); the top of Maastrichtian has been marked by the abrupt disappearance of a rich *Globotruncana–Heterohelix* suite, while the basal Palaeocene is distinguished by the residual Cretaceous planktonics dominated by *Guembelitria cretacea* (PO Zone) at the base, followed stratigraphically higher by the appearance of a typical Danian *Turborotalia eugubina–T. sabina* assemblage Zone\(^3\). Geochemical studies across this interval subsequently revealed a significant enrichment of iridium and other siderophyle elements in a 1.5 cm thick clay layer\(^4,5\), coinciding with a major depletion of Cretaceous planktonic foraminifera. Contrary to this, Lahiri et al.\(^6\) opined that 'no such widespread break' in planktonic foraminifera at the K/T iridium layer is noticeable, as a Late Maastrichtian assemblage continues stratigraphically higher, suggesting the placement of the boundary about 30 m above this layer. However, these observations have recently been discussed and rejected\(^7\). Our recent discovery of a rich suite of Danian dinoflagellate cysts and calcareous nanofossils along with the Early Tertiary nautiloid *Hercoglossa kutchensis* Tandon and Srivastava 1980 (Figures 2A–C) below the
Figure 2. a–al, Micula prinsii; b–e, Micula murus; f–h, Micula decussata; i, Micula concava; j, j1, Micula sp.; k, l, Arkhangelskiella cymbiformis; m, Eissellithus turnseiffeli; n, n1, Lithrophidites quadratus; o, Cribrisphaerella ehrenbergii; p, q, Microrhabdulus decoratus; r, s, Ceratolithodes kampferi; t, Cretahabds angustiforus; u, Gen. et sp. indet.; v, Chasmatygyus amphipous, w, Wattnaueria barnesae; x, Cyclagelosphera reinhardi; y, Thoracosphaera operculata; z, z1, Braarudosphaera bigelowii (All light micrographs under crossed polarized light except j and n under single polariser; ×2000). A–C, Hercoglossa kutchensis (scale = 2 cm).
Figure 3. Distribution of Late Maarschlienian calcareous nannofossil species in the Um Sohryngkew section.
The *Micula prinsii* zone was established for the uppermost Maastrichtian\textsuperscript{14,15} and can be correlated to the top of the *Micula murus* zone of Thierstein\textsuperscript{16} and the *Nephrolithus frequens* (CC26) zone of Sissingh\textsuperscript{17}. *M. prinsii*, which evolved from *M. murus*, has its FAD after the first appearance of both *Nephrolithus frequens* and the planktonic foraminifer marker *Abathomphalus mayaroensis*\textsuperscript{14,18,19}. It is the most significant species to document the presence of the youngest Cretaceous sequence especially in low and mid latitudes\textsuperscript{20,21}, e.g. El Kef (Tunisia), Lattenegger (Germany), Biarritz (France), DSDP site 534 (S. Atlantic)\textsuperscript{20}; Barranco del Gredero near Caravaca (Spain)\textsuperscript{22} and Hor Harar (Israel)\textsuperscript{23}.

In Um Sohryngkew section, the rich Maastrichtian nannofossil assemblage abruptly disappears above sample no. S-30 (Figure 3). Nannofossils have not been observed in the iridium-rich clay layer (sample S-31). In the immediately overlying calcareous to fine silty shales, the nannofossil assemblage is greatly reduced containing only rare *Thoracosphaera operculata*, *Thoracosphaera* sp., *Braarudosphaera bigelowii* and extremely rare *Cyclagelosphaera reinhardtii* and *Miecrantholithus* sp. These ‘survivor’ species belong to a suite of calcareous nannofossils which are believed to have survived the K/T boundary biotic crisis and extend from the Maastrichtian into the basal Danian\textsuperscript{20}. Brightly birefringent elliptical to broad elliptical coccoliths (2–5 µm) are found to occur across the K/T boundary, without any appreciable change in size. Rare occurrence of this form is recorded in the Upper Maastrichtian as well as in the basal Danian where it is found to occur consistently in the studied interval. In our opinion, records of this species above the K/T boundary are not due to reworking but seem to represent genuine occurrences. It is documented here as Gen. et sp. indet. and is listed under ‘survivor’ species for the present (Figure 3).

It is generally believed that a ‘continuous’ marine K/T boundary section in low latitudes should include the uppermost Cretaceous coccolith zone of *Micula prinsii* followed by the boundary clay within the planktonic foraminifer zone of *Globigerina fringa*, followed by *G. euubina*, in the basal Danian\textsuperscript{20}. However, the occurrence of a relict survivor Late Cretaceous planktonic foraminifer faunule belonging to the *Guembelitria cretacea* zone [PO], in the earliest Danian below the *G. fringa* zone is now recognized to be extremely significant in establishing the continuity of a complete K/T boundary sequence\textsuperscript{24–27}.

The argument of Jafar and Singh\textsuperscript{8}, that the reported ‘continuation’ of a relict Cretaceous planktonic foraminifer assemblage, representing the *G. cretacea* zone, above the iridium-rich layer in the Um Sohryngkew section\textsuperscript{3} is abnormal for a complete K/T boundary sequence, is, thus, not valid. Further, the ‘absence’ of *Micula prinsii* in several Indian sections, including Meghalaya and Andaman Islands postulated by them\textsuperscript{8} should be viewed with caution. *M. prinsii* has previously been listed in a ‘nanoplankton cocktail’ obtained from a solitary mud-volcano sample from Baratang Island that yielded a mixed assemblage of Campanian–Danian age\textsuperscript{28}. However, *M. prinsii* could not be recovered in subsequent studies of mud-volcanoes of the same region\textsuperscript{29}, thus rendering its earlier report from Andaman Islands to be questionable\textsuperscript{30}.

According to Pandey\textsuperscript{3}, the zonal planktonic foraminifer marker, *A. mayaroensis*, is absent in Meghalaya. He consequently instituted the *Globotruncana stauriformis* zone as a substitute for the Maastrichtian *A. mayaroensis* zone. Jafar and Singh\textsuperscript{8} misquoted Bhandari et al.\textsuperscript{4} by crediting them with noting the occurrence of *A. mayaroensis* in eastern Indian sections, including Meghalaya, but at the same time suggested that this species ‘may in fact be missing altogether’ from this region. *A. mayaroensis* has been recorded from the Cauvery Basin\textsuperscript{31}, the Krishna–Godavari Basin\textsuperscript{12,23}, the Andaman Islands\textsuperscript{24,35} and exotic limestone in the Ukhurl Melange Zone of the Nagalam–Manipur Ophiolite belt\textsuperscript{36}. Occurrence of a well-preserved and complete assemblage containing *A. mayaroensis* has also been reported from DSDP Site 217 in the Bengal Abyssal plain in the Indian Ocean\textsuperscript{37}.

In view of the absence of this zonal marker in the Um Sohryngkew section, correlation with the *A. mayaroensis* zone has been suggested based on the occurrence of a rich planktonic foraminifer suite containing *Globotruncana stauri*, *Rugoglobigerina rotundata* and *R. scotti*\textsuperscript{2}. However, these taxa do not provide unequivocal evidence for the presence of the youngest Maastrichtian in the section, as none of these is restricted to *A. mayaroensis* zone. Moreover, *A. mayaroensis* is not considered to be a reliable taxon for identifying the K/T boundary, especially in the shallow continental shelf sections as it is geographically and ecologically restricted\textsuperscript{27,28}. An alternative biozone, *Pseudotextularia deformis* was proposed for shallow continental shelf sections\textsuperscript{26}.

We, therefore, conclude that the present discovery of rich calcareous nannofossil assemblages from the *Micula prinsii* zone immediately below the iridium-rich clay layer illustrates the definite presence of terminal Maastrichtian sediments in this section. It apparently substantiates the planktonic foraminifer record to fulfill the criteria for a biostratigraphically complete and continuous shallow marine KTB sequence. The continuity of the section is also suggested by the occurrence of bioturbation-free calcareous shales, albeit with a modest colour change, across the 1.5 cm thick iridium-rich clay layer which marks the K/T boundary.

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Origin and significance of high-grade phosphorite in a sediment core from the continental slope off Goa, India


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A phosphorite crust was found at 380–390 cm depth interval of a sediment core collected from the topographic high occurring on the continental slope off Goa. This crust is fragile and grey to light brown in colour. Carbonate fluorapatite is the predominant mineral followed by minor pyrite. Thin section studies indicate that it is mostly homogeneous with a few bone fragments and shows porous microstructure. SEM studies show that it contains agglomerated 1–2 μm size apatite globules resembling phosphatized bacteria and coalesced bacteria. Microprobe geochemistry of the phosphorite indicates that it contains 33% P2O5 and 50% CaO with other major elements (Si, Al, Ti, Fe, Mg, Na and K) amounting to only 1.8%. The mode of the phosphorite crust formation is discussed in relation to Quaternary phosphorites in upwelling and non-upwelling regions. It is suggested that the initial substrate for the phosphorite crust was most probably a fish coprolite which phosphatized under lower rates of terrigenous sedimentation and calm environmental conditions during the Pleistocene.

In phosphorites the P2O5 content generally exceeds 18% and it may sometimes reach up to 40%. Phosphorites with higher P2O5 content are not only of scientific interest but are also of significant economic value. So far, phosphatized limestones consisting of 2–14% P2O5 (bulk analyses)3-5, the sediments6 with 0.2–2.0% P2O5 and glaucony-phosphate facies associated sediments7 were reported from the western continental margin of India. In this paper, we report the origin and significance of high-grade phosphorites (34% P2O5) sporadically occurring at subsurface depths of the sediment cores collected from the topographic high on the continental slope off Goa.