Cretaceous (Albian-Turonian) calcareous nannofossil biostratigraphy of the onshore Cauvery Basin, southeastern India

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Abstract

A suite of outcrop samples from the Cauvery Basin belonging to the mudrock-claystone dominated Karai Formation were analysed for nannofossil biostratigraphy in two newly measured sections at Karai and Garudamangalam. The age of the Karai Section is interpreted as early Albian to early Turonian, whereas the Garudamangalam Section is interpreted as late Albian to late Cenomanian. The Albian 'BC' zones of Bown et al. (1998) are applicable in both sections, whereas the Cenomanian and Turonian 'UC' zones of Burnett (1998), are only partially applicable, due to some problematic primary and secondary markers. The Albian-Cenomanian boundary appears to be continuous and is approximated in both sections using the FO of lower Cenomanian ammonites of the *M. mantelli* Zone. The Cenomanian-Turonian boundary interval is incomplete in the two sections, with a hiatus of ~0.66 Myr, indicated by the absence of the upper Cenomanian Nannofossil Zone UC5. The nannoplankton assemblages are composed of broadly cosmopolitan taxa, despite the relatively high-latitude setting of SE India during the Albian (~45ºS), which is reflected in the common occurrence of biogeographically bipolar taxa such as *Repagulum parvidentatum* and *Seribiscutum primitivum.* The palaeobiogeographic affinity of the nannoplankton, however, does not bear a distinct Austral stamp, as typical Austral taxa, such as *Sollasites falklandensis* and *Zeugrhabdotus kerguelenensis* are very rare in the studied sections. The early appearance of *Crucibiscutum hayi* in the lower Albian, and *Gartnerago segmentatum* in the upper Albian in the Cauvery Basin suggests that these two species may have originated in southern high latitudes before migrating to the northern Boreal regions. Four new calcareous nannofossil species, *Calculites karaiensis*, *Loxolithus bicyclus*, *Manivitella fibrosa* and *Tranolithus simplex* are described.

Highlights

- A high-resolution Albian-Turonian biostratigraphy is established for the Cauvery Basin using integrated calcareous nannofossil and ammonite data.
- The FO of *G. ponticula* is proposed as a new nannofossil proxy for approximating the Albian-Cenomanian boundary.
- A Cenomanian-Turonian boundary interval hiatus equivalent to Nannofossil Zone UC5 is present, representing a magnitude of ~0.66 Myr.
- The Austral character of the Cauvery Basin nannoplankton assemblages is suppressed.

Keywords: Cretaceous, Nannofossils, Ammonites, Correlation, South India, Gondwana, Karai, Garudamangalam, Palaeobiogeography, Austral

1. Introduction

The Cauvery Basin is an important Mesozoic depocentre of southern India and contains a well-developed marine Cretaceous succession that is known for its palaeontological (micro- and macrofossil) and lithological diversity. The basin is the southernmost among a series of NE-SW trending pericratonic, passive-margin rift basins on the eastern Coromandel Coast of India (Fig. 1). It has a large areal extent (~25, 000 sq. km) covering much of Tamil Nadu state, and extends into the shallow offshore area to the east (~30, 000 sq. km). The basin is known for commercial hydrocarbon production and has a Cretaceous petroleum system in place (Govindan et al., 2000; DGH, 2018). A more recent discovery in the Cretaceous by Reliance Industries Limited has opened new avenues for exploration in the deep waters (~95, 000 sq. km) of the Cauvery Basin (DGH, 2018).

The stratigraphy of the basin has been primarily worked out from outcrop geology and extended to the subsurface through drilled and seismic data (Govindan et al., 1996; Rao et al., 2010). This calls for improving stratigraphic constraints in the Cretaceous marine sedimentary successions in the basin that range from the Albian to the Maastrichtian, covering shallow marine to deep marine facies (Sundaram et al., 2001; Nagendra et al., 2011). Calcareous nannofossils are considered to be excellent for age dating Mesozoic (Jurassic and Cretaceous) marine sections, either independently, or in conjunction with ammonites and/or planktonic foraminifera. The potential of rich and abundant calcareous nannofossils, along with macrofossils, has encouraged a detailed re-investigation of the exposed outcrops of the Karai Formation (Fm.) in the Cauvery Basin. Here we present a new biostratigraphic study based upon high-resolution nannofossil investigations and correlation of two sections, Karai and Garudamangalam, that were sampled and collected during the same field session as Gale et al. (2002) and Gale et al. (2019).

The goal of this study is to apply nannofossil biostratigraphy to the two sections belonging to the Karai Fm. and to compare the results with previous investigations in the same area. These two measured sections complement the relatively few sections that have been previously analysed for biostratigraphy in the onshore Cauvery Basin and provide a platform for testing the established nannofossil zonation schemes well away from the NW European and Tethyan margin areas where they were originally developed. The Albian-Cenomanian and Cenomanian-Turonian stage boundaries have been evaluated and compared in the two sections using nannofossil proxies. Additionally, the composition of nannofossil assemblages were assessed to better understand their palaeobiogeographic affinities.

2. Geological history and Cretaceous stratigraphy

The origin of the Cauvery Basin is linked to fragmentation of eastern Gondwanaland and was initiated by the rifting of India from Antarctica-Australia during the Late Jurassic to Early Cretaceous (Powell et al., 1988; Veevers et al., 1991). This rifting led to the subsequent development of the eastern segment of the Indian Ocean during the early part of the Cretaceous

(Holmes and Watkins, 1992). The Cauvery Basin became tectonically active following downwarping of the eastern part of the Indian shield along a NE-SW basement trend, followed by a series of extensional block-faulted movements along normal faults during the Cretaceous. The Cenozoic witnessed continued basinal tilt towards the east, resulting in an easterly shift of the depocentres (Sastri et al., 1981).

Initial non-marine syn-rift sedimentation (?Barremian-Aptian) in the basin was followed by marine sedimentation during the post-rift, passive margin stage from the Albian onwards. Multiple episodes of transgression, regression, deposition, and erosion are documented from the Early Cretaceous to the Cenozoic, reflecting rift, pull-apart, sag, and tilt phases. The basin today preserves a thick succession of well-exposed Lower Cretaceous to Holocene sedimentary rocks (see reviews by Sastri et al., 1981; Prabhakar and Zutshi, 1993; Sundaram et al., 2001 and Watkinson et al., 2007). Lithostratigraphy of the exposed onshore Cauvery Basin is established with lateral and vertical facies variations relative to sea level changes, but as a result of several workers contributing to the lithostratigraphy, there are conflicts in the nomenclature and classification (e.g., Banerji, 1972; Sundaram & Rao, 1986; Acharyya & Lahiri, 1991; Kale and Phansalkar 1992a; Tewari et al., 1996a; Sundaram et al., 2001; Ramkumar et al., 2004, 2011; Nagendra & Nallapa Reddy, 2017). In this study, the lithostratigraphic division of Kale and Phansalkar (1992a) and Paranjape et al. (2015) has been followed for the Uttatur Group/Karai Fm. (Fig. 2).

The sections we studied are located within the Pondicherry Sub-basin, which is famous for its Cretaceous outcrops. Sedimentary deposits in the sub-basin can be divided into the syn-rift, continental sediments of the Sivaganga Fm., overlain unconformably by the post-rift, marine sediments of the Uttatur, Trichinopoly, and Ariyalur groups respectively (Nagendra et al., 2011). The Uttatur Group is sub-divided into the Karai and Dalmiapuram formations. The Karai Fm. comprises the oldest marine strata in the basin and was dated as late Albian to middle Turonian by Sundaram and Rao (1986). It is a mudstone dominated facies overlying the break-up unconformity or onlapping onto Precambrian crystalline basement in the western extremities of the basin (Paranjape et al., 2015). The upper contact of the Karai Fm. with the Trichinopoly Group is marked by a middle Turonian hiatus (Paranjape et al., 2013). The formation is further sub-divided into the Gypsiferous Clay and Sandy Clay Member, which comprise glauconitic, gypsiferous clays with interbeds of sandy limestones and sandstones of variable grain sizes, and rich in megafauna and microfossils (Ramkumar et al., 2004).

A GPlates palaeogeographic reconstruction (Fig. 3) for ~106 Ma (middle Albian) suggests a palaeolatitude of ~45.75ºS for the Cauvery Basin (Matthews et al., 2016). The palaeobathymetry of the basin during Karai Fm. deposition is estimated to be outer neritic (100–200 m), based on benthic foraminifera and clay mineral analyses (Nagendra et al., 2013). Previous work on foraminifera (e.g., Narayanan, 1977; Raju et al., 1991; Raju et al., 1993; Hart et al., 2001; Venkatachalapathy and Ragothaman, 1995a, b; Venkatachalapathy et al., 2014) and nannofossils (e.g., Kale and Phansalkar 1992a, b; Kale et al., 2000) of the Karai Fm. (Uttatur Group) is generally of lower stratigraphic resolution compared to this study, but provides a useful context within which the results of this study can be placed (see Discussion).

3. Material and Methods

Two complementary, overlapping stratigraphic sections, located approximately 5 km apart, near the villages of Karai and Garudamangalam (Fig. 1), were selected for study in order to provide a relatively complete lower Albian to lower Turonian succession. The sections comprise marls and calcareous clays, weathering to brown and grey (black in subcrop, according to Sundaram et al., 2001), and are variably glauconitic. Thin, glauconitic, strongly bioturbated sandy beds, typically <10 cm in thickness are present, and possibly represent storm beds or turbidites. Thicker sandstones contain moulds of aragonitic fossils. Pyrite nodules, including steinkerns of molluscs, are abundant at certain levels, and calcareous, phosphatic, and barite concretions occur less frequently. Belemnites, oysters, and serpulid worms are the most common calcitic fossils.

3.1. *The Karai Section*

The Karai section (see Text-figs. 3–4 in Gale et al., 2019) is located in sparsely vegetated badlands, north of and parallel with the road from Karai to Kulakkalnattam. A 480 m succession was logged and sampled, on average every 4.5 m, through the section. Important lithostratigraphic markers include a highly glauconitic unit (9–13.5 m), a series of five fine silty sandstones (198–211 m), and a disconformable surface, overlain by a shell bed, at 411 m, which passes laterally into a 10 m deep channel, the base of which locally contains a conglomerate made up of corals and thick-shelled bivalve fragments. A group of three-meter-thick highly glauconitic beds, each capped by a thin sandstone are present (436–446 m). An outline log of this locality with palaeoenvironmental interpretation based on trace fossils was provided by Paranjape et al. (2015).

3.2. *The Garudamangalam Section*

This section is exposed in badlands 2 km WNW of the village of Garudamangalam (see Text-fig. 6 in Gale et al., 2019), and ~200 m of Karai Fm. was logged and sampled, on average every 3 m, in a series of four traverses (A–D). The succession comprises calcareous clays and marls, with frequent red and yellow coloured, bioturbated sandstone beds, 10–50 cm in thickness. Pyritic molluscs are preserved at some levels. The lower part, up to 100 m, contains common to abundant belemnites; at 107 m, oysters become common, and persist up to 150 m. Important lithostratigraphic markers include three red sandstones, from 53–61 m, and a double sandstone pair at 108–9 m.

3.3. *Nannofossil observation*

A total of 203 samples were collected for nannofossil study from the Karai (138 samples) and Garudamangalam (65 samples) sections (Supplementary Material, Appendix A: Nannofossil sample/slide list with curatorial designation, housed in the Department of Earth Sciences, University College London). Calcareous nannofossils were analysed using simple smear slides and standard light microscope (LM) techniques (Bown and Young, 1998). The volume of sediment used for each smear slide preparation was standardised to ensure equal sample density. A BH-2 Olympus transmitted light microscope was used to view nannofossils under cross-polarized and phase-contrast light. Nannofossils were analysed semi-quantitatively, with a minimum of 500 fields of view (FOV) examined per sample via multiple (>20) traverses taken vertically and horizontally across each slide.

Five categories were used to denote species abundances, defined as follows: Abundant (A) - >10 specimens/FOV; Common (C) - 1–10 specimens/FOV; Frequent or Few (F) - 1 specimen/2–10 FOVs; Rare (R) - 1 specimen/>10 FOVs; Very Rare (VR) - 1 or 2 specimens in a sample. An estimate of total calcareous nannofossil abundance in relation to inorganic components in each sample was recorded per the following scale: High (H) - >20–30 nannofossils/FOV; Moderate (M) - 3–10 nannofossils/FOV; Low (L) - <3 nannofossils/FOV; and Barren (B) meaning no nannofossils were observed in a sample.

The state of preservation, often ranging between two categories, was assessed for each sample, according to the following criteria: G (good) - specimens show very little evidence of overgrowth or etching and their identification is straightforward; M (moderate) - specimens exhibit moderate effects of secondary alteration from etching and/or overgrowth, but identification of species is not impaired; and P (poor) - specimens exhibit strong effects of etching and/or overgrowth and identification may be difficult for some species.

Nannofossil biostratigraphy is described based on first and last occurrences (FO and LO) of identified marker species using the zonation scheme of Bown et al. (1998) and Burnett (1998). The zonation schemes of Sissingh (1977), Perch Nielsen (1985), and Bralower et al. (1993, 1995) were also applied for comparison. The abbreviation NF is used for nannofossil while describing the zones. FO is used for the first or stratigraphically lowest occurrence of the species in the section. FCO refers to the first consistent occurrence of the species in the section and typically occurs stratigraphically higher than the FO. LO is used for the last or stratigraphically highest occurrence of the species in the section.

4. Results

4.1. *Nannofossil preservation, abundance, and diversity*

Both the Karai and Garudamangalam sections contain abundant and diverse calcareous nannofossil assemblages (see full distribution charts; https://data.mendeley.com/datasets/yzrmmrd2dj/draft?a=e99ad7d2-74de-4bb5-8e5a-caba5ed84753). Nannofossil abundance and preservation are variable, but preservation is overall good to moderate (G-M). Preservation in the Albian part of the section is better than the Cenomanian. Out of the 203 samples analysed in the two sections, 9 samples were barren of nannofossils, but the rest yielded rich assemblages. The average species richness is comparable in the two sections: 54 species at Karai and 50 species in Garudamangalam. A total of ~155 taxa were identified (Supplementary Material, Appendix B: taxonomic list) with many species being reported for the first time from the Cauvery Basin in this study. Four new species *Calculites karaiensis*, *Loxolithus bicyclus*, *Manivitella fibrosa*, and *Tranolithus simplex* are described herein (see Systematic Palaeontology and Figs. 4–8).

4.2. *Biostratigraphy*

The FO and LO of index species in the study sections were used to identify the BC zones of Bown et al. (1998) and the UC zones of Burnett (1998). Tables 1 and 2 list the important nannofossil zonal and subzonal markers recognised in the Karai and Garudamangalam Section in stratigraphic order. Biozones identified in this study are described below in stratigraphic order from older to younger.

Prediscosphaera columnata Zone (BC23) Aptian-Albian boundary interval to middle Albian. Defined by the FO of *Prediscosphaera columnata*. Recognised in the lower Karai Section (22.5 m; sample KA0–KA22.5), where both *P. columnata* (subcircular) and small *P*. cf. *P. spinosa* (subelliptical) are present. The FOs of *C. hayi* and *H. albiensis* are additional events recognised in this zone.

Tranolithus orionatus Zone (BC24) middle Albian. Defined by the FO of *Tranolithus orionatus.* Recognised in the lower Karai Section (31.5 m; sample KA22.5–KA54).

Axopodorhabdus albianus Zone (BC25) middle to upper Albian. Defined by the FO of *Axopodorhabdus albianus*. Placed in the Karai Section at the FCO of *A. albianus* (sample KA54) due to its inconsistent and rare occurrence in the lower samples KA22.5 and KA45. The use of the FCO was proposed by Bown (2001) because *A. albianus* is inconsistent and rare at the base of its range. The total thickness of the BC25 Zone is measured as 121.5 m (sample KA54–KA175.5), but it could not be sub-divided into the Subzone BC25a and BC25b due to the absence of *Ceratolithina bicornuta*. The FOs of *C. anglicum* and *G. praeobliquum* lie within this zone.

Eiffellithus monechiae Zone (BC26) upper Albian. Defined by the FO of *Eiffellithus monechiae*. Recognised in the Karai Section (~9 m; sample KA175.5–KA184.5). The FO of *B. enormis* is recorded in this zone.

Eiffellithus turriseiffelii Zone (BC27a–c/UC0a–c) upper Albian to lower Cenomanian. Defined by the FO of *Eiffellithus turriseiffelii.* Recognised in full at Karai, but partially at Garudamangalam, as *E. turriseiffellii* is already present in the lowermost sample. The thickness of the zone is 116.5 m at Karai (sample KA184.5–KA301) and 96.5 m (sample GM0–GM96.5) at Garudamangalam. Subzone BC27a is recognised in both sections, based on the LO of *Hayesites albiensis*. However, Subzone BC27b–c, could not be distinguished because *Calculites anfractus* is practically absent in both sections (questionable occurrence in a single sample in Garudamangalam). The FOs of *C. ehrenbergii* and *G. theta*, and the LO of *C. anglicum* are recorded in the BC27a Subzone in the Karai section. The FOs of *B. enormis*, *G. chiasta*, *G. ponticula*, *G. segmentatum*, *G. theta*, and the LOs of *G. chiasta*, *G. stenostaurion*, *G. theta*, and *W. britannica* are found within the combined BC27b-c Subzone in the Garudamangalam section.

UC1 NF Zone lower Cenomanian. Defined by the FO of *Corollithion kennedyi*, this zone is 103.5 m thick at Karai (sample KA301–KA404.5) and 16.5 m thick at Garudamangalam (sample GM96.5–GM113). Subzones a to d were not identified because the subzonal markers were not identified in the stratigraphic order described in Burnett (1998). Some of the defining events, e.g., LO of *G. chiasta*, LO of *W. britannica,* are found stratigraphically lower, or higher, with reference to the FO of *C. kennedyi*, and their order is variable in the two sections. Other secondary events, e.g., FO of *H. anceps,* are absent.

UC2 NF Zone lower to basal middle Cenomanian. Defined by the FO of *Gartnerago segmentatum*. This zone is not differentiated at Karai because of the simultaneous FOs of *G. segmentatum* and *L. acutus* in the sample KA404.5. The zone is not recognised at Garudamangalam because the FO of *G. segmentatum* occurs stratigraphically lower than the FO of *C. kennedyi* in the upper Albian to lower Cenomanian BC27b-c Subzone interval.

UC3 NF Zone middle to upper Cenomanian. Defined by the FO of *Lithraphidites acutus,* this zone is 44.4 m thick at Karai (sample KA404.5–KA448.9) and 70.5 m thick at Garudamangalam (sample GM113–GM183.5). In both sections, the UC3 Zone was sub-divided into a combined UC3a–b (LO of *S. gausorhethium*) and UC3c–d (LO of *C. kennedyi*), but subzones UC3b (LO of *G. theta*) and UC3d (LO of *G. nanum*) could not be differentiated individually because the index taxa were either not present in the expected stratigraphic order, e.g., *G. theta*, which was found stratigraphically lower than *L. acutus*, or were absent (*G. nanum*). Additional events recognised in the UC3a–b interval include the FOs of *C. sculptus* and *M. belgicus*, and the LOs of *G. ponticula* and *S. gausorhethium*. Secondary events falling within the UC3c–d interval include the FO of *M. decoratus*, and the LOs of *C. striatus* and *C. kennedyi*. The FO of *Ahmuellerella* cf. *A. octoradiata* occurs in the UC3a–b interval at Karai, but occurs higher, in the UC3e Subzone at Garudamangalam.

UC4 NF Zone upper Cenomanian. Defined by the FO of *Cylindralithus biarcus* but not differentiated because this index species is missing.

UC5 NF Zone upper Cenomanian to lower Turonian. Defined by the LO of *Lithraphidites acutus*. The zone is interpreted as not present, as the LOs of *L. acutus* and *H. chiastia* occur in the same sample in both sections. This suggests the presence of a hiatus, equivalent to Zone UC5.

UC6 NF Zone lower Turonian. Defined by the LO of *Helenea chiastia*, the zone is present in the Karai Section with a thickness of 20.2 m (sample KA448.9–KA469.1). The lower boundary of the zone occurs at a hiatus (see above). Subzones UC6a and UC6b are distinguished based on the FO of *Eprolithus moratus*. The FO of *E. octopetalus* is recorded in the UC6a Subzone at Karai. UC6 Zone cannot be applied to the Garudamangalam Section, as no lower Turonian markers (e.g., *E. moratus*, *E. octopetalus*, *Quadrum gartneri*) were identified in the samples. The highest Karai sample (KA469.1) falls within the UC6b Subzone. *Q. gartneri* is not observed in any of the samples.

Nannofossil biostratigraphy shows that the lower to upper Albian NF Zones BC23 through BC27 of Bown et al. (1998) are present in the Karai Section, with the upper Albian Zone BC27 being the lowest recognised in the Garudamangalam Section. The Albian zones are divisible into subzones for the most part, with some exceptions (e.g., BC25a/ BC25b Subzone). In the Cenomanian, the UC zones of Burnett (1998) were applied, but only Zone UC1 (FO of *C. kennedyi*) and UC3 (FO of *L. acutus*) could be recognised with confidence. The UC2 (FO of *G.*

segmentatum) and UC4 Zone (FO of *C. biarcus*) could not be differentiated. Zone UC5 is not identified because of the presence of a hiatus. Several Cenomanian zonal and subzonal marker species are either not present, e.g., FO of *C. anfractus* (within UC0), FO of *H. anceps* (within UC1), LO of *I. compactus* (within UC3d), FO of *C. biarcus* (UC4), LO of *L. acutus* (UC5); or not consistent with the stratigraphic order reported in Burnett (1998), e.g., LO of *W. britannica* (UC1b), FO of *G. segmentatum* (UC2), thus preventing their use here. However, it is worth mentioning that Cenomanian zonal markers from the earlier CC (Sissingh, 1977; Perch-Nielsen, 1985) and NC zonation schemes (Roth, 1978; Bralower et al., 1993; 1995) such as *C. kennedyi*, *M. decoratus*, *L. acutus*, and *H. chiastia*, are all present. This suggests that the applicability of some of these more recently proposed bioevents may be problematic rather than there being significantly missing stratigraphy.

4.3. *Systematic palaeontology*

This section provides LM images of a representative selection of nannofossil taxa from the Karai Fm. (Figs. 4–8). The LM images are reproduced at constant magnification with a 2µm scale bar shown in the top left corner. Taxonomic description of four new species, *Calculites karaiensis*, *Loxolithus bicyclus*, *Manivitella fibrosa* and *Tranolithus simplex*, are included herein. The taxonomy follows the scheme of Bown & Young (1997) and the online nannoplankton database, Nannotax (Young et al., 2017; http://www.mikrotax.org/Nannotax3). The descriptive terminology follows the guidelines of Young et al. (1997). Only those bibliographic references that are not included in Perch-Nielsen (1985) and Nannotax are given in the references.

HETEROCOCCOLITHS

Murolith coccoliths

Family Chiastozygaceae Rood et al., 1973 emend. Varol & Girgis, 1994

Genus *Loxolithus* Noël, 1965

Type species: *Cyclolithus armilla* Black, *in* Black & Barnes, 1959

Loxolithus bicyclus sp. nov.

Fig. 4, no. 9–12

1998 *Loxolithus* sp. 2, Bralower and Bergen, p. 75, pl. 1, fig. 2

Derivation of name: From '*cyclus*' in Latin meaning cycle, referring to the two distinct rim cycles observed in the species. **Diagnosis**: Medium to large-sized elliptical muroliths with a narrow bicyclic rim and a broad, open, central area. The inner rim cycle is bright in XPL with spiralling extinction lines. **Differentiation**: The species is distinguished from *L. armilla* by its clearly bicyclic rim, whereas *L. armilla* is unicyclic. **Holotype**: Fig. 4, no. 9. **Paratype**: Fig. 4, no. 11 (11 and 12 are the same specimen). **Dimensions**: **Holotype** L = 8.5 μm; **Paratype** L = 6.75 μm. **Type locality**: Garudamangalam, Cauvery Basin, India. **Type level**: Karai Fm., lower Cenomanian, sample GM101, Zones UC1. **Abundance**: Rare. **Occurrence**: Zone BC27–UC6 (upper Albian–lower Turonian), Karai Fm.

Genus *Tranolithus* Stover, 1966

Type species: *Tranolithus manifestus* Stover, 1966

Tranolithus simplex sp. nov.

Fig. 4, no. 27–32

Derivation of name: From '*simplex*' in Latin meaning simple, referring to the simple appearance of the central area transverse bar. **Diagnosis**: A small to medium-sized murolith with a narrow rim and broad central area spanned by a simple transverse bar. **Description:** The narrow rim appears unicyclic in XPL, and the rim and bar have similar, low birefringence, with the bar being slightly brighter. A central hole in the bar is most likely a spine base. **Differentiation**: Similar to the Jurassic species *Zeugrhabdotus erectus* but the latter has a more birefringent bar which is clearly crystallographically disjunct. **Remarks**: The species has been placed within the genus *Tranolithus* and not *Zeugrhabdotus* because the overall LM appearance is closer to other *Tranolithus* species such as *T. orionatus* and *T. gabalus*, however the distinction between these two genera is questionable. **Holotype**: Fig. 4, no. 27. **Paratype:** Fig 4, no. 30 (30–32 are the same specimen). **Dimensions**: **Holotype** L = 7.5 µm; **Paratype** L = 8.0 µm. **Type locality**: Karai, Cauvery Basin, India. **Type level**: Karai Fm, lower Cenomanian; sample KA373 (Subzone UC1). **Abundance**: Frequent to Rare. **Occurrence**: Zone BC23–UC6 (lower Albian–lower Turonian), Karai Fm.

Placolith Coccoliths

Family Tubodiscaceae Bown & Rutledge *in* Bown & Young, 1997

Genus *Manivitella* Thierstein, 1971

Type species: *Cricolithus pemmatoideus* Deflandre *in* Manivit, 1965 designated by Thierstein, 1971

Manivitella fibrosa sp. nov.

Fig. 7, no. 1–6

Derivation of name: From '*fibra*' in Latin meaning fibre, referring to the fibrous, striated appearance of the coccolith rim. **Diagnosis**: Large, elliptical placolith with a narrow, striated rim and a broad, vacant central area. The rim is composed of two narrow shields that are dark in XPL and a third, very narrow and rather high collar-cycle which is bright in XPL. The distal shield has a highly striated appearance in XPL. Under PC, the rim appears as a dark band of uniform thickness. **Differentiation**: In XPL this species is darker than *M. pemmatoidea* and the distal shield is more finely striated. The outer edge of the inner cycle is not beaded in appearance, which makes the separation easier from *M. pemmatoidea*. This species does not have a clearly bicyclic appearance (in XPL) that is characteristic of the genus *Tubodiscus* (e.g., *T. burnettiae*), hence it is placed under the genus *Manivitella*. **Holotype**: Fig. 7, no. 2. **Paratype**: Fig. 7, no. 4. **Dimensions**: **Holotype** L = 13.5 µm; **Paratype** L = 14.5 µm. **Type locality**: Karai, Cauvery Basin, India. **Type level**: Karai Fm, upper Albian, sample KA278.5 (Zone BC27). **Abundance**: Frequent to Rare. **Occurrence**: Zone BC24–UC3 (middle Albian–middle Cenomanian), Karai Fm.

HOLOCOCCOLITHS

Family Calyptrosphaeraceae Boudreaux & Hay, 1969

Genus *Calculites* Prins & Sissingh *in* Sissingh, 1977

Type species: *Tetralithus obscurus* Deflandre, 1959

Calculites karaiensis sp. nov.

Fig. 7, no. 40–42; Fig. 8, no. 1–8

Derivation of name: From '*Karai*', the place from which it is described. **Diagnosis**: An elliptical, small holococcolith with a rim formed from 6 to 7 blocks. The blocks are crystallographically distinct, asymmetric, and separated by slightly irregular sutures. A longitudinal and two diagonal sutures can usually be distinguished. The surface of the holococcolith appears to be smooth under LM. **Differentiation**: Distinguished from other mid-Cretaceous holococcolith species, which typically have 4 or less blocks, by the possession of 6–7 irregular blocks (compare with *C. percernis*, Fig. 7, no. 38–39). **Holotype**: Fig. 8, no.1. **Paratype**: Fig. 8, no. 6 (6–8 are the same specimen). **Dimensions**: **Holotype** L = 4.5 µm; **Paratype** L = 6.0 µm. **Type locality**: Karai, Cauvery Basin, India. **Type level**: Karai Fm., lower Turonian, sample KA459.3 (Subzone UC6b). **Abundance**: Frequent, observed in two samples (KA445.7, KA459.3). **Occurrence**: Subzone UC3c-d–UC6b (middle Cenomanian–lower Turonian), Karai Fm.

5. Discussion

5.1. Stratigraphic remarks

5.1.1. *Albian zonation*

The Albian marker species *P. columnata*, *T. orionatus*, *A. albianus*, *E. monechiae*, and *E. turriseiffelii* are all readily recognised in the Karai Section demonstrating the cosmopolitan nature of these biostratigraphically useful taxa. *P. columnata* is present in the lowest sample examined (KA0), indicating an intra-BC23 NF Zone (or CC8a Subzone) position for the base of the Karai Section. The FO of *P. columnata* (subcircular) occurs in the very uppermost Aptian in the Albian GSSP (Kennedy et al., 2000; 2014) and so provides a good approximation for this stage boundary.

The BC25a/ BC25b (LO of *C. bicornuta*) and BC27c (FO of *C. anfractus*) NF subzones could not be differentiated in this study, due to the absence of the index species. Several other secondary markers used in the BC zonation, such as *C. hamata*, *B. boletiformis*, and *T. tessellatus* are also absent in the Karai Fm. All of these taxa are thought to be restricted to NW European high-latitudes (Crux, 1991; Bown, 2001), making their absence in the Cauvery Basin notable, but not entirely surprising.

A noteworthy feature of the Karai nannoflora is the early stratigraphic appearance of *Crucibiscutum hayi* in the lower Albian (sample KA4.5, BC23 Zone), contrasting with its reported first appearance in the BC27 NF Zone (or CC9b Subzone) in the upper Albian (Bown, 2001). Based on this observation, an Austral (southern high-latitude) origin during the early Albian is proposed for this species, along with a subsequent migration to Tethyan and Boreal latitudes during the late Albian.

5.1.2. *Cenomanian and Turonian zonation*

The UC zonation scheme of Burnett (1998) was developed in order to improve Upper Cretaceous biostratigraphic resolution by replacing problematic markers from the earlier CC and NC zonation schemes of Sissingh (1977) and Roth (1978). Biogeographic differences are accommodated through the provision of separate information for two regions, Europe and the Indian Ocean, with the Indian Ocean region sub-divided into the Tethyan-Intermediate and

Austral provinces. In this study, the global suite of UC zones and subzones, irrespective of region or province, was taken into consideration to test its applicability and obtain the best stratigraphic resolution for the studied sections.

The Cenomanian to lower Turonian UC zones and subzones are not uniformly applicable in the two sections due to rarity of the index species, inconsistent stratigraphic ordering compared with Burnett (1998), or stratigraphic breaks in the section (Figure 9a, b). *Calculites anfractus* was practically not identified in the Cauvery Basin, preventing the identification of Subzone BC27c/ UC0c, but the rarity or absence of this species has been noted elsewhere (Gale et al., 2011), suggesting that the subzone is probably not globally applicable. The subzonal bioevents FO of *H. anceps* (UC1 Zone; Europe/ Indian Ocean), FO of *Q. intermedium* (UC5 Zone; Europe/ Indian Ocean), LO of *I. compactus* (UC3 Zone; Europe), LO of *R. hollandicus* (UC1 Zone, Europe/ Indian Ocean) were also not identified in the Karai sections, but again these events do not appear to be consistently reported. Other subzonal markers are present, but they could not be used to assign subzones either because of rare occurrence (e.g., FO of *C. sculptus*, FO of *L. pseudoquadratus*), or inconsistencies in their relative stratigraphic order (e.g., LO of *W. britannica*, FO of *P. cretacea*) with respect to zone defining datums (e.g., FO of *C. kennedyi*) in the two sections. Table 3 gives a summary of the Cenomanian zone and subzone markers used in Burnett (1998) and Lees (2002) compared with the Cauvery Basin.

The FO of *G. segmentatum* varies in its stratigraphic positioning in the two sections. At Karai, the FCO of *G. segmentatum* coincides with the FO of *L. acutus*, rendering the UC2 Zone inapplicable in the section. At Garudamangalam, the FCO of *G. segmentatum* lies stratigraphically lower (Subzone BC27b–c) than the FO of *C. kennedyi* (UC1 Zone). As a result, the UC2 Zone is not recognized in this section either, however, we consider this is likely due to an extended lower range for *G. segmentatum*, rather than any significant stratigraphic hiatus (see further discussion below). Distinct size shifts are seen in *G. segmentatum* with early forms, referred to here as *G.* cf. *G. segmentatum*, being relatively small (~5 μm in length) and larger, more typical sizes (> 8 μm in length) and more consistent occurrences found stratigraphically higher, after a gap of ~45–75 m (FCO, samples KA404.5 and GM62). Small sizes are rarely observed after the FCO of the species. The early appearance of this species in the late Albian at Garudamangalam suggests that *G. segmentatum* may have evolved earlier in southern high-latitudes, before migrating to Boreal regions, comparable to the observation made for *C. hayi* in the early Albian. In general, *Gartnerago* is considered a high-latitude form, and may be particularly common in the Austral area (Thierstein, 1981; Lees, 2002).

Cylindralithus biarcus (= *Rotelapillus biarcus* of Lees and Bown, 2005) is questionably identified in the Cenomanian at Karai (sample KA435.9, UC3 Zone) but not at Garudamangalam. Very rare specimens were found in two samples in the Turonian section (KA469.1, KA464.2). Overall, the FO of this species could not be reliably identified. As a result, the Zone UC4 could not be differentiated, but we consider this is due to the unreliability of the index species, rather than the presence of any significant stratigraphic gap.

In the uppermost Cenomanian part of the Karai Section, the co-occurring LOs of several important index species, *A. albianus*, *L. acutus*, and *H. chiastia* (sample KA448.2) suggest the presence of a hiatus, equivalent to the UC5 Zone interval. This observation is repeated at Garudamangalam, where the LOs of *L. acutus* and *H. chiastia* occur in the same sample

(GM183), but the LO of *A. albianus* is recorded slightly lower in the section (GM170.5). The LO of *H. chiastia* defines the base of the UC6 Zone, and the latter is considered a reliable proxy for the Cenomanian-Turonian boundary (Burnett, 1998). Nannofossil data, therefore, suggests an apparent hiatus in the upper Cenomanian (UC5 NF Zone interval) at Garudamangalam as well, which falls within the *Calycoceras* (*C.*) *asiaticum* Ammonite Zone (Gale et al., 2019).

The lower Turonian is recognized at Karai, based on the presence of *Eprolithus octopetalus* and *E. moratus*. The FO of *E. moratus* is used to define the Subzone UC6b. No Turonian markers are present at the Garudamangalam Section, but the absence of *Eprolithus moratus* in the samples above (GM183.5–GM191) the LO of *H. chiastia* (sample GM183) is indicative of Subzone UC6a and the lower Turonian. This, however, conflicts with the ammonite data (Gale et al., 2019), which indicates that the highest sediments present at Garudamangalam fall within the upper Cenomanian *Pseudocalycoceras* (*P.*) *harpax* Ammonite Zone, *Euomphaloceras* (*E.*) *euomphalum* fauna. This fauna indicates a position low within the upper Cenomanian (Fig. 9b).

The nannofossil marker, *Zeugrhabdotus xenotus*, is reworked in the upper Cenomanian and lower Turonian section at Garudamangalam (samples GM174 and GM190), which is the only obvious example of reworking observed in the study. *Quadrum gartneri* is not observed in any sample, even though it has been previously reported from the Uttatur Group (Kale and Phansalkar, 1992a; b). The identification of this taxon, and therefore the base of NF Zone UC7 in the lower Turonian is often problematic, most likely due to its rare and sporadic distribution (Berrocoso et al., 2012, etc.).

The stratigraphic thickness of the identified nannofossil zones varies between the two sections, with the majority of zones thicker at Karai (total thickness, ~480 m) compared with Garudamangalam (total thickness, ~200 m). The exception is the middle–upper Cenomanian UC3 NF Zone, which is thicker in Garudamangalam (~70 m) than Karai (~45 m). This can be attributed to local variations in basin sedimentation rates (Figure 10 a, b; age-depth plots). Kale and Phansalkar (1992b) have reported a condensed middle Cenomanian section (CC10, *M. decoratus* Zone) in the Terani-Garudamangalam section of the Cauvery Basin on the basis of nannofossil data, but not in the Karai-Kulakkalnattam section.

5.2. *Albian-Cenomanian and Cenomanian-Turonian stage boundary*

The Albian-Cenomanian boundary appears to be stratigraphically continuous in the studied sections, at least at the level of biostratigraphic resolution achieved in this study, with the base of the Cenomanian identified at Karai a short distance beneath the sample KA341.5 (341.5 m), and at Garudamangalam close to the sample GM53 (53 m), using the FO of lower Cenomanian ammonites of the *M. mantelli* Ammonite Zone. The first occurrence of lower Cenomanian ammonites appears to be more consistent in the studied sections than the FO of *C. kennedyi* to delineate the base of the Cenomanian (see Discussion in Section 5.4). Recent studies support the observation regarding the anomalous FO of *C. kennedyi* (Silva Jr. et al., 2020). At the Cenomanian GSSP at Mont Risou (France), the FO of *C. kennedyi* lies just above the Albian-Cenomanian boundary (Kennedy et al., 2004).

Table 4 provides a comparison of the nannofossil bioevents around the Albian-Cenomanian boundary in the Mont Risou section (Burnett *in* Gale et al., 1996) and the Cauvery Basin. Most nannofossil bioevents are common to both regions, although there are some inconsistencies in the relative stratigraphic order of the events. The FOs of *G. chiasta*, *G. theta*, and *G. ponticula*, and the LOs of *E. paragogus* (= *S. glaber*), *H. albiensis*, and *W. britannica* all support identification of the boundary interval in the Cauvery Basin. Kennedy et al. (2004) reported the LO of *Gartnerago stenostaurion* (= *Arkhangelskiella antecessor*) in the upper Albian at Mont Risou. *G. stenostaurion* shows a patchy distribution in the Cauvery sections and was not used to evaluate the boundary in this study.

The Cenomanian-Turonian boundary is associated with a stratigraphic break (hiatus) in both Cauvery sections. At Karai, the hiatus occurs between samples KA448.2 (448.2 m) and KA448.9 (448.9 m), and is indicated by the co-occurring LOs of the upper Cenomanian index species *A. albianus*, *H. chiastia*, and *L. acutus*, followed by the FO of the lower Turonian index species, *E. octopetalus*. This is in agreement with ammonite and inoceramid occurrences (Fig. 9a; Gale et al., 2019). Biostratigraphically, the Cenomanian-Turonian boundary interval is incomplete and Zone UC5 is missing. Zone UC4 was not differentiated due to the problematic index species, *C. biarcus*. A comparable Cenomanian-Turonian boundary interval hiatus is interpreted in Garudamangalam, even though the lower Turonian is inferred, based on the absence of *E. moratus* in the samples above the LO of *H. chiastia*. However, this falls within the upper Cenomanian *Calycoceras asiaticum* fauna (*P. harpax* Ammonite Zone; Gale et al., 2019), demonstrating disparity here between nannofossil and ammonite biostratigraphies (Fig. 9b). This study is the first to report an upper Cenomanian-lowermost Turonian unconformity in the Karai

Fm. on the basis of nannofossil data. At Karai, the duration of the hiatus is estimated to be ~0.66 Myr, using the calibrated ages for the LO of *L. acutus* (94.39 Ma) and the FO of *E. moratus* (93.73 Ma) (Ogg and Hinnov, 2012). The magnitude of the hiatus is difficult to estimate at Garudamangalam because of the lack of Turonian index species, but is likely similar to that observed at Karai (Fig. 10b). Previously, Ramkumar et al. (2011) interpreted the Cenomanian-Turonian boundary as an unconformity, marking a major sequence boundary in the Cauvery Basin, using bulk geochemical profiles. Cenomanian-Turonian boundary hiatuses have also been recognized elsewhere in the Indian Ocean (e.g., Kale and Phansalkar, 1992b; Lees, 2002). Additionally, the stratigraphic order of extinctions of upper Cenomanian nannofossil indices, such as *A. albianus*, *C. kennedyi*, and *L. acutus*, has been found to be inconsistent in outcrop and core samples in the Cretaceous Western Interior Basin, USA (Bralower and Bergen, 1998; Corbett and Watkins, 2013).

5. 3. *Comparison with previous age interpretations (nannofossils and planktonic foraminifera)*

Previous nannofossil biostratigraphy of the Uttatur Group has been based on the same outcrop and quarry samples documented in four publications (Jafar and Rai, 1989; Kale and Phansalkar, 1992a; b; Kale et al., 2000). Five CC NF zones (Perch-Nielsen, 1979; 1985) were recognised (Zone CC7–CC11) based on the FOs of *C. litterarius*, *P. columnata*, *E. turriseiffelii*, *M. decoratus*, and *Q. gartneri* (Fig. 2). This succession of zones was described as continuous without any stratigraphic breaks. In comparison, this study ascribes the age of the marine Karai Section as ranging from the early Albian (BC23 Zone = CC8 Zone) to early Turonian (UC6b

Subzone = intra CC10 Zone), showing that the CC11 Zone (middle Turonian) identified in the previous work, is not present.

Several papers describe foraminifera from the Karai Shale, but they are difficult to correlate with this study because they are either based on wells/shallow cores (e.g., Govindan et al., 1996; Tewari et al., 1996b) or outcrops, with very little stratigraphic and sample information (Nagendra et al., 2013; Venkatachalapathy et al., 2014). Nagendra et al. (2013) interpreted the age of the exposed Karai Shale in the badlands area as late Albian to middle Turonian, based on the planktonic foraminifera index species *Planomalina buxtorfi*, *Hedbergella portsdownensis*, *Rotalipora reicheli*, and *Praeglobotruncana stephani*. Details of the zones or species distributions are not given in the paper, but overall, it can be said that although the planktonic foraminiferal ages and the nannoplankton ages described in this study overlap to a degree, the sections studied appear to have different locations with varying sampling resolutions.

5.4. *Comparison with ammonite stratigraphy*

In the Karai Section, upper Albian ammonites of the *P. (S.) rostrata* Zone first occur at 63 m, which falls within NF Zone BC25 (Figure 9a). This is a mismatch, because elsewhere, the lower part of BC25 NF Zone falls within the middle Albian in terms of ammonite faunas. In the Col de Palluel sections, southeastern France (Bown *in* Gale et al., 2011), the base of NF Zone BC25 (FO of *A. albianus*) falls at or within the base of the middle Albian. The FO of *E. turriseiffellii* at 184.5 m, and the LO of *H. albiensis* at 278.5 m at Karai correspond in order to the FO and LO of these species in SE France, but there, *E. turriseiffellii* appears at the base of the

M. fallax Ammonite Zone, and *H. albiensis* within the *D. perinflatum* Ammonite Zone (Gale et al., 2011; Fig. 49). At Karai, both appear within the *P. (S.) rostrata* Ammonite Zone.

At Karai, the FO of *C. kennedyi* at 301 m (base of NF Zone UC1) significantly predates the FO of lower Cenomanian ammonites of the *M. mantelli* Zone at 341.5 m, whereas at Garudamangalam, *C. kennedyi* appears at 96.5 m, above the occurrence of lower Cenomanian ammonites, in a barren interval beneath the lowest middle Cenomanian ammonites of the *C. asiaticum* Zone (Fig. 9b). In the UK and elsewhere (Burnett, 1998; see also Gale et al., 1996; 2011), *C. kennedyi* appears in the lowest subzone of the *M. mantelli* Ammonite Zone, the *N. carcitanense* Ammonite Subzone.

At Karai, the base of NF Zone UC3 (FO of *L. acutus*, 404.5 m) falls in the uppermost part of the lower Cenomanian, probably of *M. dixoni* Ammonite Zone age, immediately underlying the FO of middle Cenomanian ammonites of the *C. cunningtoni* Ammonite Zone at 410 m. At Garudamangalam, the base of UC3 NF Zone falls at 113 m, within the middle Cenomanian, and close to the base of the *C. asiaticum* Ammonite Zone. In the UK, the base of NF Zone UC3 is close to the base of the middle Cenomanian.

The absence of NF Zone UC5 at Karai, at a level of 448.9 m, marking a hiatus, is matched by the absence of late Cenomanian ammonites of the *M. geslinianum* and *N. juddii* Ammonite Zones, with which NF Zones UC4–5 correspond (Burnett, 1998). The association of the lower Turonian inoceramid, *Mytiloides*, with nannofossils of Zone UC6 in the Karai Section corresponds well with the occurrences in the UK (Burnett, 1998).

Some of the mismatches between ammonite and nannofossil occurrences can perhaps be related to non-preservation of ammonites at key intervals. For example, at Karai, there is a gap in the ammonite record of 54 m between the LO of Albian mortoniceratids and the FO of lower Cenomanian ammonites of the *M. mantelli* Zone, within which the base of NF Zone UC1 (FO of *C. kennedyi)* falls. In a similar fashion, the presence of nannofossils of BC25 Zone, which are elsewhere associated with middle Albian ammonites (Gale et al., 2011) are associated in the Karai Section with ammonites of the upper Albian *P. (S.) rostrata* Zone. The mismatch between ammonite and nannofossil zonal boundaries in the Cauvery Basin has been mentioned in previous studies (e.g., Kale and Phansalkar, 1992b) but not discussed in any detail.

The base of the Cenomanian stage is taken at the FO of the planktonic foraminifer, *Rotalipora globotruncanoides*, which occurs in the uppermost Albian Ammonite Zone of *Arraphoceras briacensis*, shortly beneath the first occurrence of ammonites of the lowermost Cenomanian *M. mantelli* Zone (Kennedy et al., 2004). The base of NF Zone UC1 occurs within the lowest part of this zone (Burnett, 1998).

In the Cauvery Basin, a discrepancy in the FO of *C. kennedyi* (NF Zone UC1) is noted with respect to the FO of lower Cenomanian *M. mantelli* Ammonite Zone fauna at Karai and Garudamangalam. In the Karai Section, *C. kennedyi* appears first at 301 m (sample KA301) and then occurs consistently from 337–448.04 m (sample KA337–KA448.04), after a gap of seven samples (sample KA305.5–KA332.5). In the Garudamangalam Section, *C. kennedyi* occurs consistently from its first appearance at 96.5 m (sample GM96.5) up to 159.5 m (sample GM159.5). The consistent occurrence of *C. kennedyi* observed at Garudamangalam can be equated with Karai (sample KA337–KA448.04), but the first appearance (sample KA 301) and gap observed at Karai does not correlate with Garudamangalam (see distribution charts). Overruling any possibility of caving in the Karai Section, it is reasonable to interpret that the base of *C. kennedyi* at Garudamangalam could be truncated and, therefore, does not represent its true base (Fig. 10b). Due to the observed variance, the FO of *C. kennedyi* was not employed to delineate the base of the Cenomanian.

In view of the low stratigraphic occurrence of *C.kennedyi* at Karai, and the higher occurrence at Garudamangalam, it is perhaps best to provisionally estimate the base of the Cenomanian in the Cauvery Basin (Karai Section) a short distance beneath the first Cenomanian ammonites (341.5 m, *M. mantelli* Ammonite Zone). The FOs of *G. ponticula* (332.5 m), small *G.* cf. *G. segmentatum* and *G. chiasta* (328 m) are the closest nannofossil events that fall below the first Cenomanian ammonites in the Karai Section (Fig. 9a). At Garudamangalam, the FO of *G. ponticula* (53 m) and the FO and LO of *G. chiasta* (46 m and 53 m respectively) lie closest to the base of the *M. mantelli* Ammonite Zone, facilitating the placement of the Albian-Cenomanian boundary provisionally around 53m (Fig. 9b). The FO of *G. ponticula* is hereby proposed as a new nannofossil proxy for the Albian-Cenomanian boundary.

The base of the Turonian in the Karai Section is taken at the base of NF Zone UC6, at a significant hiatus. The base of UC6 Zone falls within the *Watinoceras devonense* Ammonite Zone, which marks the base of the Turonian (Kennedy et al., 2005).

5.5. *Palaeobiogeographic character of the Cauvery nannofossils*

The good to moderate preservation of nannofossils in the Cauvery Basin makes it possible to characterize the assemblages from a palaeobiogeographic perspective. The nannofossil assemblages typically show high species richness of at least 50 species per sample, and are generally dominated by cosmopolitan taxa, such as, *Biscutum*, *Chiastozygus*, *Eiffellithus*, *Lithraphidites*, *Retecapsa*, *Rhagodiscus*, *Staurolithites*, *Watznaueria*, and *Zeugrhabdotus* spp.

In order to make meaningful palaeobiogeographic comparisons, a sub-study was undertaken in which Albian-Cenomanian samples from the Cauvery Basin were quantitatively compared with coeval sections from onshore Europe (SE France: Col de Pré Guittard Section, Mont Risou Section; S. England: BGS Selborne 1 & 2 boreholes, Folkestone-Warren Section) and the Pacific Ocean (Hole 1213A, 17R–21R; 1214A, 7R–10R; 1207B, 25R–27R, ODP Leg 178, Shatsky Rise) (Kanungo, 2005). The Cauvery Basin nannofloras are very similar to those of Europe and the Pacific region with the majority of taxa (85–90%) showing cosmopolitan distribution across these regions. This indicates low provinciality during the mid-Cretaceous (Albian-Cenomanian) interval, an observation that has also been confirmed by other studies, e.g., Bown (2001) and Gale et al. (2011).

The term 'Austral' in this work refers to a southern high-latitude province recognised in the distribution of Cretaceous nannofossils (e.g., Watkins et al., 1996; Street and Bown, 2000; Lees, 2002). In general, high-latitude nannofossil assemblages typically show lower diversities than low-latitudes (Panera, 2012), but more specifically there are around three or four species/taxa that are reported to have exclusively Austral distribution during the Albian-Cenomanian interval (e.g., *S. falklandensis*, *Z. kerguelenensis*). The Cauvery Basin assemblages exhibit a high-latitude character, evidenced by the consistent and common occurrence of *Repagulum parvidentatum* and *Seribiscutum primitivum*, though more pronounced in the lower Albian to lower Cenomanian section. Both of these taxa are well-known for their bipolar, high-latitude distribution in Boreal and Austral latitudes (Roth and Bowdler, 1981; Wise, 1983; Mutterlose, 1992; Watkins et al., 1996; Street and Bown, 2000; Lees, 2002; McAnena et al., 2013, Kanungo et al., 2018). These two taxa gradually become rare and sporadically distributed towards the upper part of the studied section (middle Cenomanian to lower Turonian) and can be related to the late Cenomanian-late Turonian warming phase in the Indian Ocean, which resulted in a southern shift in the Austral palaeobiogeographic zone (Lees, 2002). GPlates palaeogeographic reconstructions show that the palaeolatitudinal position of the Cauvery Basin did not change significantly through the study interval, being 45º45'S in the middle Albian (106 Ma), and 43º45'S in the early Turonian (93 Ma) (Matthews et al., 2016). The consistent presence of *Gartnerago* spp. (*G. chiasta*, *G. theta*, *G. segmentatum*) and *Octocyclus reinhardtii* is a further indication of the high-latitude character of these assemblages (e.g., Thierstein, 1981; Watkins et al., 1996; Lees, 2002).

Two additional species, *Sollasites falklandensis* and *Zeugrhabdotus kerguelenensis*, have been recognised as exclusively Austral taxa (Wise and Wind, 1977; Wise, 1983; Bralower and Siesser, 1992; Herrle and Mutterlose, 2003; Panera, 2011), but they are rare in the Karai and Garudamangalam sections. *Sollasites falklandensis* is found in just one sample (very rare) at Karai and *Zeugrhabdotus kerguelenensis* is sporadically found at Garudamangalam. *S. falklandensis* was previously reported from the Dalmiapuram Grey Shale of the Cauvery Basin (Bralower et al., 1993) and the southeastern Indian Ocean (Bralower et al., 1993). *Z.*

kerguelenensis, was initially described as a high-latitude species (Huber and Watkins, 1992; Watkins et al., 1996) but later shown to be an Austral-Temperate taxon (Lees, 2002). Nevertheless, it is dominantly an Austral taxon. The very rare occurrence of these taxa along with the absence of other southern high-latitude taxa (e.g., *G. nanum*, *C. naturalisteplateauensis*) indicate a relatively muted Austral character to the Cauvery nannofloras, with the assemblages dominated by cosmopolitan taxa, and likely reflecting the moderately high-latitude setting of the basin during the mid-Cretaceous interval.

A number of notable absences in the assemblages are also palaeobiogeographically informative, including the Boreal taxa such as *Braloweria boletiformis*, *Ceratolithina bicornuta*, and *Tegulalithus tessellatus* (Crux 1991; Bown et al., 1998). The absence of *Ceratolithina* spp. (*C. copis, C. duplex, C. naturalisteplateauensis*) is perplexing because the genus has been reported from a number of Indian Ocean sites (Lees, 2002). The Tethyan, neritic-adapted genus, *Nannoconus* (Street and Bown, 2000) is also absent, but has been reported from the basin previously. *Nannoconus* (*N. regularis* and *N. truittii*) is reported in quarry samples, but not from the Karai-Kulakkalnattam and Garudamangalam outcrops (Jafar and Rai, 1989; Kale and Phansalkar, 1992a, b; Kale et al., 2000). Similarly, the neritic taxon, *Braarudosphaera* (Roth and Bowdler, 1981; Siesser et al; 1992; Kelly et al., 2003) is found in just one sample. The near absence of *Braarudosphaera* and *Nannoconus* supports a more outer neritic palaeobathymetry for the Karai Fm., an observation consistent with benthic foraminifera indicators (Nagendra et al., 2013).

6. Conclusions

1. Using the nannofossil zonation schemes of Bown et al. (1998) and Burnett (1998), the age of two new Karai Fm. sections is established. The Karai Section is shown to be early Albian (BC23 NF Zone) to early Turonian (UC6b NF Subzone) in age. The stratigraphic range of the Garudamangalam Section is shorter, ranging from late Albian (BC27a Subzone) to late Cenomanian (UC3e Subzone).

2. Overall, the applied nannofossil zonation schemes offer higher stratigraphic resolution than earlier schemes, as they offer additional secondary markers/events that are applicable in the Karai Fm. (e.g., FO of *G. praeobliquum*, LO of *E. paragogus*, LO of *Z. xenotus*). The Albian (BC) zones of Bown et al. (1998) are all recognisable, whereas, the Cenomanian (UC) zones of Burnett (1998) are only partially applicable. Zones UC2 (FO of *G. segmentatum*) and UC4 (FO of *C. biarcus*) were not recognised. Several subzones are, similarly, difficult to recognise, due to the rarity of markers (UC0c Subzone, FO of *C. anfractus*), or inconsistencies in their stratigraphic order (e.g., UC1b Subzone, LO of *W. britannica*), with respect to the zonation scheme of Burnett (1998).

3. Two NF Zones, UC2 (lower Cenomanian, FO of *G. segmentatum*) and UC4 (upper Cenomanian, FO of *C. biarcus*) are rendered unusable as zonal index markers. The applicability of these markers is considered to be problematic due to their rarity or inconsistency, rather than there being significantly missing stratigraphy in the basin.

4. The application of *C. kennedyi* as a reliable indicator of the lower Cenomanian is considered questionable due to a discrepancy observed in its first occurrence (FO) with respect to the FO of lower Cenomanian ammonite fauna of the *M. mantelli* Zone at Karai

and Garudamangalam. This could, in part, be related to the non-preservation of ammonites at key intervals in the basin, causing some of the observed mismatches between the ammonite and nannofossil zones.

5. The Albian-Cenomanian boundary interval appears to be continuous with the base of the Cenomanian placed a short distance beneath the first Cenomanian ammonites of the *M. mantelli* Ammonite Zone, which lies close to 341.5 m at Karai, and around 53 m at Garudamangalam. The utility of additional bioevents such as the FO of *G. ponticula* (proposed here as a new nannofossil proxy for the boundary), FO of *G. chiasta*, and the LO of *E. paragogus* is helpful in delineating the boundary.

6. The Cenomanian-Turonian boundary interval is incomplete, indicated by the clustered last occurrences of *A. albianus*, *H. chiastia* and *L. acutus.* A hiatus equivalent to Zone UC5 is present at Karai, representing ~0.66 Myrs.

7. The nannoplankton assemblages are composed of broadly cosmopolitan taxa, despite the high-latitude setting of southeastern India during the mid-Cretaceous. An Austral character is indicated by the common and consistent presence of bipolar taxa such as *R. parvidentatum* and *S. primitivum*, especially within the lower Albian to lower Cenomanian section. The dominance of these two taxa gradually decreases by the Turonian, most likely in response to peak warming and a southern shift of the Austral province. The palaeobiogeographic affinity of the assemblages, however, does not bear a

strong Austral stamp, as typical Austral taxa (e.g., *S. falklandensis*, *Z. kerguelenensis*) are very rare in the studied sections.

8. The early appearance of *C. hayi* in the early Albian, and *G. segmentatum* in the late Albian in the Cauvery Basin suggests that these two species may have originated in southern high-latitudes before migrating to northern regions.

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Data Availability: Nannofossil distribution charts of the Karai and Garudamangalam sections, which constitute the principal datasets of this study can be accessed through the Mendeley database (https://data.mendeley.com/datasets/yzrmmrd2dj/draft?a=e99ad7d2-74de-4bb5-8e5a-caba5ed84753).

Supplementary Material: Appendix A (NF sample/slide list), Appendix B (Taxonomic list).

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Table Captions (4 tables)

Table 1. Nannofossil zone and subzone markers recognised in the Karai Section, Karai Fm. (in stratigraphic order).

Table 2. Nannofossil zone and subzone markers recognised in the Garudamangalam Section, Karai Fm. (in stratigraphic order).

Table 3. Summary (presence/absence) of Cenomanian zone and subzone markers in the Karai and Garudamangalam sections, Cauvery Basin, compared with their occurrences reported in Burnett (1998) and Lees (2002).

Table 4. Relative stratigraphic order of nannofossil events around the Albian-Cenomanian boundary interval in the Cauvery Basin and Mont Risou GSSP in SE France (Gale et al., 1996).

Figures Captions (10 figures, Figures 1–3 and Figure 9a, b are in colour)

Figure 1. Location map of (A) Cauvery Basin, and (B) Karai and Garudamangalam sections (Pondicherry Sub-Basin) in Tamil Nadu, SE India.

Figure 2. Lithostratigraphic division and stratigraphic position of the Uttatur Group and Karai Fm., onshore Cauvery Basin, SE India (modified after Paranjape et al., 2015).

Figure 3. Palaeogeographic reconstruction of the Cauvery Basin in the middle Albian (106 Ma) and early Turonian (93 Ma) using GPlates (Matthews et al., 2016).

Figure 4. Nannofossil species recorded in the Karai Fm., Karai and Garudamangalam sections (scale bar 2 µm). 1, *Chiastozygus litterarius*, sample KA377.5 (KA377.5-NF/SK). 2, *Chiastozygus platyrhethus*, sample KA314.5 (KA314.5-NF/SK). 3–5, *Chiastozygus spissus*, sample GM72.5, (GM72.5-NF/SK). 6–7, *Chiastozygus trabalis*, sample GM102.5 (GM102.5-NF/SK). 8, *Loxolithus armilla*, sample KA350.5 (KA350.5-NF/SK). 9–12, *Loxolithus bicyclus*, n. sp., (9) HOLOTYPE, (11) PARATYPE, 11–12 same specimen, sample GM101 (GM101-NF/SK). 13–14, *Staurolithites* cf. *S. angustus*, sample KA171 (KA171-NF/SK). 15–16, *Staurolithites laffittei*, sample KA 445.7 (KA445.7-NF/SK). 17–18, *Staurolithites mutterlosei*, sample KA287.5 (KA287.5-NF/SK). 19, *Staurolithites gausorhethium*, sample GM62 (GM62-NF/SK). 20, *S. gausorhethium*, sample GM3.5 (GM3.5-NF/SK). 21–22, *Eiffellithus paragogus*,

sample GM56 (GM56-NF/SK). 23–25, *Staurolithites* sp., sample GM75.5 (GM75.5-NF/SK). 26, *Tranolithus orionatus*, sample KA157.5 (KA157.5-NF/SK). 27–29, *Tranolithus simplex*, n. sp., (27) HOLOTYPE, sample KA373, (KA373-NF/SK). 30–32, *T. simplex*, n. sp., (30) PARATYPE, sample GM37 (GM37-NF/SK). 33, *Tranolithus gabalus*, sample KA157.5 (KA157.5-NF/SK). 34, *Zeugrhabdotus bicrescenticus*, sample KA445.7 (KA445.7-NF/SK). 35, *Zeugrhabdotus diplogrammus*, sample KA373 (KA373-NF/SK). 36–37, *Zeugrhabdotus kerguelenensis* (side view), sample GM65 (GM65-NF/SK). 38–39, *Zeugrhabdotus* cf. *Z. embergeri*, sample GM81.5 (GM81.5-NF/SK). 40, *Zeugrhabdotus howei*, sample KA469.1 (KA469.1-NF/SK). 41, *Z. howei*, sample KA445.7 (KA445.7-NF/SK). 42, *Zeugrhabdotus noeliae*, sample KA157.5 (KA157.5-NF/SK).

Figure 5. Nannofossil species recorded in the Karai Fm., Karai and Garudamangalam sections (scale bar 2 µm). 1, *Zeugrhabdotus noeliae*, sample KA157.5 (KA157.5-NF/SK). 2–3, *Zeugrhabdotus xenotus*, sample KA287.5 (KA287.5-NF/SK). 4, *Amphizygus brooksii*, sample KA428.5 (KA428.5-NF/SK). 5, *Eiffellithus gorkae*, sample KA469.1 (KA469.1-NF/SK). 6, *Eiffellithus turriseiffelii*, sampleGM19 (GM19-NF/SK). 7–8, *Eiffellithus vonsalisiae*, sample GM113 (GM113-NF/SK). 9–11, *Eiffellithus monechiae*, sample KA180 (KA180-NF/SK). 12–13, *Zeugrhabdotus clarus*, sample GM31 (GM31-NF/SK). 14, *Helicolithus compactus*, sample KA464.2 (KA464.2-NF/SK). 15, *Helicolithus trabeculatus*, sample KA180 (KA180-NF/SK). 16, *Tegumentum stradneri*, sample GM49 (GM49-NF/SK). 17, *Percivalia fenestrata*, sample GM22 (GM22-NF/SK). 18, *P. fenestrata*, sample GM86 (GM86-NF/SK). 19–20, *Rhagodiscus achlyostaurion*, sample GM56 (GM56-NF/SK). 21, *Rhagodiscus asper*, sample KA445.7 (KA445.7-NF/SK). 22–23, *R. asper* (large), sample KA22.5 (KA22.5-NF/SK). 24, *Rhagodiscus*

infinitus, sample KA153 (KA153-NF/SK). 25–26, *Rhagodiscus hamptonii*, sample GM28 (GM28-NF/SK). 27, *Rhagodiscus gallagheri*, sample KA445.7 (KA445.7-NF/SK). 28, *R. gallagheri*, sample GM10 (GM10-NF/SK). 29, *Rhagodiscus reniformis*, sample GM113 (GM113-NF/SK). 30, *Rhagodiscus splendens*, sample KA459.3 (KA459.3-NF/SK). 31–32, *Corollithion kennedyi*, sample GM96.5 (GM96.5-NF/SK). 33–34, *Helicolithus leckiei*, sample GM113 (GM113-NF/SK). 35, *Corollithion exiguum*, sample KA459.3 (KA459.3-NF/SK). 36, *Corollithion protosignum*, sample KA135 (KA135-NF/SK). 37, *Corollithion signum*, sample GM59 (GM59-NF/SK). 38–39, *Rotelapillus laffittei*, sample KA459.3 (KA459.3-NF/SK). 40, *Stoverius achylosus*, sample KA464.2 (KA464.2-NF/SK). 41–42, *Cylindralithus biarcus*, sample KA464.2 (KA464.2-NF/SK).

Figure 6. Nannofossil species recorded in the Karai Fm., Karai and Garudamangalam sections (scale bar 2 µm). 1, *Cylindralithus nudus*, sample KA305.5 (KA305.5-NF/SK). 2, *C. nudus* (side view), sample GM62 (GM62-NF/SK). 3–4, *Cylindralithus sculptus*, sample KA445.7 (KA445.7-NF/SK). 5–6, *Cylindralithus serratus*, sample GM78.5 (GM78.5-NF/SK). 7–8, *Axopodorhabdus albianus*, sample KA180 (KA180-NF/SK). 9–10, *Cribrosphaerella ehrenbergii*, sample GM59 (GM59-NF/SK). 11–12, *Hemipodorhabdus* cf. *H. gorkae*, sample GM37 (GM37-NF/SK). 13, *Tetrapodorhabdus decorus*, sample KA 445.7 (KA445.7-NF/SK). 14, *Octocyclus reinhardtii*, sample KA469.1 (KA469.1-NF/SK). 15, *Biscutum constans*, sample KA445.7 (KA445.7-NF/SK). 16, *B. constans* (large), sample GM113 (GM113-NF/SK). 17, *Seribiscutum primitivum*, sample GM0 (GM0-NF/SK). 18, *S. primivitum*, sample KA433 (KA433-NF/SK). 19–20, *Crucibiscutum hayi*, sample GM0 (GM0-NF/SK). 21–22, *Sollasites falklandensis*, sample KA22.5 (KA22.5-NF/SK). 23, *Prediscosphaera columnata* (small, circular), sample KA180

(KA180-NF/SK). 24, *P. columnata* (subcircular), sample GM81.5 (GM81.5-NF/SK). 25, *P. columnata* (large), sample GM89 (GM89-NF/SK). 26, *Prediscosphaera cretacea*, sample GM102.5 (GM102.5-NF/SK). 27–28, *Prediscosphaera* cf. *P. ponticula*, sample GM113 (GM113-NF/SK). 29, *Prediscosphaera spinosa*, sample GM113 (GM113-NF/SK). 30, *P. spinosa*, sample GM53 (GM53-NF/SK). 31, *Cretarhabdus conicus*, sample KA457.4 (KA457.4-NF/SK). 32, *Cretarhabdus striatus*, sample KA323.5 (KA323.5-NF/SK). 33–35, *Cretarhabdus multicavus*, sample GM19 (GM19-NF/SK). 36, *Flabellites oblongus*, sample KA85.5 (KA85.5-NF/SK). 37, *Helenea chiastia*, sample KA368.5 (KA368.5-NF/SK). 38–39, *Retecapsa* cf. *R. angustiforata*, sample KA448.9 (KA448.9-NF/SK). 40, *Retecapsa surirella*, sample GM72.5 (GM72.5-NF/SK). 41, *Tubodiscus burnettiae*, sample KA85.5 (KA85.5-NF/SK). 42, *Manivitella pemmatoidea*, sample KA274 (KA274-NF/SK).

Figure 7. Nannofossil species recorded in the Karai Fm., Karai and Garudamangalam sections (scale bar 2 µm). 1, *Manivitella fibrosa*, n. sp., sample K274 (KA274-NF/SK). 2, *M. fibrosa*, n. sp., HOLOTYPE, sample KA278.5 (KA278.5-NF/SK). 3, *M. fibrosa*, n. sp., sample GM65 (GM65-NF/SK). 4, *M. fibrosa*, n. sp., PARATYPE, sample KA391 (KA391-NF/SK). 5–6, *M. fibrosa*, n. sp., sample KA292 (KA292-NF/SK). 7, *Watznaueria barnesiae*, sample KA451.9 (KA451.9-NF/SK). 8, *Watznaueria biporta*, sample KA469.1 (KA469.1-NF/SK). 9, *Watznaueria britannica*, sample GM49 (GM49-NF/SK). 10, *Watznaueria ovata*, sample GM65 (GM65-NF/SK). 11–12, *Broinsonia enormis*, sample KA 451.9 (KA451.9-NF/SK). 13–14, *Broinsonia galloisii*, GM22 (GM22-NF/SK). 15–16, *Broinsonia matalosa*, sample KA386.5 (KA386.5-NF/SK). 17–19, *Gartnerago stenostaurion*, sample KA292 (KA292-NF/SK). 20–22, *Broinsonia* cf. *B. viriosa*, sample KA85.5 (KA85.5-NF/SK). 23, *Crucicribrum anglicum*, sample KA220,

(KA220-NF/SK). 24–25, *Gartnerago chiasta*, sample GM46 (GM46-NF/SK). 26–27, *Gartnerago praeobliquum,* sample GM3.5 (GM3.5-NF/SK). 28, *Gartnerago segmentatum*, sample KA469.1 (KA469.1-NF/SK). 29, *G. segmentatum*, sample GM89 (GM89-NF/SK). 30–31, *Gartnerago ponticula*, sample GM89 (GM89-NF/SK). 32, *G. ponticula*, sample KA400, (KA400-NF/SK). 33–34, *Gartnerago theta*, sample GM56 (GM56-NF/SK). 35, *Laguncula dorotheae*, sample KA180 (KA180-NF/SK). 36, *Laguncula* cf. *L. montrisouensis* (top right), sample KA22.5 (KA22.5-NF/SK). 37, *Repagulum parvidentatum*, sample GM81.5 (GM81.5-NF/SK). 38–39, *Calculites percernis*, sample KA445.7 (KA445.7-NF/SK). 40–42, *Calculites karaiensis*, n. sp., sample KA459.3 (KA459.3-NF/SK).

Figure 8. Nannofossil species recorded in the Karai Fm., Karai and Garudamangalam sections (scale bar 2 µm). 1–2, *Calculites karaiensis*, n. sp., (1) HOLOTYPE, sample KA459.3 (KA459.3-NF/SK). 3–5, *C. karaiensis*, n. sp., sample KA459.3 (KA459.3-NF/SK). 6–8, *C. karaiensis*, n. sp., (6) PARATYPE, sample KA459.3 (KA459.3-NF/SK). 9, *Lapideacassis glans*, sample KA428.5 (KA428.5-NF/SK). 10, *Lapideacassis* cf. *L. cornuta*, sample KA469.1 (KA469.1-NF/SK). 11–12, *Lithraphidites acutus*, sample KA404.5 (KA404.5-NF/SK). 13, *Lithraphidites carniolensis*, sample KA368.5 (KA368.5-NF/SK). 14–15, *Lithraphidites pseudoquadratus*, sample GM102.5 (GM102.5-NF/SK). 16, *Microrhabdulus belgicus*, sample KA459.3 (KA459.3-NF/SK). 17, *Microrhabdulus decoratus*, sample KA 448.9 (KA448.9-NF/SK). 18, *Eprolithus floralis*, sample KA319 (KA319-NF/SK). 19, *E. floralis*, sample KA445.7 (KA445.7-NF/SK). 20, *E. floralis*, sample KA424 (KA424-NF/SK). 21, *E. floralis* (side view), sample KA305.5 (KA305.5-NF/SK). 22, *Eprolithus* spp. (side view), sample KA469.1 (KA469.1-NF/SK). 23, *Eprolithus* spp. (side view), sample KA459.3 (KA459.3-

NF/SK). 24, *Eprolithus octopetalus,* sample KA448.9 (KA448.9-NF/SK). 25, *E. octopetalus*, sample KA464.2 (KA464.2-NF/SK). 26, *Eprolithus moratus*, sample KA451.9 (KA451.9-NF/SK). 27, *E. moratus*, sample KA464.2 (KA464.2-NF/SK). 28, *Radiolithus planus*, sample KA424 (KA424-NF/SK). 29, *Radiolithus* cf. *R. planus*, sample GM46 (GM46-NF/SK). 30, *Quadrum octobrachium*, sample KA448.9 (KA448.9-NF/SK). 31, *Q. octobrachium*, sample KA451.9 (KA451.9-NF/SK). 32–34, *Quadrum eneabrachium*, sample KA448.9 (KA448.9-NF/SK). 35, *Hayesites albiensis*, sample KA58.5 (KA58.5-NF/SK). 36–37, *H. albiensis*, sample KA63 (KA63-NF/SK). 38–39, *Hayesites irregularis*, sample KA4.5 (KA4.5-NF/SK). 40–42, *Braarudosphaera* cf. *B. africana*, sample GM28 (GM28-NF/SK).

Figure 9 (a). Summary of biostratigraphic zones and nannofossil/macrofossil events in the Karai Section, Cauvery Basin.

Figure 9 (b). Summary of biostratigraphic zones and nannofossil/macrofossil events in the Garudamangalam Section, Cauvery Basin.

Figure 10. Age-depth plots showing approximate sedimentation rates of **(a)** Karai Section, (**b)**. Garudamangalam Section, Cauvery Basin.