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Cretaceous climate oscillations in the southern palaeolatitudes: New stable isotope evidence from India and Madagascar

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A R T I C L E I N F O

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A B S T R A C T

Palaeotemperatures for the Cretaceous of India and Madagascar have been determined on the basis of oxygen isotopic analysis of well-preserved Albian belemnite rostra and Maastrichtian bivalve shells of from the Trichinopoly district, southern India, and Albian nautiloid and ammonoid cephalopods from the Mahajang Province, Madagascar. The Albian (possibly late Albian) palaeotemperatures for Trichinopoly district are inferred to range from 14.9 °C to 18.5 °C for the epipelagic zone, and from 14.3 °C to 15.9 °C for the mesopelagic zone, based on analyses of 65 samples; isotopic palaeotemperatures interpreted as summer and winter values for near-bottom shelf waters in this area fluctuate from 16.3 to 18.5 °C and from 14.9 to 16.1 °C, respectively. The mentioned palaeotemperatures are very similar to those calculated from isotopic composition of middle Albian belemnites of the middle latitude area of Pas-de-Calais in Northern hemisphere but significantly higher than those calculated from isotopic composition of Albian belemnites from southern Argentina and the Antarctic and middle Albian belemnites of Australia located within the warm-temperate climatic zone. Isotopic analysis of early Albian cephalopods from Madagascar shows somewhat higher palaeotemperatures for summer near-bottom shelf waters in this area (20.2–21.6 °C) in comparison with late Albian palaeotemperatures calculated from southern India fossils, but similar winter values (13.3–16.4 °C); however, the latter values are somewhat higher than those calculated from early Albian ammonoids of the tropical–subtropical climatic zone of the high latitude area of southern Alaska and the Koryak Upland. The new isotopic palaeotemperature data suggest that southern India and Madagascar were located apparently in middle latitudes (within the tropical–subtropical climatic zone) during Albian time. In contrast to the Albian fossils, isotope results of well-preserved early Maastrichtian bivalve shells from the Ariyalur Group, Trichinopoly district, are characterised by lower $\delta^{18}O$ values (up to −5.8‰) but normal $\delta^{13}C$ values, which might be a result local freshwater input into the marine environment. Our data suggest that the early Maastrichtian palaeotemperature of the southern Indian near-bottom shelf waters was probably about 21.2 °C, and that this middle latitude region continued to be a part of tropical–subtropical climatic zone, but with tendency of increasing of humidity at the end of Cretaceous time.

1. Introduction

The palaeoclimatic and palaeogeographic reconstruction of the Indian plate during the late Palaeozoic–early Mesozoic is of considerable interest because of the location of India in the Southern hemisphere in that time (e.g., Clarke and Jenkyns, 1999; MacLeod and Huber, 2001; Wilson and Norris, 2001; Huber et al., 2002; Price and Hart, 2002; Petrizzo and Huber, 2006). According to Hay et al. (1999), in the Early Cretaceous there are three large continental blocks with shallow seas: (1) North America–Eurasia, (2) South America–Antarctica–India–Madagascar–Australia, and (3) Africa; in the Late Cretaceous India, in their opinion, separated from Madagascar.

Bowen (1961a) attempted a significant palaeotemperature study based on the oxygen-isotopic composition of Cretaceous fossils of southern India. However, his work, probably the first one of its kind to be conducted for the Cretaceous southern India, was

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based on only three "*Belemnites fibula*" (=*Parahibolites blanfordi*) (Doyle, 1985) samples collected from the basal limestone and clays (probably of late Albian age), belonging to the latest Aptian – Coniacian Uttatur Group (e.g., Narayanan, 1977; Ravindran et al., 1995; Tewari et al., 1996; Hart et al., 2001; Watkinson et al., 2007) of the Trichinopoly district, Cauvery Basin. As a result, palaeotemperatures of 21.4°–22.4 °C were calculated, using the biogenic calcite equation of Epstein et al. (1953).

After publication of a paper by Bowen (1961a), some additional data on stable isotope composition of Cretaceous carbonates (Ghosh et al., 1995; Ayyasami, 2006; Gupta et al., 2007) from central and southern India, as well as on diversity of Cretaceous foraminifera of this area (Govindan, 1980) were published, which were used by their authors for palaeoclimatic and palaeogeographic reconstructions. On the basis of these data on oxygen-isotopic composition of benthic and planktic foraminifera from the lower Cenomanian to upper Turonian portion of the Karai Formation of the Cauvery Basin, Gupta et al. (2007) obtained palaeotemperatures of 21–23 °C and 28–29 °C, respectively, which is in agreement with Govindan's (1980) conclusion that Late Cretaceous foraminiferal faunas of the Cauvery Basin, in contrast to Early Cretaceous fauna, are composed of tropical elements of Tethyan affinity.

From all Mesozoic fossils found in Madagascar, only the Late Jurassic (Oxfordian) ammonoid *Perisphinctites* and bivalve *Astarte* have been recently investigated in isotopic respect (Lécuyer and Bucher, 2006).

The present study was carried out with the objectives of (1) obtaining representative oxygen- and carbon-isotope data from the Albian of both southern India and Madagascar and the Maastrichtian of southern India; (2) comparing the new results with previous data from the Cretaceous of India and other middle to high-latitude regions; (3) using the new isotope data for palaeotemperature reconstruction. Our results provide additional records of oxygen isotope compositions of Cretaceous fossils from India. Carbon-isotope composition of Early Cretaceous organogenic carbonates from India has not been recorded earlier. Data on oxygen- and carbon-isotopic composition of Cretaceous fossils from Madagascar have been obtained for the first time.

2. Geological setting and stratigraphy

2.1. Southern India

The Trichinopoly area is situated in the southeastern part of India and is part of the structurally elongated Cauvery Basin located between latitudes 08°30′ and 12°30′N and longitudes 78°30′ and 80°30′E. Cretaceous outcrops are sporadic and present in four places, namely Trichinopoly (=Tiruchirappalli) in the south and Ariyalur, Vridhachalam and Pondicherry in the north along the western margin of the basin. The outcrops in the Trichinopoly area are the largest with an area extent of 400 sq. km, and range in age from Neocomian through Maastrichtian to the Paleocene, representing a total time span of 135–54.8 Ma. The Cretaceous of the Cauvery Basin comprises a complete shallow marine sequence with a very rich faunal succession in Karai, Palimisai, TANCEM Mines and Periya Nagular (TAMIN Mines) localities (Govindan et al., 1998). Biostratigraphy is well-constrained both by megafauna (e.g., Blanford, 1861: Spengler, 1910; Sastri et al., 1977; Fürsich and Pandey, 1999; Sundaram et al., 2001) and the microfaunal remains (Narayanan, 1977; Govindan et al., 1996; Chidambaram, 2000; Hart et al., 2001; Watkinson et al., 2007).

Cretaceous sediments of the Cauvery Basin were first studied and mapped by Blanford (1862). Subsequent investigations include those by Kossmat (1897), Krishnan (1943), Rama Rao (1956), Tewari et al. (1996), Govindan et al. (1996, 1998), Yadagiri and Govindan (2000), Hart et al. (2001), Sundaram et al. (2001), Nagendra et al. (2001, 2002a, 2002b) and Watkinson et al. (2007).

2.2. Northwestern Madagascar

Albian sediments and aragonite ammonoid shells from the *Cleoniceras besairei* Zone (Ambarimaningu Formation) of the Mahajang Province, Madagascar, were first studied by Collignon (1932, 1949, 1950a, 1950b). The ammonites are found in the hard, basal glauconitic sandstone layer, 15–20 cm thick, exposed in a longquarry, which was dug along the escarpment (ammonite bed), above the ammonite bed follows a nearby 15 cm thick layer of dark grey, glauconitic siltstone with gastropods, bivalves and microfossils (microfossil bed) (Kiel, 2006).

3. Material and methods

The macrofossil samples for the isotope analyses in this study were collected from the Trichinopoly area, Cauvery Basin, southern India (R. Nagendra's and Y. Shigeta's coll.) (Fig. 1) and Mahajang Basin, Madagascar (Y. Shigeta's coll.) (Fig. 2). The collections comprise mainly mollusc (bivalves, belemnites and ammonoids) shells.

Most well-preserved material from southern India used for isotopic analysis consisted of: (1) exceptionally well-preserved belemnite rostra from the middle part (Albian) of the Karai Shale Formation of the Trichinopoly district, determined as *Parahibolites blanfordi* (Spengler) and *Tetrabelus* cf. *seclusus* (Blanford) (Fig. 3), and (2) well-preserved bivalve *Lopha* sp. shells from the upper part of the Kallankurichchi Formation (Maastrichtian) of the Trichinopoly.

Investigated early Albian cephalopods from Madagascar consist of one nautiloid species (*Cymatoceras*? sp.) and four ammonoid species – *Cleoniceras besairei* Collignon, *Eotetragonites umbilicostriatus* Collignon, *Desmoceras* sp., and *Douvilleiceras* sp. (Fig. 4).

The following criteria were used in this study to determine diagenetic alteration: (1) visual signs; (2) percentage of aragonite in a skeleton, when the shells were originally represented by 100% aragonite, or presence of diagenetic admixture in both original aragonite or calcite (using X-ray analysis), 3) a degree of integrity of skeleton microstructure, determined under a scanning electron microscope) (SEM) and (4) preliminary metallic-element measurements (using X-ray spectrometer coupled with a SEM to get energy-dispersion X-ray microanalytical (EDX) spectra).

Selected shell samples from our collection were broken into pieces, etched for 8–10 min with 1.0% HCl (with frequent interruptions for visual control – total treatment duration was about 3–6 min, as recommended by Sælen (1989), Podlaha et al. (1998) and Voigt et al. (2003)), and examined with a scanning electron microscope (SEM, EVO 50 XVP) at the Analytical Center of the Far Eastern Geological Institute (FEGI), Vladivostok, in order to obtain textural information and to ascertain the degree of diagenetic alteration.

Samples for our isotopic analyses were carefully removed from the shells and rostra using a special method (Zakharov et al., 2005, 2007a): material was taken by a scalpel mainly from narrow, small areas along growth striations on the external surface of bivalve, nautiloid and ammonoid shells and from successive growth portions in the belemnite rostra, which enabled shell (rostrum) material formed apparently during different seasons of the year to be identified. The same method has been used earlier by some other workers (e.g., Stevens and Clayton, 1971).

Oxygen- and carbon-isotope measurements were carried out using Finnigan MAT-252 mass spectrometer at FEGI, Vladivostok. The laboratory gas standard used in the measurements was

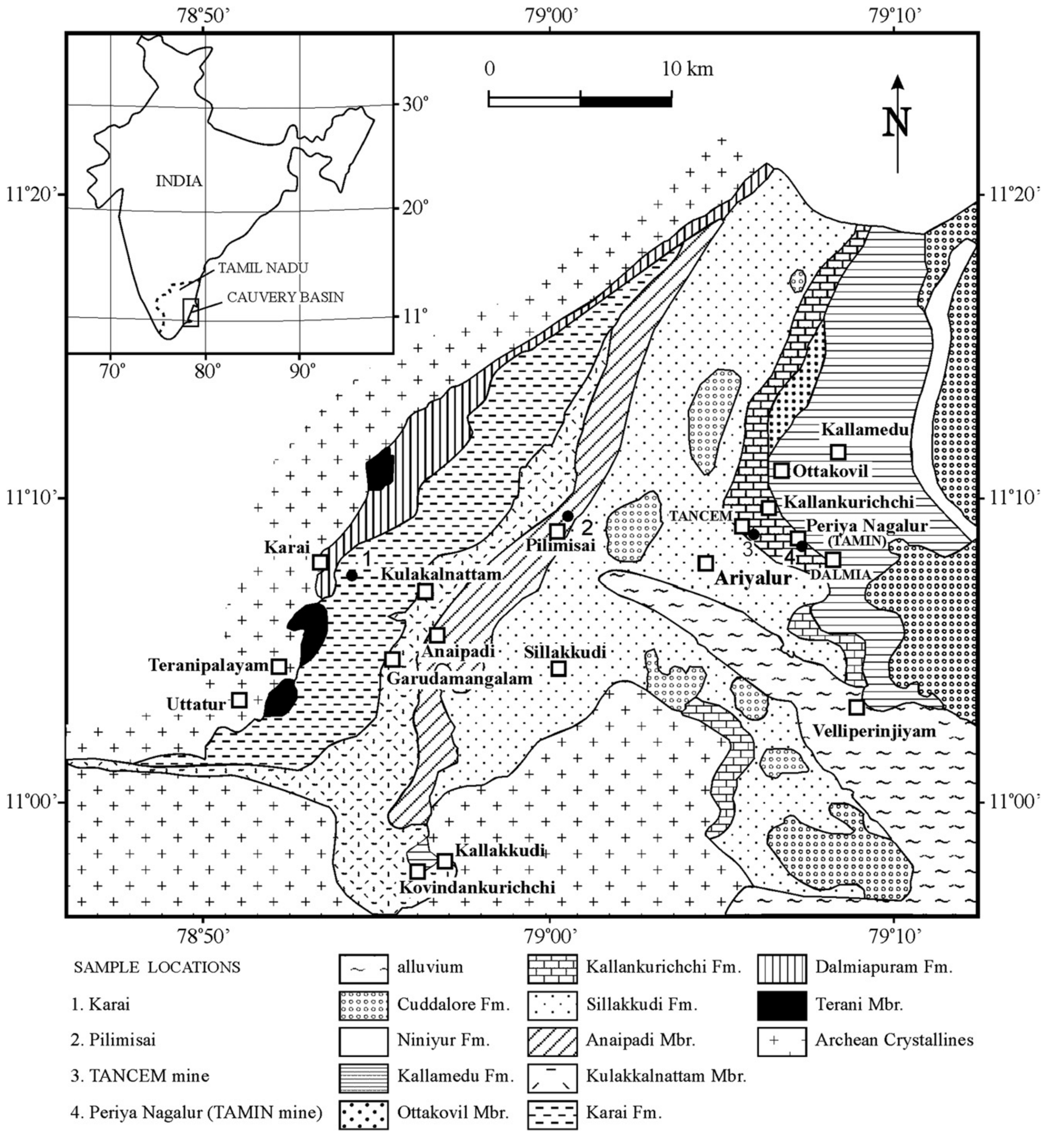

Fig. 1. Location map of Cretaceous outcrops in the Cauvery Basin, southern India (based on Tewari et al., 1996).

calibrated relatively to NBS-19 standard $\delta^{13}C = 1.93‰$ and $\delta^{18}O = -2.20‰$ (Coplen et al., 1983). Reproducibility of replicate standards was always better than 0.1‰. X-ray powder analyses were carried out using a DRON-3 diffractometer also at FEGI, following the method of Davis and Hooper (1963). Elemental concentrations (Na, Mg, Fe etc) were determined by dispersion energy X-ray spectrometer INCA Energy 350 (Oxford) at FEGI (Fig. 5).

SEM and trace element geochemical (EDX spectra) study of Late Albian belemnite rostra and Early Maastrichtian bivalves from Cauvery Basin, Southern India (R. Nagendra's and Y. Shigeta's collections), and early Albian cephalopods from the Mahajang Basin, Madagascar, suggest that all of them, apparently, retain their original texture and oxygen- and carbon-isotopic composition. It was confirmed additionally by X-ray diffraction analysis that shows the lack of secondary admixtures, including α-SiO_2, in the investigated calcitic bivalve shells and belemnite rostra from southern India and almost aragonitic cephalopod shells from Madagascar. Nevertheless, diagenetic alterations cannot be entirely excluded, especially in the apical line area of belemnite

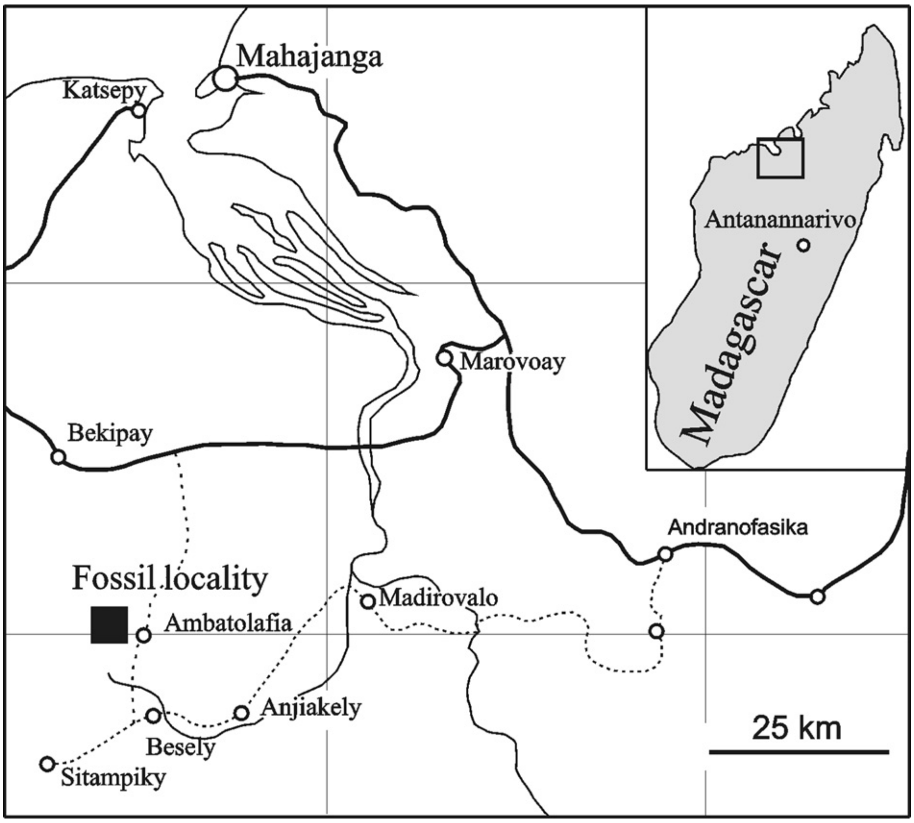

Fig. 2. The early Albian fossil locality in the Mahajanga Basin, northeastern Madagascar (based on Kiel, 2006).

rostra and some portions of oyster bivalve shells, as suggested by the chemical tests.

4. $\delta^{18}O$ and $\delta^{13}C$ values of carbonate fossils

4.1. Southern India

4.1.1. Upper Albian–Coniacian

From the middle part of the Karai Shale Formation of the Trichinopoly area (Fig. 6, point 1) nine belemnite (*Parahibolites blanfordi* and *Tetrabelus* cf. *seclusus*) rostra with well-preserved microstructure were investigated. SEM photographs of belemnite rostra (Figs. 7–9) show that they have the radial and concentric structures, which can be easily recognized in the transverse section. The radial structures have been formed by thin calcite prisms traversing part of the rostrum, except for its central (axle) area, to its outer border (Fig. 7a and b). In the central longitudinal section, the combination of radial and concentric structures in the outlying of the central area part of a rostrum give rise to a wedge-shaped structure, with well-preserved prismatic microstructure (Figs. 7c, 7e, 7f, 8a, 8b and 8c). Thin calcite prisms located within the investigated tooth-like locus (later generation) are oriented almost perpendicular to the selected section, but others (earlier generation) have more obliquity with respect to the section (Fig. 8b, 8c and 9a). The central part of the rostrum located along the apical line is characterised by granular structure (Figs. 7c, 7d, 9b and 9c).

All materials for isotopic investigation were obtained from eight belemnite *Parahibolites blanfordi* rostra (In-10a (57 samples), In-10b (two samples), In-10c (two samples), In-10d (two samples), In-10e (two samples), In 11 (one sample), In-12 (one sample) and In-15 (one sample)) and a single belemnite *Tetrabelus* cf. *seclusus* rostrum (In-14 (one sample). All of them (69 samples) are represented by original calcite without any α-SiO_2 admixture (Table 1). EDX spectra show that only a minor diagenetic alteration has been documented. Relatively high values for Fe (0.19–0.24 weight %) for belemnite rostrum In-10b analyzed were found only within two points in its central part (near apical line) (Fig. 5). In two other points, located at the outlying part of rostrum, relatively high values for Na (0.27–0.28%) and Mg (0.31–0.37%) but not for Fe were discovered. However all parts of the belemnite rostra, including portions located near their apical line area, seem to be non-luminescent.

$\delta^{18}O$ and $\delta^{13}C$ values for late Albian belemnite rostra from the Bad Land locality (Karai) of the Trichinopoly area vary between −1.7 and −0.6‰ and +0.1 and +1.3‰, respectively (Fig. 10; Table 1).

No undoubted morphological indicators, corresponding to the warmest or coldest seasons, for Cretaceous belemnites from the Trichinopoly area, as well as oyster bivalves from the same area, have been found, therefore their individual age was determined in question using only detailed data on ontogenetic fluctuation of $\delta^{18}O$ and $\delta^{13}C$ values in their skeleton.

The relationship of $\delta^{18}O$ with $\delta^{13}C$ values in the belemnite *Parahibolites blanfordi* was investigated in the sample In-10a. $\delta^{18}O$ values of this sample were found to be weakly correlatable with $\delta^{13}C$ through its early ontogenetic stage but strongly correlatable with $\delta^{13}C$ during its late ontogenetic stage (Fig. 11).

The possible Late Albian or Cenomanian ammonite *Desmoceras latidorsatum* (Michelin) and Coniacian ammonites *Damesites sugata* (Forbes), *Kossmaticeras* sp., *Pachydiscoides* sp. from the Pilimisai River section (Fig. 6, point 2) are characterised by calcitised shells and therefore they have not been used for isotopic analyses.

4.1.2. Maastrichtian

Well-preserved mollusc shells from the lower Maastrichtian level of the Kallankurichchi Formation of the TAMIN Mines and Periya Nagular (Trichinopoly area) include those of the oyster *Lopha*

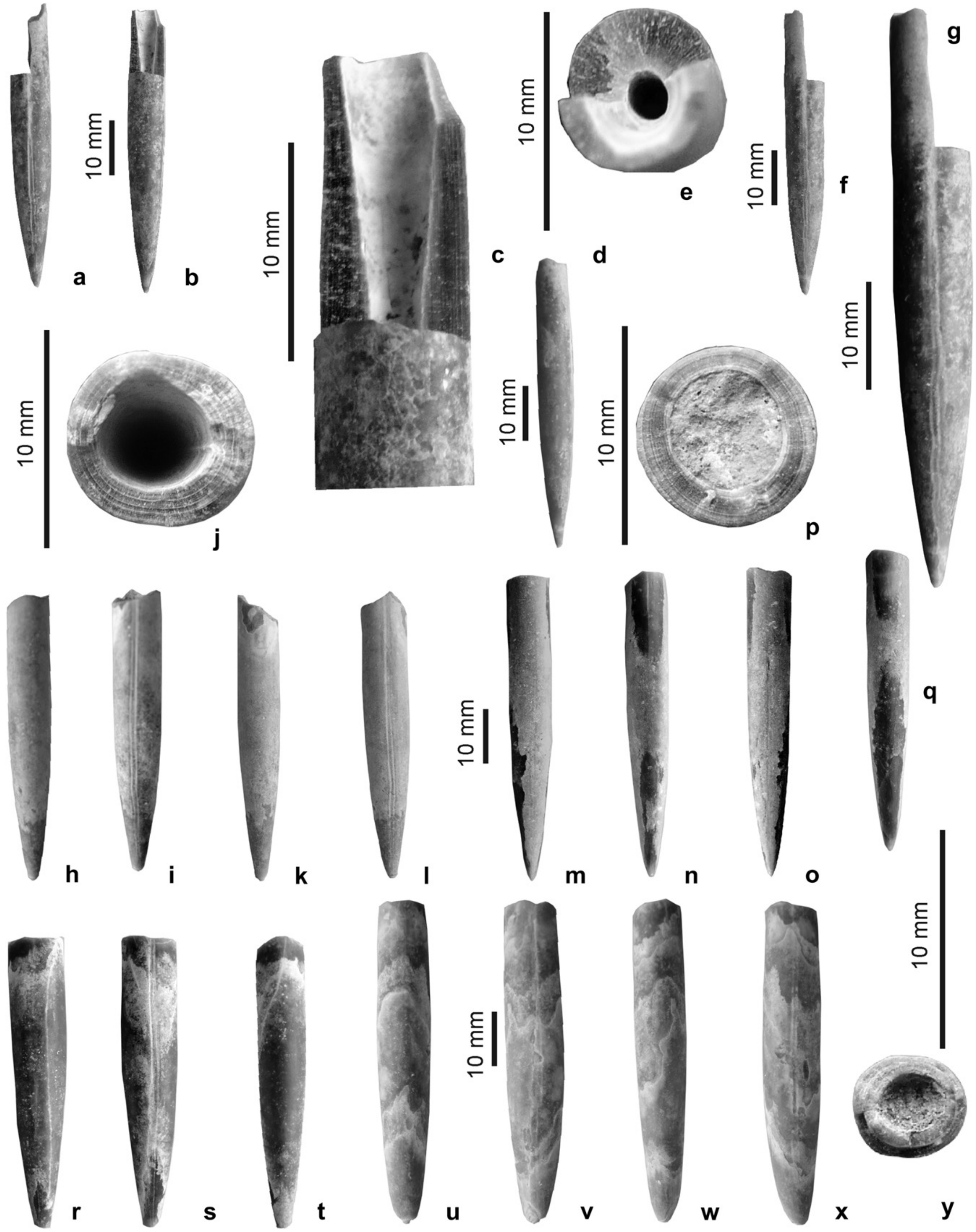

Fig. 3. Investigated belemnite rostra from the Albian of the Cauvery Basin, southern India (Y. Shigeta's collection). a–t and y – *Parahibolites blanfordi* (Spengler): a–g – specimen In-11, h–l – specimen In-12, m–q – specimen In-13, r–t and y – specimen In-15. u–x – *Tetrabelus* cf. *seclusus* (Blanford), specimen In-14.

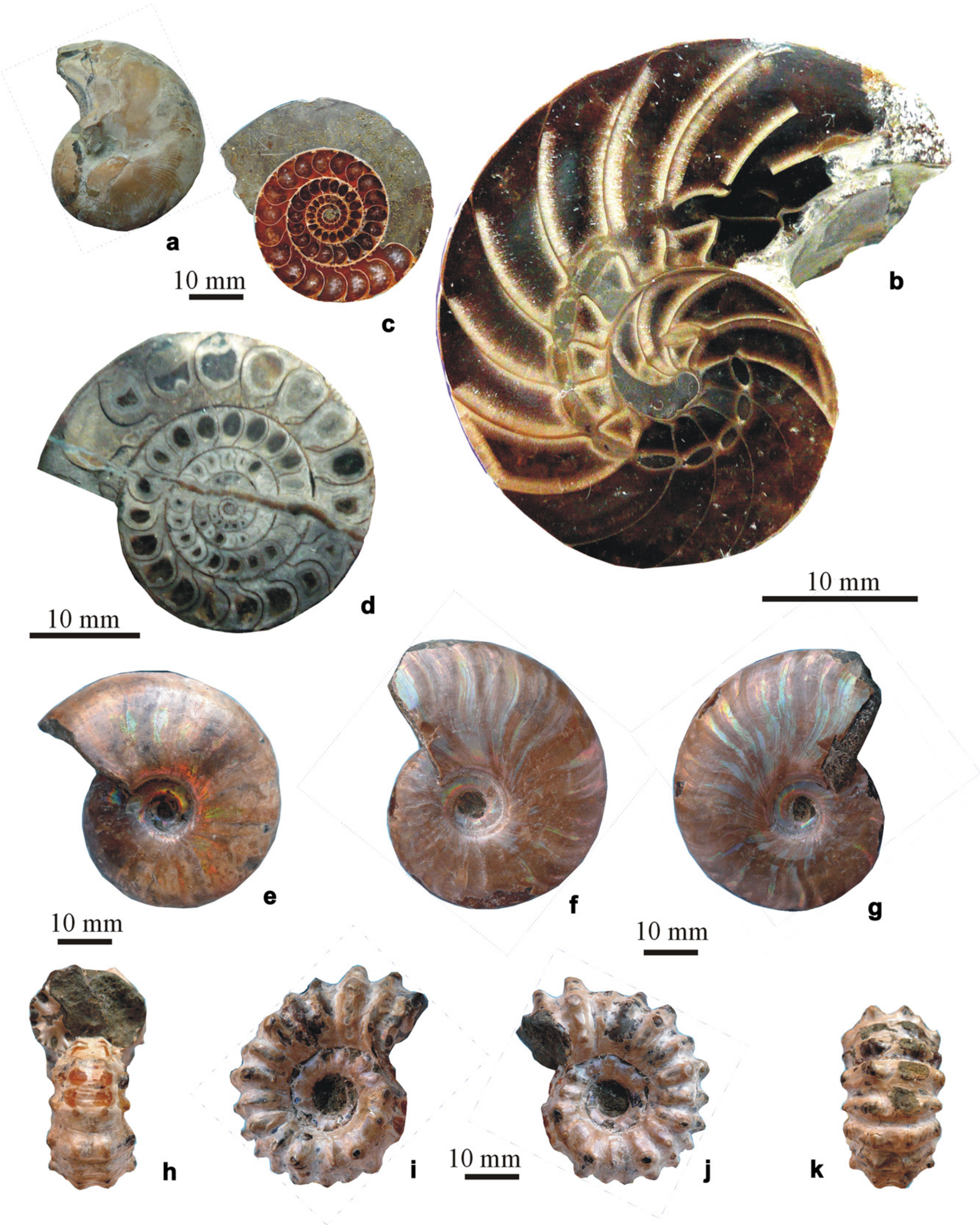

Fig. 4. Investigated cephalopod shells from the Lower Albian of the Mahajanga Basin. a–b – *Cymatoceras*? sp. (specimen M-1), c–d – *Eotetragonites unbilicostriatus* Collignon: c – specimen M-2, d – specimen M-2a, e – *Desmoceras* sp. (specimen M-4), f–g – *Cleoniceras besairei* Collignon (specimen M-5), h–k – *Douvilleiceras* sp. (specimen M-5) (Y. Shigeta's collection).

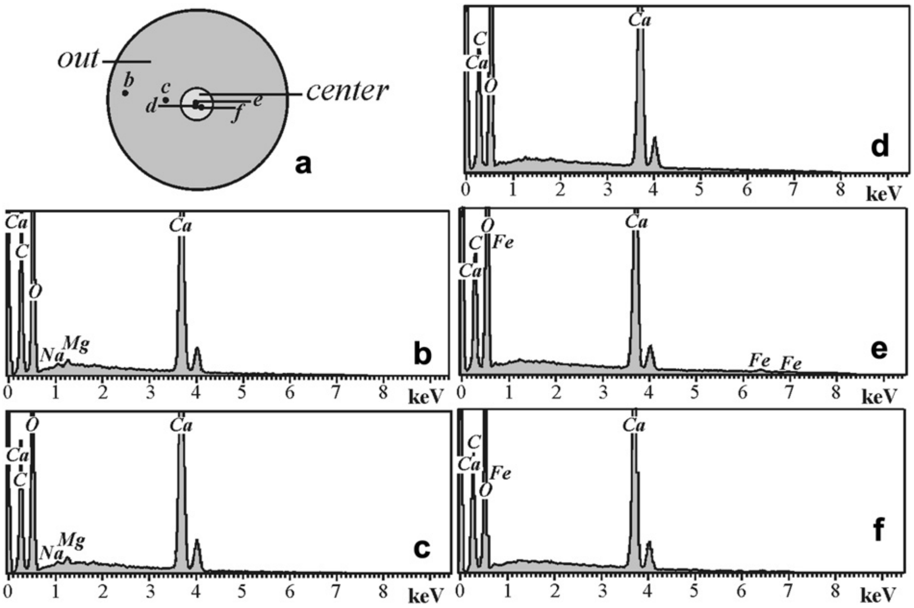

Fig. 5. Geochemical spectra from the belemnite rostrum In-10b. a – location of points investigated (d–f) in the rostrum cross-section, b–c – geochemical profiles for the outlying of the central area part of the rostrum, d–f – geochemical spectra for the central (near apical line) part of the rostrum. Other abbreviations as in Fig. 5.

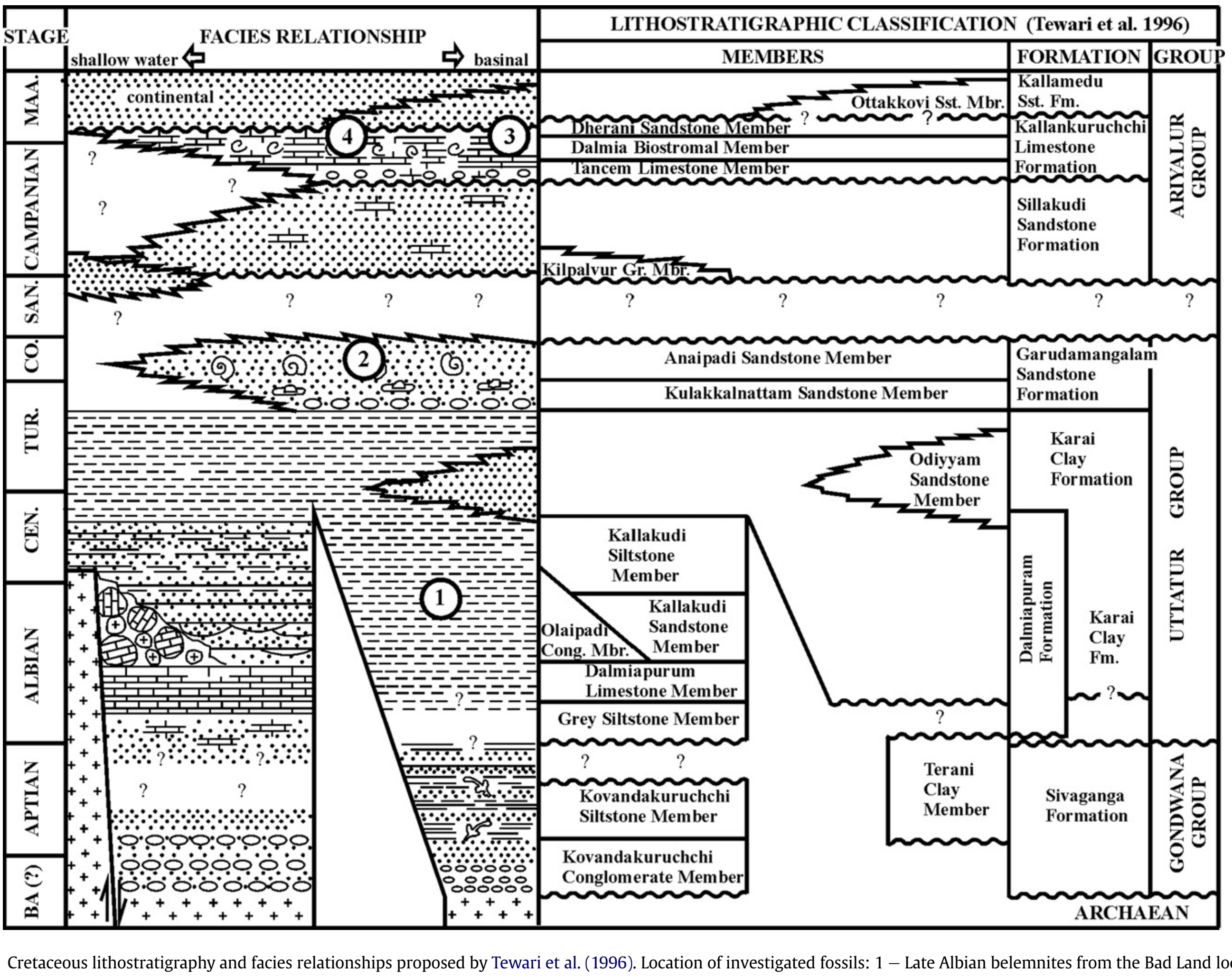

Fig. 6. Cretaceous lithostratigraphy and facies relationships proposed by Tewari et al. (1996). Location of investigated fossils: 1 – Late Albian belemnites from the Bad Land locality, Karai area; 2 – location of ammonites from the Pilimisai River; 3 and 4 – Early Maastrichtian bivalves from the TAMIN Mines and Periya Nagalar.

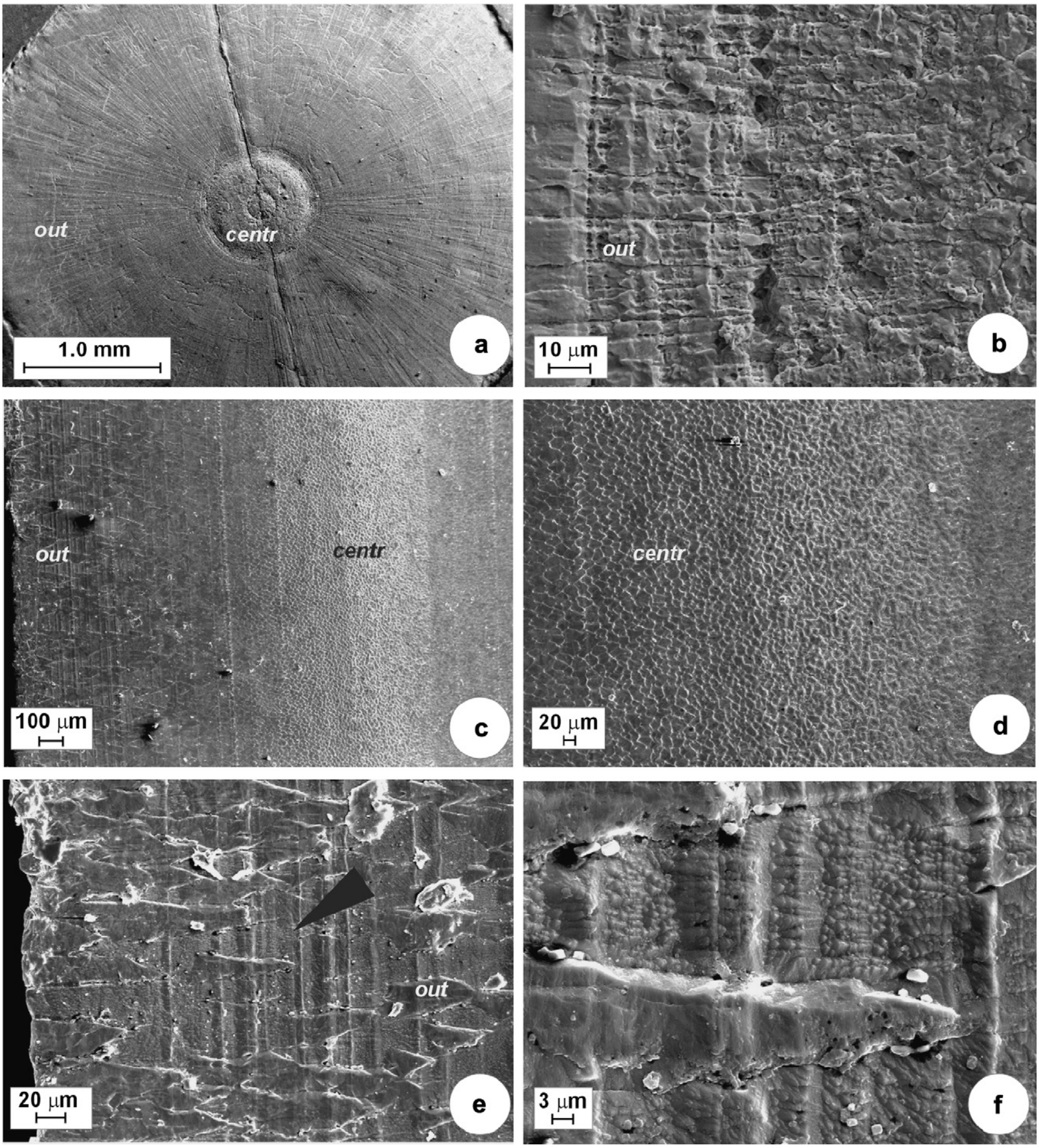

Fig. 7. SEM photomicrographs of belemnites *Parahibolites blanfordi* (Spengler). from southern India. a – cross-section of the rostrum In-10b, etched surface shows its central part (*centr*), with two growth rings and without radial sculpture, and outlying part (*out*) with numerous concentric growth rings and distinct radial sculpture; b – the detail of Fig. 7a shows concentric and radial microstructure of the outlying part of the rostrum in cross-section; c–f – longitudinal section of the rostrum In-10e: c – etched surface shows central (*centr*) and outlying (*out*) parts of the rostrum; d – the detail of Fig. 7c shows well-preserved granular structure of the central part of the rostrum, locating along the apical line; e – the detail of Fig. 7c shows wedge-shaped structure of the outlying part of the rostrum (left position with respect to the apical line); f – well-preserved prismatic calcite in the tooth-like locus arrowed in Fig. 7e.

(=“*Alectryonia*”) sp. (Fig. 6, point 4). In the SEM photomicrographs of the oyster bivalve shell well-preserved thin calcitic slabs were recognized.

The isotopic composition of one specimen (In-2a) has been investigated in detail (35 samples). Relatively high values for Fe (1.67–5.76 weight %), Si (6.17–13.23 weight %), and Al (2.60–4.78 weight %) for this specimen were found only in two points located in a single crack along lamination. Material from these points was excluded from isotopic investigation. In the other 29 points of specimen In-2a, located in different layers of the same cross-section, Fe, Si, and Al have not been found by X-ray energy dispersive spectrometry.

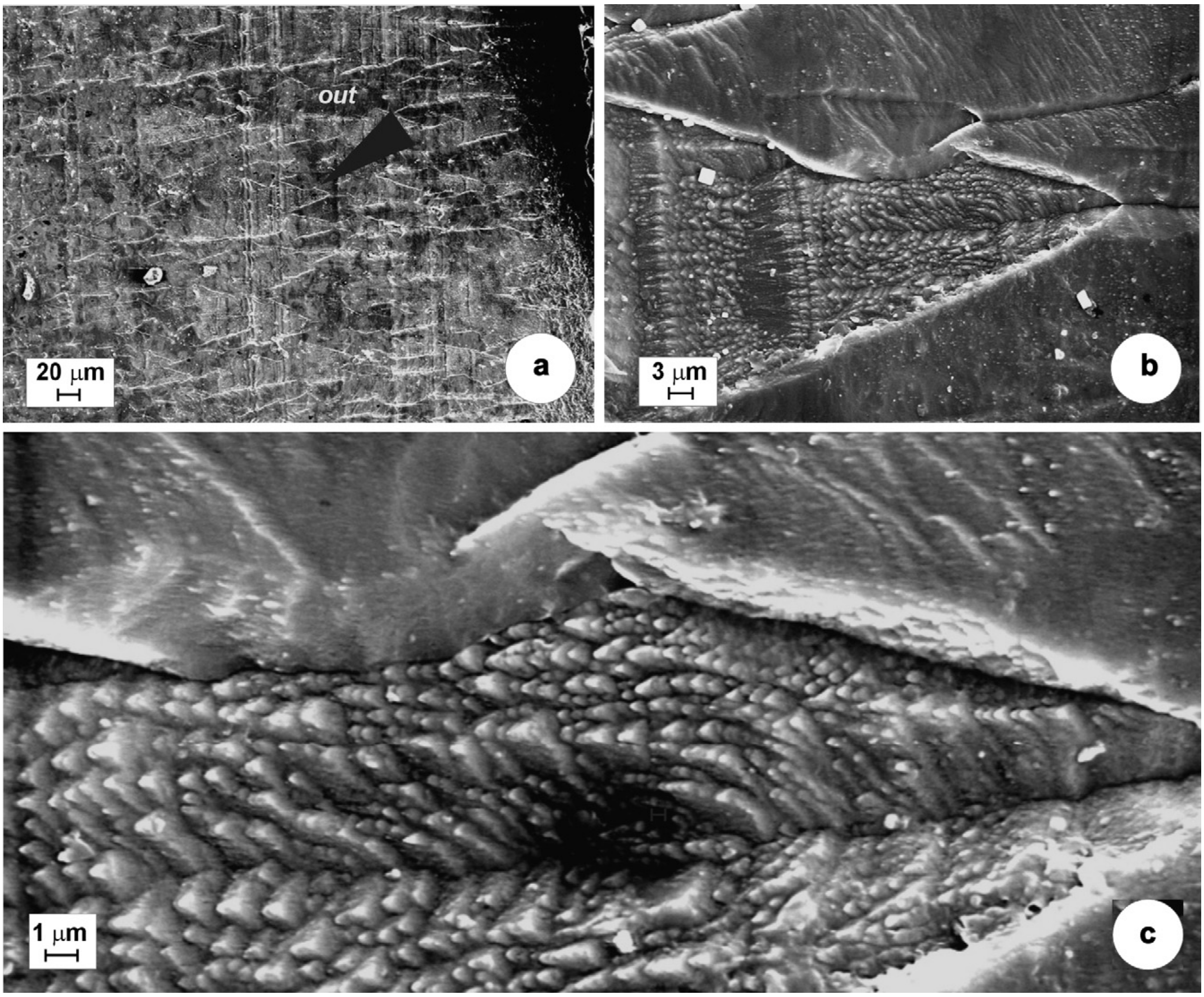

Fig. 8. Well-preserved prismatic microstructure in the tooth-like locus – SEM photomicrographs of belemnite *Parahibolites blanfordi* (Spengler), longitudinal section of the rostrum In-10e from southern India. a – etched surface shows original wedge-shaped structure of the outlying part of the rostrum (right position with respect to the apical line), similar with that showing in Fig. 7e; b – well-preserved prismatic microstructure in the tooth-like locus arrowed in Fig. 8a; c – part of Fig. 8b, showing different orientation of thin calcite prisms within the investigated tooth-like locus and beyond the bounds of it (portion from the right of it generated during a later stage of belemnite ontogenesis).

$\delta^{18}O$ and $\delta^{13}C$ values of the bivalve mollusc (specimen In-2a) representing its different ontogenetic stages fluctuate between −5.8 and −2.2‰ and between −1.4 and +0.8‰, respectively (Table 2). The relationship between $\delta^{18}O$ and $\delta^{13}C$ in the bivalve *Lopha* sp. shell In-2a was investigated. The sample shows that $\delta^{18}O$ values correlate well with $\delta^{13}C$ (Fig. 12).

Other *Lopha* sp. shells (specimens In-2a-2 and In-2b), as well as *Gryphaea* sp. (specimens In-1 and In-3) and *Exogyra* sp. (specimen In-4) shells, show also very low $\delta^{18}O$ values (to −5.6‰), but normal $\delta^{13}C$ values fluctuated from −2.2 to +2.6‰ (Table 2).

Isotopic composition of the early Maastrichtian brachiopods *Carneithyris* sp. and *Chatwinothyris* sp. from the Kallankurichchi Formation (TAMIN Mines) (Fig. 6, point 3) have not been investigated because of poor preservation of their microstructure.

4.2. Madagascar

SEM photographs of cephalopod shells from the lower Albian of Madagascar (e.g., Figs. 13 and 14) show that it is possible to recognize their original structure (e.g. external prismatic, nacreous, inner prismatic, and wrinkle layers). The SEM photographs of Cretaceous molluscs from southern India and Madagascar show that nautiloid, ammonoid, belemnite and bivalve skeletons fulfil diagenetic screening criteria and were therefore considered suitable for isotopic analysis. It was confirmed by results of the X-ray analysis that show the lack of secondary admixtures, including α-SiO_2.

Isotopic analyses suggest that investigated portions of some early Albian cephalopod shells from Madagascar were secreted in significantly different conditions. For instance, ammonoid *Douvilleiceras* sp. shell is characterised by lowest $\delta^{18}O$ values fluctuating from −1.3 to −1.1‰, but ammonoid *Eotetragonites umbilicostriatus* shell by highest $\delta^{18}O$ values (fluctuating from −0.2 to +0.4‰); at the same time the former is characterised by only positive $\delta^{13}C$ values (0.1–0.9), but latter by only negative ones, fluctuating between −2.0 and −0.5‰ (Table 3, Fig. 15). More or less similar oxygen-isotopic composition has been discovered in nautiloid *Cymatoceras*? sp. and ammonoids *Desmoceras* sp. and *Cleoniceras besairei*. However, samples taken from *Cymatoceras*? sp. and *Cleoniceras besairei* show only negative $\delta^{13}C$ values, but *Desmoceras* sp. is characterised by mainly positive values.

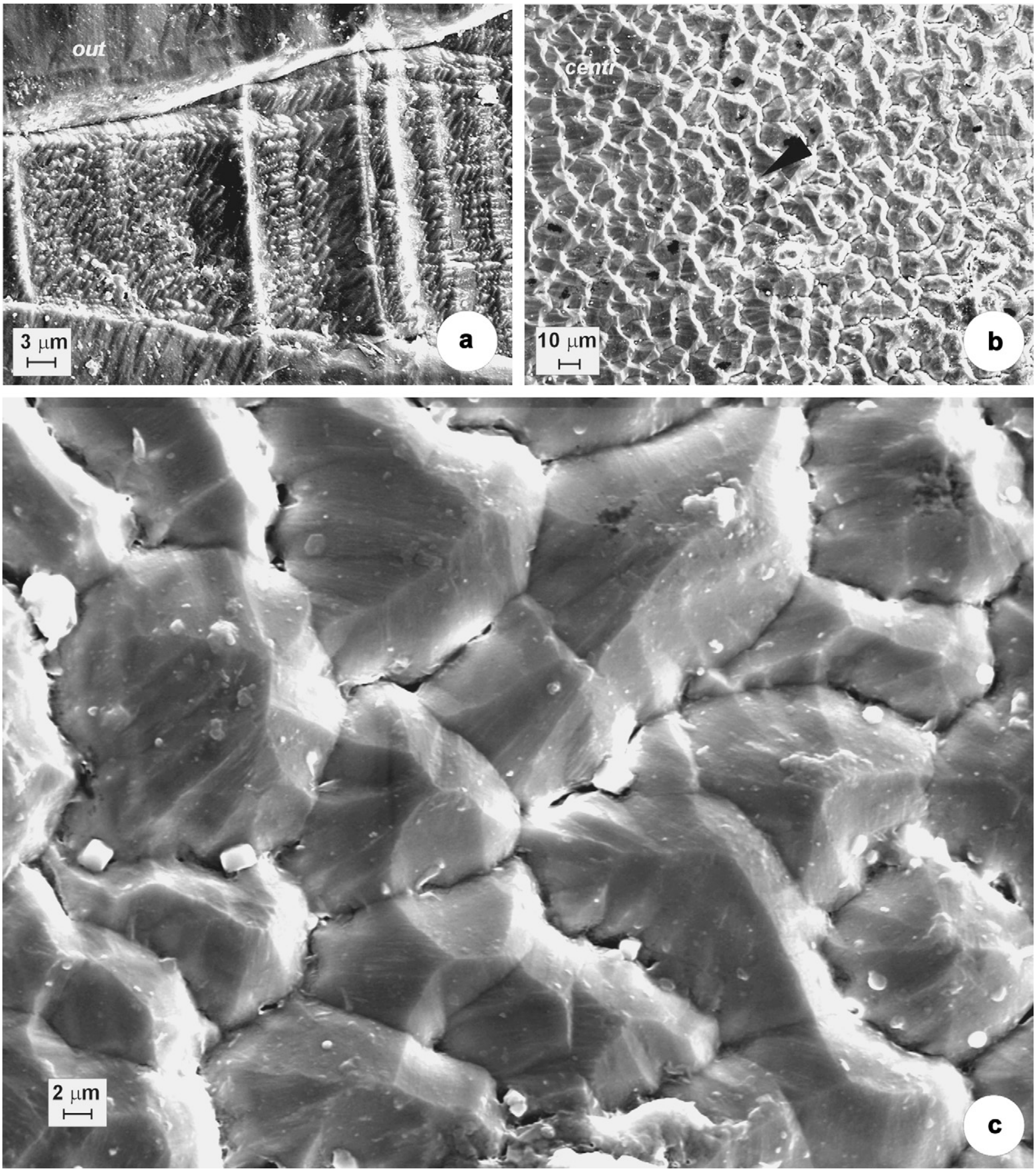

Fig. 9. SEM photomicrographs of belemnite *Parahibolites blanfordi* (Spengler), longitudinal section of the rostrum In-10e from southern India: a – etched surface shows well-preserved prismatic calcite in another tooth-like locus of the outlying part of the rostrum; b – detail of Fig. 7d shows well-preserved pellets of the central part of the rostrum (granular structure); c – detail of Fig. 9b shows configuration of pellets (grains).

5. Main results and discussion

5.1. Biostratigraphy

According to Sundaram et al. (2001) and Ravindran et al. (1995), the Karai Formation seems to be late Albian–early Turonian and Aptian–Turonian in age, respectively. However, Watkinson et al. (2007) wrote that the date of the onset of marine clay sedimentation (Karai Clay Formation) remains vague, but may well be earliest Albian. The R. Nagendra's belemnite sample locality, namely the Bad Land (11°07′43.9″N and 78°53′51.66″E), is about 1.5 km south-east of the village of Karai. Y. Shigeta recently collected additionally some belemnite rostra from the Karai Clay Formation at the Bad Land locality (eastern region of the village of Karai, 11°07′28.7″N and 78°54′24.7″E). Beside a systematical belonging of belemnites, there are two reasons to consider the late

Table 1
Carbon and oxygen isotope analyses of late Albian belemnites *Parahibolites blanfordi* (Spengler) (*P.b.*) and *Tetrabelus* cf. *seclusus* (Blanford) (*T.*cf *s.*) rostra from the middle part of the Karai Shale Formation (Uttatur Group) of the Cauvery Basin, southern India (D – diameter).

Sample	Rostrum	Location (D, mm)	Diagenetic alteration			$\delta^{13}C$ (V-PDB) (‰)	$\delta^{18}O$ (SMOW) (‰)	$\delta^{18}O$ (V-PDB) (‰)	T °C
			Original calcite (%)	Admixture (α–SiO_2)	Colour				
In-10a-1 (*P.b.*)	In-10a	6.90–7.00	100	No	Colourless	0.58	29.98	–0.9	15.6
In-10a-2 (*P.b.*)	Same rostrum	6.80–6.90	100	No	Colourless	0.63	30.01	–0.9	15.5
In-10a-3 (*P.b.*)	Same rostrum	6.70–6.80	100	No	Colourless	0.45	30.25	–0.6	14.5
In-10a-4 (*P.b.*)	Same rostrum	6.60–6.70	100	No	Colourless	0.43	30.31	–0.6	14.3
In-10a-5 (*P.b.*)	Same rostrum	6.55–6.60	100	No	Colourless	0.41	29.80	–1.1	16.3
In-10a-6 (*P.b.*)	Same rostrum	6.50–6.55	100	No	Colourless	0.57	30.31	–0.6	14.3
In-10a-7 (*P.b.*)	Same rostrum	6.45–6.50	100	No	Colourless	0.20	30.16	–0.7	14.9
In-10a-8 (*P.b.*)	Same rostrum	6.40–6.45	100	No	Colourless	0.44	30.12	–0.8	15.0
In-10a-9 (*P.b.*)	Same rostrum	6.30–6.40	100	No	Colourless	0.45	29.99	–0.9	15.6
In-10a-10 (*P.b.*)	Same rostrum	6.20–6.30	100	No	Colourless	0.46	30.18	–.0.7	14.8
In-10a-11 (*P.b.*)	Same rostrum	6.10–6.20	100	No	Colourless	0.52	30.31	–0.6	14.3
In-10a-12 (*P.b.*)	Same rostrum	6.10–6.15	100	No	Colourless	0.65	30.19	–0.7	14.8
In-10a-13 (*P.b.*)	Same rostrum	6.05–6.10	100	No	Colourless	0.65	30.18	–0.7	14.8
In-10a-14 (*P.b.*)	Same rostrum	6.00–6.05	100	No	Colourless	0.73	30.13	–0.8	15.0
In-10a-15 (*P.b.*)	Same rostrum	5.95–6.00	100	No	Colourless	0.61	30.13	–0.8	15.0
In-10a-16 (*P.b.*)	Same rostrum	5.90–5.95	100	No	Colourless	0.71	30.24	–0.6	14.6
In-10a-17 (*P.b.*)	Same rostrum	5.85–5.90	100	No	Colourless	0.67	29.97	–0.9	15.6
In-10a-18 (*P.b.*)	Same rostrum	5.80–5.85	100	No	Colourless	0.59	30.10	–0.8	15.1
In-10a-19 (*P.b.*)	Same rostrum	5.70–5.80	100	No	Colourless	0.74	30.18	–0.7	14.8
In-10a-20 (*P.b.*)	Same rostrum	5.60–5.70	100	No	Colourless	0.69	30.32	–0.6	14.3
In-10a-21 (*P.b.*)	Same rostrum	5.50–5.60	100	No	Colourless	0.70	30.16	–0.7	14.9
In-10a-22 (*P.b.*)	Same rostrum	5.40–5.50	100	No	Colourless	0.55	30.15	–0.7	14.9
In-10a-23 (*P.b.*)	Same rostrum	5.20–5.40	100	No	Colourless	0.59	30.12	–0.8	15.0
In-10a-24 (*P.b.*)	Same rostrum	5.10–5.20	100	No	Colourless	0.56	30.15	–0.7	14.9
In-10a-25 (*P.b.*)	Same rostrum	5.05–5.10	100	No	Colourless	0.63	30.26	–0.6	14.5
In-10a-26 (*P.b.*)	Same rostrum	5.00–5.05	100	No	Colourless	0.43	29.77	–1.1	16.4
In-10a-27 (*P.b.*)	Same rostrum	4.90–5.00	100	No	Colourless	0.58	30.00	–0.9	15.5
In-10a-28 (*P.b.*)	Same rostrum	4.85–4.90	100	No	Colourless	0.43	30.13	–0.8	15.0
In-10a-29 (*P.b.*)	Same rostrum	4.80–4.85	100	No	Colourless	0.35	29.96	–0.91	15.7
In-10a-30 (*P.b.*)	Same rostrum	4.75–4.80	100	No	Colourless	0.36	29.99	–0.9	15.6
In-10a-31 (*P.b.*)	Same rostrum	4.70–4.75	100	No	Colourless	0.23	29.68	–1.2	16.8
In-10a-32 (*P.b.*)	Same rostrum	4.65–4.70	100	No	Colourless	0.35	30.02	–0.9	15.4
In-10a-33 (*P.b.*)	Same rostrum	4.60–4.65	100	No	Colourless	0.32	29.81	–1.1	16.3
In-10a-34 (*P.b.*)	Same rostrum	4.50–4.60	100	No	Colourless	0.30	29.94	–0.9	15.8
In-10a-35 (*P.b.*)	Same rostrum	4.40–4.50	100	No	Colourless	0.27	29.9	–1.0	15.9
In-10a-36 (*P.b.*)	Same rostrum	4.35–4.40	100	No	Colourless	0.39	29.6	–1.3	17.1
In-10a-37 (*P.b.*)	Same rostrum	4.30–4.35	100	No	Colourless	0.34	29.84	–1.0	16.2
In-10a-38 (*P.b.*)	Same rostrum	4.25–4.30	100	No	Colourless	0.49	30.13	–0.8	15.0
In-10a-39 (*P.b.*)	Same rostrum	4.20–4.25	100	No	Colourless	0.62	30.09	–0.8	15.2
In-10a-40 (*P.b.*)	Same rostrum	4.10–4.20	100	No	Colourless	0.66	29.93	–1.0	15.8
In-10a-41 (*P.b.*)	Same rostrum	4.00–4.10	100	No	Colourless	0.76	29.94	–0.9	15.8
In-10a-42 (*P.b.*)	Same rostrum	3.95–4.00	100	No	Colourless	0.71	29.96	–0.9	15.7
In-10a-43 (*P.b.*)	Same rostrum	3.90–3.95	100	No	Colourless	0.50	29.91	–1.0	15.9
In-10a-44 (*P.b.*)	Same rostrum	3.80–3.90	100	No	Colourless	0.78	29.81	–1.1	16.3
In-10a-45 (*P.b.*)	Same rostrum	3.70–3.80	100	No	Colourless	0.77	29.60	–1.3	17.1
In-10a-46 (*P.b.*)	Same rostrum	3.60–3.70	100	No	Colourless	0.89	29.77	–1.1	16.4
In-10a-47 (*P.b.*)	Same rostrum	3.50–3.60	100	No	Colourless	0.83	29.83	–1.0	16.2
In-10a-48 (*P.b.*)	Same rostrum	3.40–3.50	100	No	Colourless	0.85	29.86	–1.0	16.1
In-10a-49 (*P.b.*)	Same rostrum	3.20–3.40	100	No	Colourless	0.95	29.90	–1.0	15.9
In-10a-50 (*P.b.*)	Same rostrum	3.00–3.20	100	No	Colourless	0.85	29.85	–1.0	16.1
In-10a-51 (*P.b.*)	Same rostrum	2.80–3.00	100	No	Colourless	0.78	29.91	–1.0	15.9
In-10a-52 (*P.b.*)	Same rostrum	2.40–2.60	100	No	Colourless	0.64	30.18	–0.7	14.8
In-10a-53 (*P.b.*)	Same rostrum	2.10–2.20	100	No	Colourless	0.69	29.85	–1.0	16.1
In-10a-54 (*P.b.*)	Same rostrum	2.00–2.10	100	No	Colourless	0.51	29.70	–1.2	16.7
In-10a-55 (*P.b.*)	Same rostrum	1.80–2.00	100	No	Colourless	0.52	29.65	–1.2	16.9
In-10a-56 (*P.b.*)	Same rostrum	1.70–1.80	100	No	Colourless	0.70	29.76	–1.1	16.5
In-10a-57 (*P.b.*)	Same rostrum	1.60–1.70	100	No	Colourless	0.71	29.58	–1.3	17.2
In-10b-1 (*P.b.*)	In-10b	5.80–6.00	100	No	Colourless, yellowish	0.90	29.40	–1.5	18.1
In-10b-2 (*P.b.*)	Same rostrum	5.70–5.80	100	No	Colourless	1.10	30.30	0.6	14.4
In-10c-1 (*P.b.*)	In-10c	5.20–5.30	100	No	Colourless	–2.5	25.50	–5.2	–
In-10c-2 (*P.b.*)	Same rostrum	5.10–5.20	100	No	Colourless	–0.3	29.30	–1.6	18.5
In-10d-1 (*P.b.*)	In-10d	4.40–4.50	100	No	Colourless	1.1	30.40	–0.5	14.0
In-10d-2 (*P.b.*)	Same rostrum	4.30–4.40	100	No	Colourless	1.4	30.40	–0.5	14.0
In-10e-1 (*P.b.*)	In-10e	3.95–4.00	100	No	Colourless	–0.2	30.00	–0.9	15.60
In-10e-2 (*P.b.*)	Same rostrum	3.90–3.95	100	No	Colourless	1.0	30.30	–0.6	14.4
In-11-1 (*P.b.*)	In-11	7.80–7.90	100	No	Colourless	0.8	30.20	–0.7	14.7
In-12-1 (*P.b.*)	In-12	8.30–6.40	100	No	Cream	0.6	29.2	–1.7	18.8
In-15-1 (*P.b.*)	In-15	8.80–8.90	100	No	Colourless	1.3	29.8	–1.1	16.3
In-14-1 (*T.*cf *s.*)	In-14	9.90–10.00	100	No	Colourless	0.1	29.5	–1.4	17.5

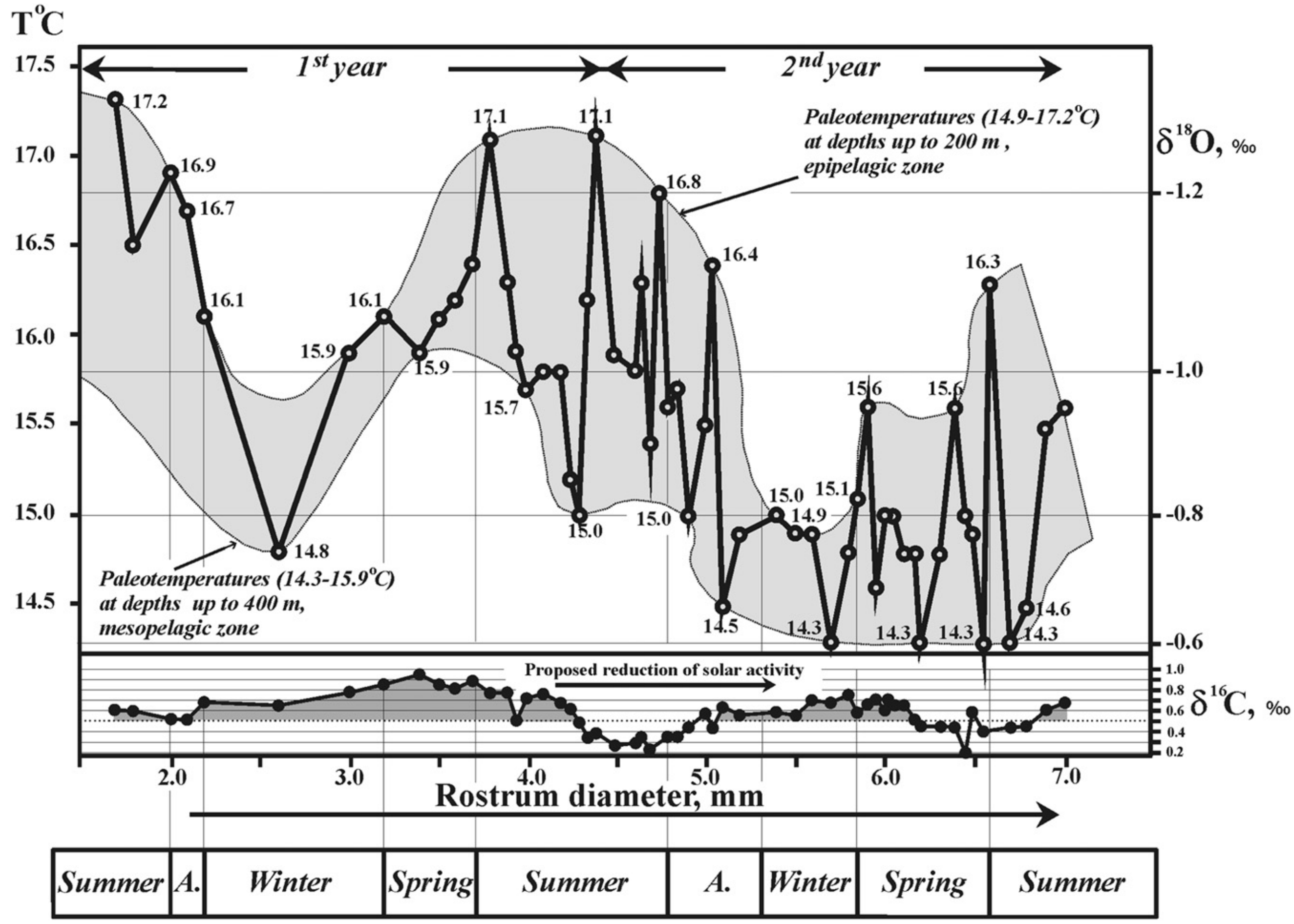

Fig. 10. Possible seasonal growth temperatures for the single two-years-old *Parahibolites blanfordi* (Spengler), specimen In-2a, from the Upper Albian of the Karai Shale Formation of the Cauvery Basin, southern India (interpretation from 57 samples).

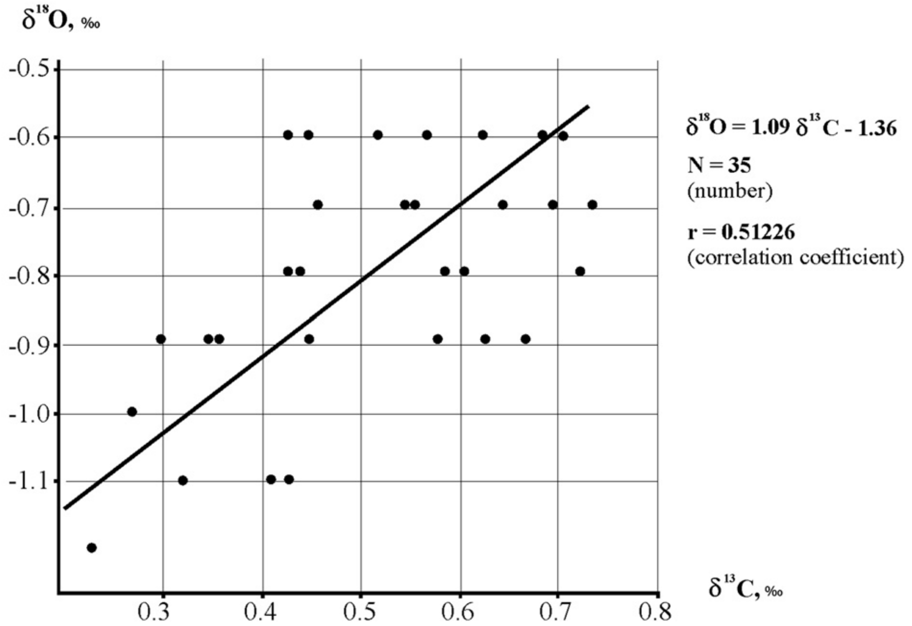

Fig. 11. Scatter plot and regression line of $\delta^{18}O$ and $\delta^{13}C$ values for belemnite *Parahibolites blanfordi* (Spengler) from southern India (sample In-10a, late Ontogenesis data).

Table 2
Carbon and oxygen isotope analyses of early Maastrichtian bivalve shells from the Kallankurichchi Formation (Ariyalur Group) of the Cauvery Basin, southern India (L – length).

Sample	Species	Location (L, mm)	Diagenetic alteration			$\delta^{13}C$ (VPDB) (‰)	$\delta^{18}O$ (SMOW) (‰)	$\delta^{18}O$ (VPDB) (‰)	T °C	"T" °C
			Original calcite (%)	Admixture (α–SiO_2)	Colour					
In-2a-4	*Lopha* sp.	0–2	100	No	Light grey	−1.4	25.1	−5.6	–	38.0
In-2a-5	Same shell	2–4	100	No	Light grey	−1.3	26.2	−4.6	–	32.7
In-2a-6	Same shell	4–6	100	No	Light grey	−0.3	27.1	−3.7	–	28.2
In-2a-7	Same shell	6–8	100	No	Light grey	−0.9	28.7	−2.2	21.2	–
In-2a-8	Same shell	8–10	100	No	Light grey	0.8	28.1	−2.7	–	23.4
In-2a-10	Same shell	12–14	100	No	Light grey	−0.3	27.9	−2.9	–	24.4
In-2a-11	Same shell	14–16	100	Trace	Light grey	−0.5	27.2	−3.6	–	27.7
In-2a-12	Same shell	16–18	100	No	Light grey	−0.8	26.7	−4.1	–	30.2
In-2a-13	Same shell	18–20	100	No	Light grey	−0.6	26.6	−4.1	–	30.2
In-2a-14	Same shell	20–22	100	No	Light grey	−0.8	27.5	−3.3	–	26.3
In-2a-15	Same shell	22–24	100	No	Light grey	−0.2	27.4	−3.4	–	26.7
In-2a-16	Same shell	24–26	100	Trace	Light grey	−1.1	26.7	−4.1	–	30.2
In-2a-17	Same shell	26–28	100	No	Light grey	−1.0	26.6	−4.2	–	30.7
In-2a-18	Same shell	28–30	100	No	Light grey	−0.7	26.7	−4.0	–	29.7
In-2a-19	Same shell	30–32	100	Trace	Light grey	0.1	26.8	−4.0	–	29.7
In-2a-20	Same shell	32–34	100	No	Light grey	0.4	27.4	−3.4	–	26.7
In-2a-21	Same shell	34–36	100	No	Light grey	0	27.4	−3.4	–	26.7
In-2a-23	Same shell	38–40	100	No	Light grey	0.7	26.7	−4.1	–	30.2
In-2a-24	Same shell	40–42	100	No	Light grey	−0.5	27.9	−2.9	–	24.4
In-2a-25	Same shell	42–44	100	Trace	Light grey	0.7	28.3	−2.5	–	22.5
In-2a-26	Same shell	44–46	100	No	Light grey	0.6	27.8	−3.0	–	24.8
In-2a-27	Same shell	46–48	100	No	Light grey	0.6	28.1	−2.7	–	23.4
In-2a-28	Same shell	48–50	100	No	Light grey	0.7	28.7	−2.2	21.2	–
In-2a-29	Same shell	50–52	100	No	Light grey	0.2	28.4	−2.5	–	22.5
In-2a-30	Same shell	52–54	100	No	Light grey	0.5	28.6	−2.3	–	21.6
In-2a-31	Same shell	54–56	100	No	Light grey	0.1	28.1	−2.7	–	23.4
In-2a-32	Same shell	56–58	100	No	Light grey	0.4	28.7	−2.2	21.2	–
In-2a-33	Same shell	58–60	100	Trace	Light grey	0.2	28.4	−2.5	–	22.5
In-2a-34	Same shell	60–62	100	No	Light grey	−0.3	27.8	−3.0	–	24.8
In-2a-35	Same shell	62–64	100	Trace	Light grey	0.7	28.4	−2.5	–	22.5
In-2a-36	Same shell	64–66	100	No	Light grey	0.7	28.0	−2.8	–	23.9
In-2a-3	Same shell	Inner surface	100	No	Light pink	−0.8	26.7	−4.0	–	29.7
In-2a-2	*Lopha* sp.	Inner surface	100	No	Light pink	−2.0	24.9	−5.8	–	39.1
In-2b-1	*Lopha* sp.	Inner surface	100	No	Light grey	1.5	28.9	−2.0	20.3	–
In-2b-2	Same shell	External side at $H = 60$ mm				2.6	29.0	−1.9	19.8	–
In-1-1	*Gryphaea* sp.	35.5–37.0	100	No	White	−2.2	25.7	−5.0	–	34.0
In-3-1	*Gryphaea* sp.	50.0–52.0	100	No	White	−1.8	26.0	−4.8	–	33.8
In-4-1	*Exogyra* sp.	25.0–26.0	100	No	Colourless	0.1	27.3	−3.5	–	27.2

Albian age for the belemnite rostra from the Bad Land locality now. First, there is information that the Karai Clay Formation yields some belemnites associated with late Albian ammonites (*Mortoniceras inflatum* Zone) (Sundaram et al., 2001). Secondary, some typical late Albian ammonoids from the Bad Land locality are present in the collection, stored in the one of private museums in Central India (Hyderabad). However, belemnites-yielding sediments from the Bad Land locality have been considered earlier by R. Nagendra as beeng of Late Turonian age (Zakharov et al., 2006a).

Exact location of Bowen's (1961a) belemnites from the Uttatur Group of Trichinopoly district is unknown, but we expect that they were originated from the upper Albian part of the Dalmiapurum Formation (*Mortoniceras inflatum* Zone).

The foraminiferal assemblage in the Kallankuruchchi Limestone Formation, yielding oyster bivalve molluscs (*Lopha*), was considered to be typical of the very latest Campanian and the Maastrichtian (Tewari et al., 1996; Hart et al., 2001; Nagendra et al., 2002b). However, R. Nagenra argues in favour of an early Maastrichtian age for *Lopha* from the Kallankuruchchi Limestone Formation now.

5.2. Mode of life of fossil cephalopods and palaeotemperatures

Since Müller-Stoll's (1936) studies, the original mineralogy of belemnite rostra has been a much debated subject (e.g., Kabanov, 1967; Jeletzky, 1966; Longinelli et al., 2003; Naidin, 1969; Stahl and Jordan, 1969; Barskov, 1972; Spaeth, 1973; Bandel and Kulicki, 1988; Dunca et al., 2006). Some of these works emphasize the variation in isotopic composition which can result from the diagenetic alteration of belemnite rostra. However, Veizer (1974) showed that by combining trace element analysis and textural analysis (by SEM and under CL), belemnite rostrum material could be successfully screened and unaltered material must be selected for isotopic analysis.

In recent years, several detail studies of diagenetic and morphological aspects of some Jurassic and Cretaceous belemnite rostra have been conducted (e.g., Sælen, 1989; Bailey et al., 2003; Gröcke et al., 2003; Voigt et al., 2003; Florek et al., 2004; Rosales et al., 2004; McArthur et al., 2004; Pirrie et al., 2004; Price and Mutterlose, 2004; Wierzbowski, 2004; Fürsich et al., 2005). These studies have shown that the original mineralogy was low-Mg calcite and that the aragonite found in both the Callovian *Belemnoteuthis polonica* Makowski and Albian *Neohibolites minimus* (Miller) rostra (e.g., Spaeth, 1973) does not necessarily indicate that all belemnite rostra were originally composed of this mineral. Sælen (1989) believes that the original rostrum more probably consisted of radial structures that accreted periodically in a concentric fashion. The model proposed by Sælen (1989) allows the use of variations in $\delta^{18}O$ between bands in well-preserved belemnite rostra for seasonal palaeotemperature calculation, as was originally hypothesized by Urey et al. (1951).

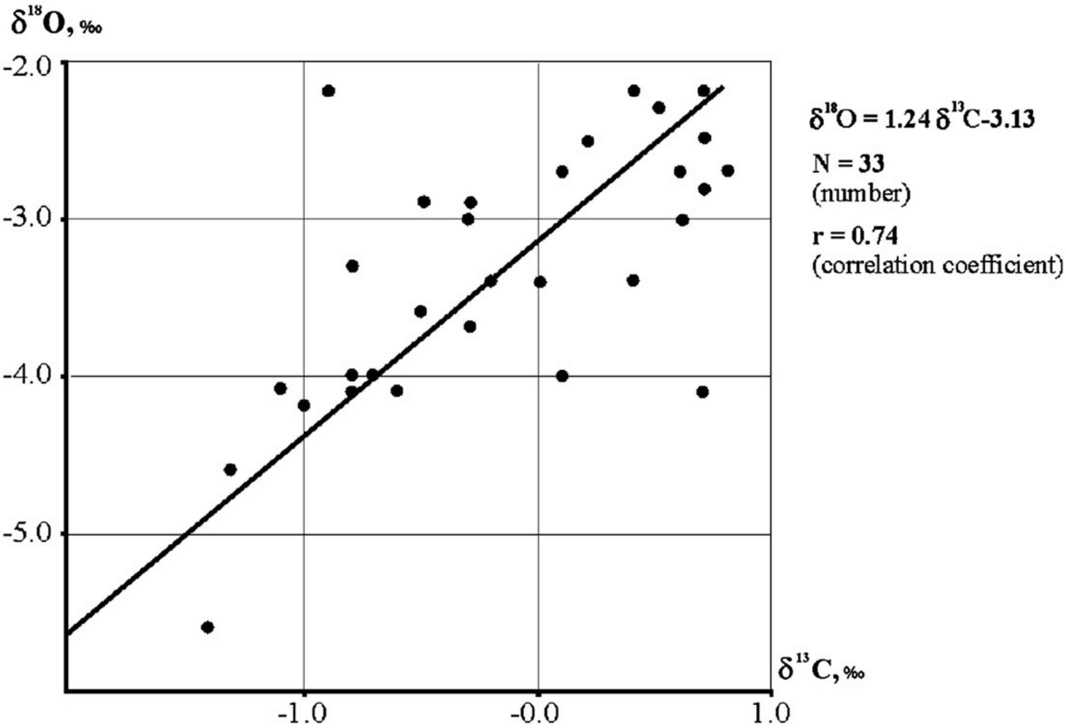

Fig. 12. Scatter plot and regression line of $\delta^{18}O$ and $\delta^{13}C$ values for bivalve *Lopha* sp. from the lower Maastrichtian of the Kallankurichchi Formation in southern India (sample In-2a).

There is no agreement among workers on the life habits of belemnites. According to Naidin (1969), Westermann (1973) and Hewitt (2000) calculations, the depth limit of inhabitation of belemnites, investigated by them, was about 100–200 m, although investigated *Cylindroteuthis* can occur at deeper levels. Wierzbowski (2004) gave an example of the habitat of Late Jurassic belemnites of the Boreal–Subboreal Province which lived in a relatively shallow sea (not deeper than 100–150 m).

In Huber and Hodell's (1996) opinion, information on the palaeobiology (palaeoecology) of belemnite is limited, because they are an extinct group of organisms lacking any close living relatives. They drawn attention to an interesting fact that $\delta^{18}O$ palaeotemperatures yielded by the late Albian–Cenomanian and Santonian–early Campanian belemnites from James Ross (Antarctic) (Pirrie and Marshall, 1990; Ditchfield et al., 1994) are similar to the $\delta^{18}O$ palaeotemperatures derived from middle to upper bathyal benthic foraminifera from coeval sediments of South Atlantic (Huber et al., 1995). They found that if the $^{18}O/^{16}O$ ratios of belemnites and benthic foraminifera approximate the $\delta^{18}O$ composition of the ambient water in which they grew, their similar temperature values for both the late Albian–Cenomanian (11.93 °C and 12.46–13.52 °C, respectively) and the Santonian–early Campanian (13.40–13.63 °C and 14.08–15.55 °C, respectively) may imply that belemnites mineralized their rostra beyond shelfal depths. Pirrie et al. (2004) also suggest that while some belemnites were shelf dwelling, other taxa were nektonic and it is possible that the rostra were calcified in deep water environments.

Results of our SEM and geochemical investigations of belemnite rostra from the upper Albian of the Cauvery Basin (Bad Land locality) likely agree with Sælen's (1989) interpretation, according to which all layers in the majority of belemnite rostra were originally built of a low-Mg calcite, which is the most stable component during limestone diagenesis, and that their concentric pattern is due to a laminar variation in the organic content.

Our analyses of the isotopic composition of Albian belemnite rostra from the *Pas-de-Calais* area in north France show that $\delta^{18}O$ values in their adult stage are frequently lower than those in their juvenile stage (Zakharov et al., 2006c, 2006d). Such regularity was first pointed out by Teiss and Naidin (1973) in Campanian–Maastrichtian belemnite rostra from the Russian Platform. Palaeotemperatures calculated from some adult and juvenile stages of Albian rostra of the *Pas-de-Calais* area are 15.2–20.7° and 12.4–14.4 °C, respectively; higher belemnite temperature level is comparable with palaeotemperature (21.9 °C) calculated from aragonite-preserved *Oxytropidoceras* ammonoid shell, which occurs with cited belemnites, and with those (19.6–21.6 °C) calculated from coeval well-preserved *Otohoplites* and *Beudanticeras* ammonoid shells from the neighbouring Normandy area (Zakharov et al., 2006c). An example of the deep water habitat of belemnites are late Campanian–Maastrichtian ones of the tropical Pacific (Magellan Rise) (Zakharov et al., 2007a, 2007b). Zakharov's et al. (2006c, 2006d, 2007a, 2007b) interpretation is consistent with Huber and Hodell's (1996) and Pirrie's et al. (2004) idea, according to which belemnites can reach colder deep-water levels. By contrast, most isotopically investigated Cretaceous ammonoids show that optimal temperatures of their growth are comparable to those obtained from their co-occurring benthos on the shelf (Smyshlyaeva et al., 2002; Moriya et al., 2003; Zakharov et al., 2003, 2005, 2006c).

Based on isotopic data (Zakharov et al., 2006c, 2006d, 2007a, 2007b), it has been suggested that belemnites, similar to Recent *Nautilus*, may have engaged in significant short-term vertical migrations in the water column. A depth limit for the living *Nautilus* seems to be 800 m, but they live abundantly at depths of 500–600 m (Ward and Martin, 1980; Westermann and Ward, 1980; Ward et al., 1981, 1984; Hewitt and Westermann, 1988; Oba et al., 1992; O'Dor et al., 1993). Ward's et al. (1984) data, obtained using ultrasonic transmitters, show that the mean day and night depths of investigated individuals in the Palau population of *Nautilus*

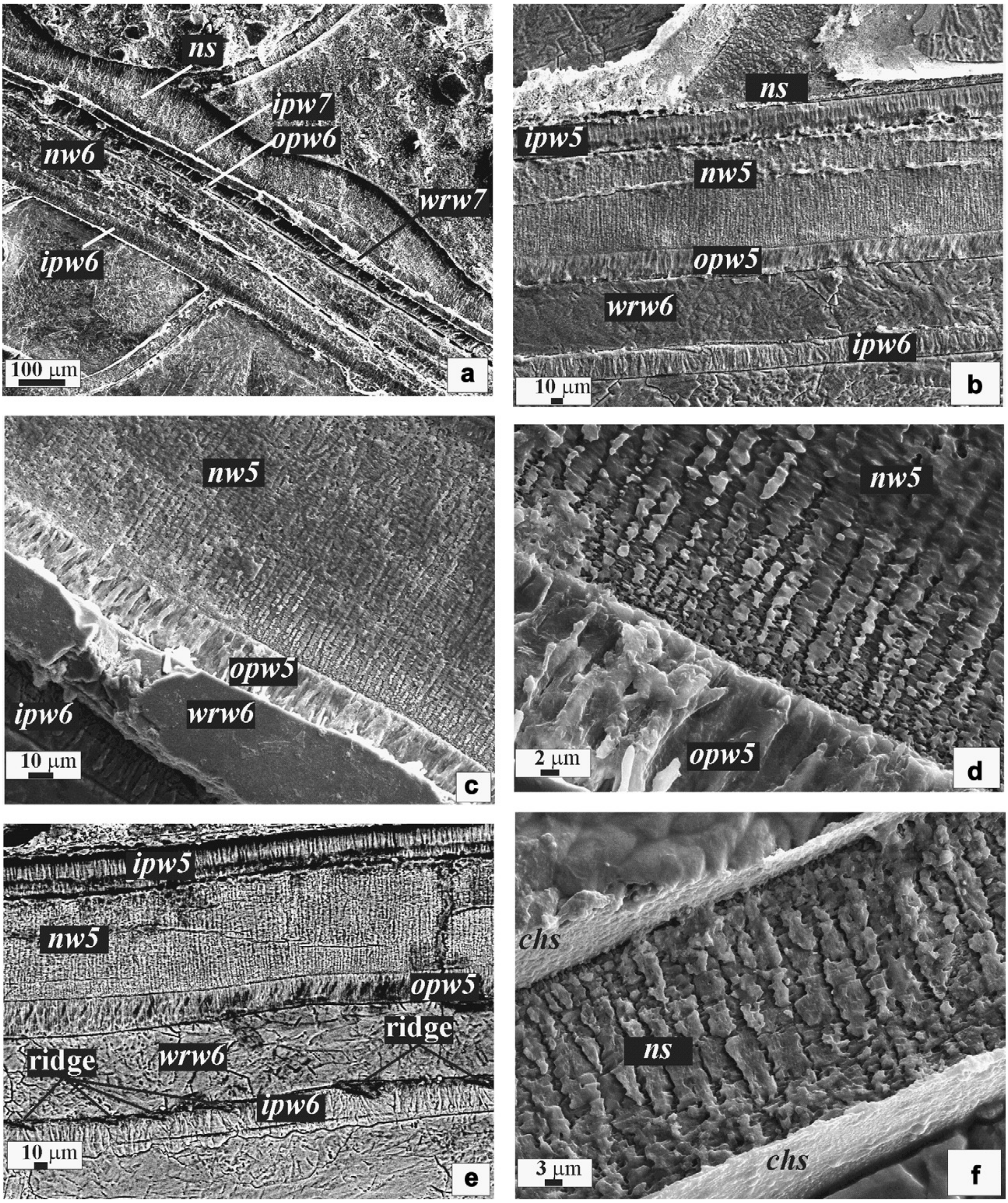

Fig. 13. SEM images of well-preserved ammonoid *Eotetragonites* sp. shell structure, specimen M-2 from Madagascar. a – median section of the shell wall and septa in the 6th and 7th whorles, b – median section of the shell wall and septum in the 5th and 6th whorls, c – the detail of Fig. 13b, d – the detail of Fig. 13c, e – median section of the shell wall and septum in the 5th and 6th whorles (was made in special regime, showing location of the wrinkle layer ridges), f – median section of the septum in the 7th whorl. *ns*–nacreous layer of the septum, *ipw5* and *ipw6* – inner prismatic layers in the 5th and 6th whorls, *nw5* and *nw6* – nacreous layers in the 5th and 6th whorls, *ipw5* and *ipw6* – inner prismatic layers in the 5th and 6th whorls, *wrw6* and *wrw7* – wrinkle layers in the 6th and 7th whorls, *ipw5* and *ipw7* – inner prismatic layers in the 5th and 7th whorls, *ns*–nacretic layer of the septum, *chs* – chitinous element.

fluctuated from 120 to 441 m and from 67 to 321 m, respectively. Zakharov's et al. (2007a, 2007b) data on isotopic composition of late Campanian–Maastrichtian belemnite rostra from Central paleo-Pacific (DVGI and Gelendzhik guyots of the Magellan Rise) show that the belemnites could possibility migrate within the water column with extreme palaeotemperatures of 17.1° and 9.4 °C, suggesting that their depth limit for the Tropical Zone apparently was more than 600–1000 m.

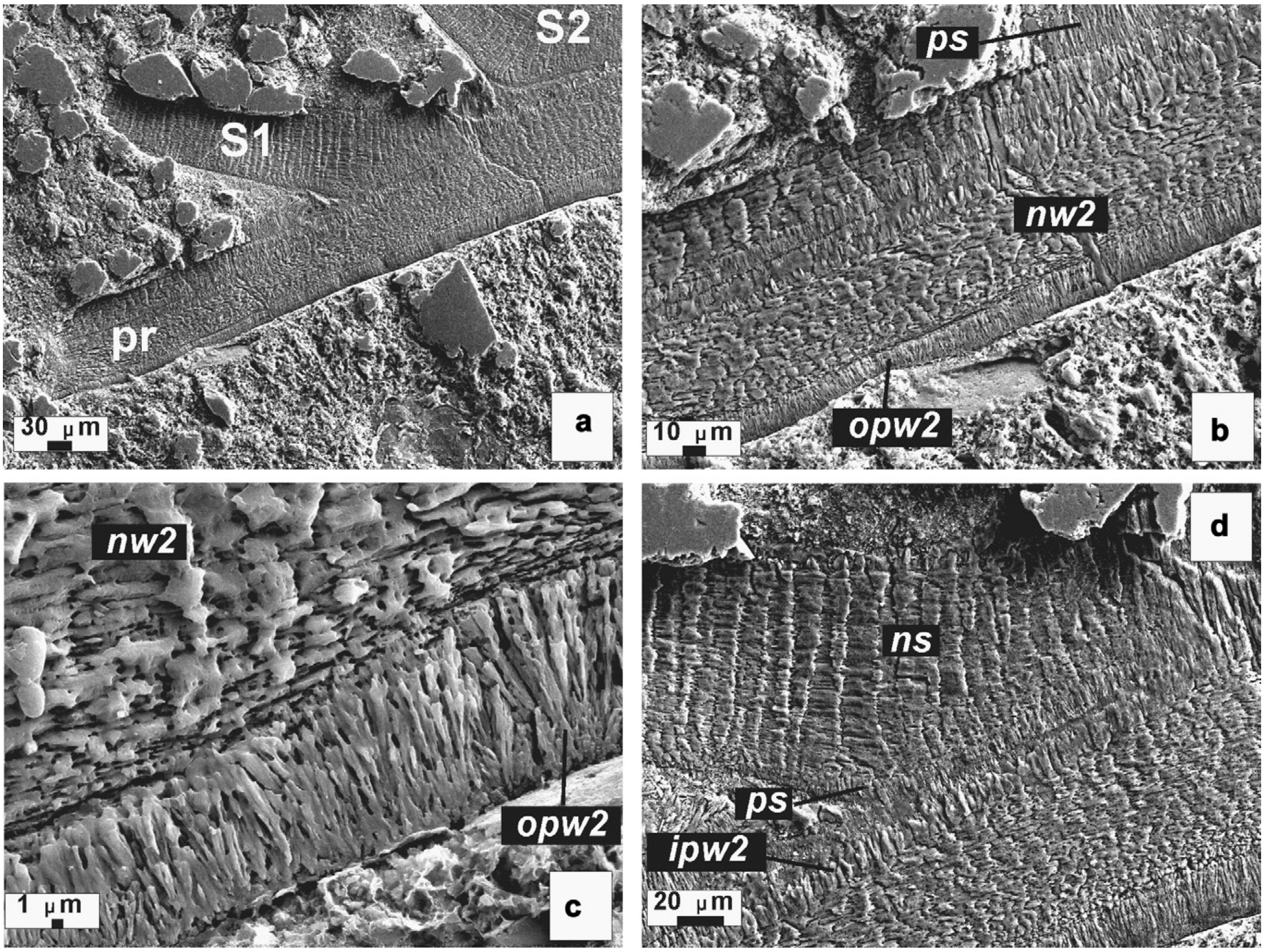

Fig. 14. SEM images of well-preserved *Cymatoceras* sp. shell structure, including structure of proseptum, M-1 from Madagascar. a – proseptum, b – median section of the shell wall and septum in the 1st whorl, c and d – the details of Fig. 12b and a, respectively. Designations: *pr* – proseptum, *S1* and *S2* – 1st and 2nd septa, *ps* – prismatic layer of the septum, *ns* – nacreous layer of the septum, *nw2* – nacreous layer in the 2nd whorl, *opw2* – outer prismatic layer in the 2nd whorl. *Ipw2* – inner prismatic layer in the 2nd whorl.

Thus, if the idea on significant vertical migrations of belemnites is correct, the full-fledged reconstruction of their habitat may be done only on the basis of a large complex of palaeotemperature evidences, but not restricted isotopic data. For reconstruction of palaeotemperatures from well-preserved belemnites it is very important to investigate their oxygen- and carbon-isotope composition in detail, by using samples from different stages of their ontogenesis to have a good knowledge of their position within the water column during life. Only in this case we do have a chance to find in the rostrum of a belemnite an excellent mobile palaeothermometer.

Detailed investigation of the *Parahibolites blanfordi* rostrum In-10a from the upper Albian of southern India allows us to conclude, firstly, that highest (14.9–17.2 °C) and lowest (14.3–15.9 °C) palaeotemperatures obtained from the belemnite (Fig. 10), possibly engaging in short-term vertical migrations in the water column, apparently reflect temperature conditions of the epipelagic and mesopelagic zones, respectively. Highest temperature values of the reputed epipelagic zones and lowest values of the possible mesopelagic zone, scattered under ontogenetic stages, locate in sinusoidal lines shown in Fig. 10. It allows us to surmise that the highest portions of temperature sinusoids are connected with warmest seasons of the year and their lowest portions with coolest seasons. If our assumption is true, lifetime of the investigated *Parahibolites blanfordi* is approximately two years, which agrees with results obtained from some other belemnite species (e.g., Stevens and Clayton, 1971; Dunca et al., 2006).

Secondly, it may be concluded that average annual temperatures for near-bottom shelf waters of the southern India region during late Albian do not appear to have exceeded 16.1 °C; isotopic palaeotemperatures interpreted as summer and winter values for near-bottom shelf waters fluctuate from 16.3° to 17.2 °C and from 14.9° to 16.1 °C, respectively (see a set of data from the reputed epipelagic zone) (Fig. 10). Results obtained may be corrected on the basis of data on eight other rostra from this locality (16.3–18.8° and 14.7–16.1 °C, respectively) (Table 1).

The late Albian isotopic palaeotemperatures (21.4–22.4 °C) determined by Bowen (1961a) for the presumably Dalmiapurum Formation are based on $\delta^{18}O$ fluctuations between −1.31 and −1.10‰ in the three investigated samples. Bowen (1961a) utilized the biogenic calcite equation of Epstein et al. (1953) to convert the oxygen isotope composition of the late Albian belemnites:

$$t = 16.5 - 4.3(\delta - A) + 0.14(\delta - A)^2 \quad (1)$$

where t (°C) is the ambient temperature, δ (‰) is the oxygen isotope ratio of the calcite (versus VPDB), and A (‰) is the $\delta^{18}O$ value of the water in which the calcium carbonate is precipitated. The author used this as conversation formula taking A as zero

Table 3
Carbon and oxygen isotope analyses of early Albian aragonitic cephalopod shells from the Ambarimaninga Formation of the Mahajanga Basin, Madagasca (H – height).

Sample	Species	Location (H in mm)	Diagenetic alterations				δ^{13}C (VPDB), ‰	δ^{18}O (VPDB), ‰	T, °C
			Diagenetic stage	Aragonite, %	Admix–ture, %	Colour			
M1-2	*Cymatoceras*? sp.	$H = 21.2$	1st	96 ± 3	0	Cream	−0.6	−0.4	17.2
M1-3	Same shell	$H = 19.5$	1st	97 ± 3	0	Cream	−0.5	−0.2	16.4
M2-1	*Eotetragonites unbilicostriatus* Collignon	$H = 12.8$	1st	97 ± 3	0	Cream	−1.3	0.4	13.3
M2-2	Same shell	$H = 12.2$	2nd	93 ± 3	0	Cream	−0.8	−0.1	15.8
M2-3	Same shell	$H = 12.1$	1st	100	0	Cream	−1.0	−0.1	15.8
M2-4	Same shell	$H = 12.0$	1st	96 ± 1	0	Cream	−1.3	0.0	15.5
M2-5	Same shell	$H = 11.8$	1st	98 ± 2	0	Cream	−1.6	−0.2	16.4
M2-8	Same shell	$H = 10.8$	1st	96 ± 3	0	Cream	−1.4	0.3	14.2
M2-9	Same shell	$H = 10.1$	2nd	91 ± 3	0	Cream	−1.8	0.1	15.1
M2-10	Same shell	$H = 9.4$	1st	96 ± 3	0	Cream	−1.8	0.1	15.1
M2-12	Same shell	$H = 8.1$	1st	95 ± 3	0	Cream	−2.0	0.1	15.4
M2-13	Same shell	$H = 7.4$	1st	97 ± 3	0	Cream	−0.5	0.3	14.2
M3-4	*Cleoniceras besairei* Collignon	$H = 22.9$	2nd	93 ± 3	0	Silvery-cream	−0.5	−0.3	16.8
M3-6	Same shell	$H = 21.1$	2nd	88 ± 3	0	Silvery-cream	−1.5	−0.7	18.5
M3-7	Same shell	$H = 21.0$	2nd	88 ± 3	0	Silvery-cream	−1.1	−0.7	18.5
M3-9	Same shell	$H = 20.1$	1st	95 ± 3	0	Silvery-cream	−1.7	−0.8	19.0
M3-10	Same shell	$H = 19.5$	2nd	90 ± 3	0	Silvery-cream	−1.4	−0.8	19.0
M3-11	Same shell	$H = 19.1$	2nd	90 ± 3	0	Silvery–cream	−1.8	−07	18.5
M3-12	Same shell	$H = 17.7$	2nd	93 ± 3	0	Silvery-cream	−1.6	−0.5	17.7
M3-13	Same shell	$H = 17.8$	1st	91 ± 3	0	Silvery–cream	−1.4	−0.6	18.1
M3-14	Same shell	$H = 16.9$	2nd	90 ± 3	0	Silvery-cream	−1.4	−0.7	18.5
M3-17	Same shell	$H = 16.2$	1st	97 ± 3	0	Silvery-cream	−1.6	−0.5	17.7
M3-20	Same shell	$H = 14.6$	2nd	87 ± 3	0	Silvery-cream	−1.8	−0.6	18.1
M3-21	Same shell	$H = 13.3$	1st	90 ± 3	0	Silvery-cream	−1.4	−0.5	17.7
M3-22	Same shell	$H = 13.2$	1st	95 ± 3	0	Silvery-cream	−1.3	−0.7	18.5
M3-24	Same shell	$H = 13.0$	1st	95 ± 3	0	Silvery-cream	−2.1	−0.9	19.4
M3-25	Same shell	$H = 12.8$	2nd	90 ± 3	0	Silvery-cream	−1.9	−0.7	18.5
M3-26	Same shell p.	$H = 12.2$	2nd	93 ± 3	0	Silvery-cream	−1.3	−0.5	17.5
M3-29	Same shell	$H = 11.3$	1st	100	0	Silvery-cream	−0.7	−0.3	16.8
M3-30	Same shell	$H = 11.0$	1st	100	0	Silvery-cream	−0.4	−0.2	16.4
M4-1	*Desmoceras* sp.	$H = 18.2$	1st	96 ± 3	0	Silvery-cream	1.2	0.0	15.5
M4-2	Same shell	$H = 17.8$	1st	96 ± 3	0	Silvery-cream	0.9	−0.3	16.8
M4-5	Same shell	$H = 16.2$	2nd	90 ± 3	0	Silvery-cream	0.3	−0.7	18.5
M4-7	Same shell	$H = 15.9$	2nd	93 ± 3	0	Silvery-cream	0.7	−0.5	17.7
M4-9	Same shell	$H = 15.0$	2nd	94 ± 3	0	Silvery-cream	0.8	−0.2	16.4
M4-11	Same shell	$H = 14.8$	1st	98 ± 2	0	Silvery-cream	−0.1	−0.8	19.0
M4-13	Same shell	$H = 14.0$	1st	100	0	Silvery-cream	−0.4	−0.9	19.4
M4-14	Same shell	$H = 13.7$	1st	100	0	Silvery-cream	0.0	−1.1	20.3
M4-18	Same shell	$H = 11.9$	1st	100	0	Silvery-cream	0.2	−1.3	21.1
M5-2	*Douvilleiceras* sp.	$H = 12.0$	2nd	91 ± 3	0	Silvery-cream	0.2	−1.4	21.6
M5-3	Same shell	$H = 11.0$	1st	100	0	Cream	0.2	−1.4	21.6
M5-4	Same shell	$H = 10.5$	1st	97 ± 3	0	Cream	0.5	−1.3	21.1
M5-5	Same shell	$H = 10.0$	1st	100	0	Cream	0.4	−1.3	21.1
M5-6	Same shell	$H = 9.5$	2nd	94 ± 3	0	Cream	0.1	−1.3	21.1
M5-9	Same shell	$H = 8.5$	1st	97 ± 3	0	Cream	0.3	−1.3	21.1
M5-11	Same shell	$H = 8.3$	1st	96 ± 3	0	Cream	0.2	−1.2	20.7
M5-12	Same shell	$H = 8.0$	1st	97 ± 3	0	Cream	0.3	−1.2	20.7
M5-13	Same shell	$H = 7.6$	1st	96 ± 3	0	Cream	0.2	−1.3	21.0
M5-16	Same shell	$H = 7.3$	1st	100	0	Cream	0.2	−1.2	20.7
M5-17	Same shell	$H = 7.2$	2nd	93 ± 3	0	Cream	0.2	−1.1	20.2
M5-19	Same shell	$H = 7.0$	2nd	93 ± 3	0	Cream	0.3	−1.2	20.7
M5-20	Same shell	$H = 6.8$	1st	95 ± 3	0	Cream	0.4	−1.2	20.7
M5-21	Same shell	$H = 6.5$	1st	100	0	Cream	0.6	−1.2	20.7
M5-22	Same shell	$H = 6.0$	1st	97 ± 3	0	Cream	0.9	−1.1	20.3
M5-23	Same shell	$H = 5.8$	1st	100	0	Cream	0.8	−1.1	20.3

(i.e. assuming the mean Cretaceous ocean delta to be the same as that of present day seas).

In this paper we use the form proposed by Anderson and Arthur (1983):

$$T(^\circ\mathrm{C}) = 6.0 - 4.14\left(\delta^{18}\mathrm{O}_{\mathrm{calcite}} - \delta_{\mathrm{W}}\right) + 0.13\left(\delta^{18}\mathrm{O}_{\mathrm{calcite}} - \delta_{\mathrm{W}}\right)^2 \quad (2)$$

where T (°C) is the ambient temperature, $\delta^{18}\mathrm{O}_{\mathrm{calcite}}$ (‰) is the oxygen isotope ratio of the calcite (versus VPDB), and δ_{W}(‰) is the δ^{18}O of ambient water (versus VSMOW). A δ_{W} of −1.0‰ VSMOW is thought to be appropriate for an ice-free world (e.g., Shackleton and Kennet, 1975; Hudson and Anderson, 1989; Pirrie and Marshall, 1990; Price and Hart, 2002; Huber et al., 2002).

The revised isotope data suggest that the late Albian palaeotemperatures for the presumably Dalmiapurum Formation of the Trichinopoly district, judging from Bowen's (1961a) data, range between 16.5 °C and 17.4 °C. Shallow-water palaeotemperatures (14.3–18.5 °C) calculated by us for the upper Albian of the Karai Shale Formation of the same area on the basis of data from *Parahibolites blanfordi* rostra from the Bad Land

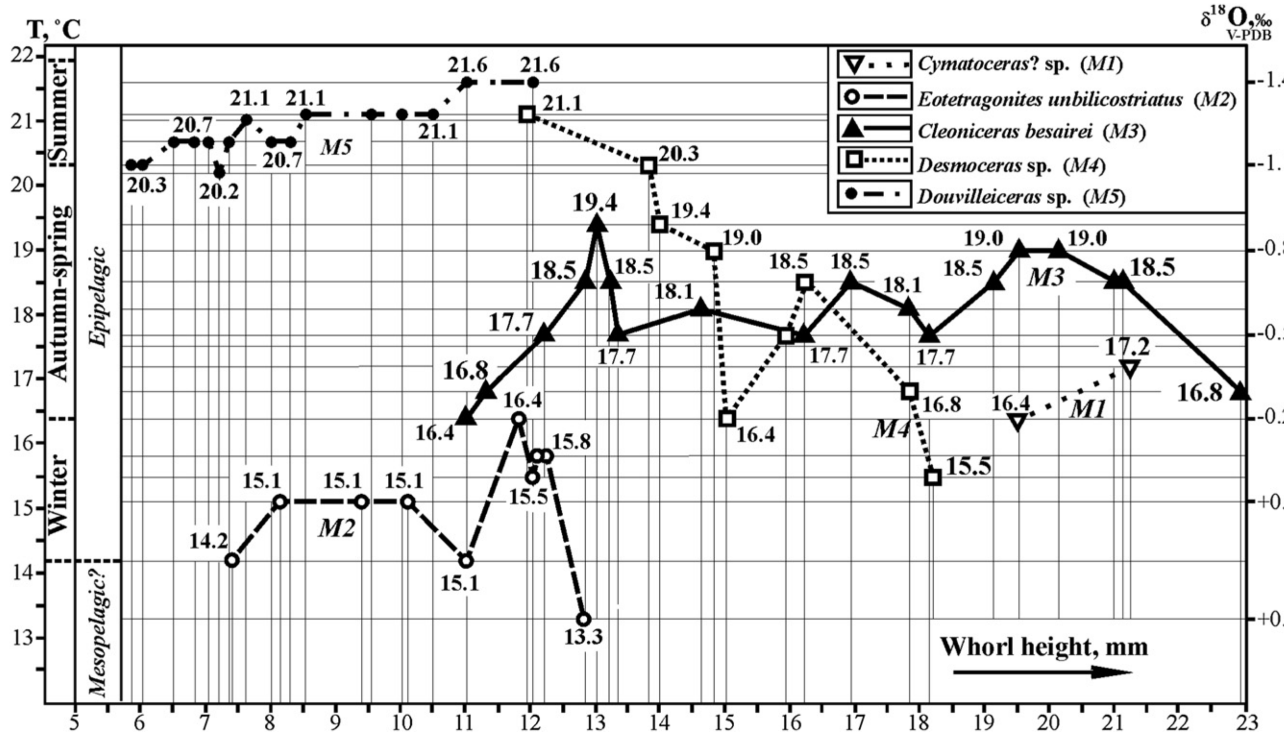

Fig. 15. Palaeotemperatures in the northwestern Madagascar marine basin at early Albian time. 1 – *Douvilleiceras* sp., 2 – *Cleoniceras besairei* Collignon, 3 – *Cymatoceras* sp., 4 –*Desmoceras* sp., 5 – *Eotetragonites umbilicostriatus* Collignon.

locality are similar to those calculated from restricted Bowen's (1961a) oxygen-isotope data.

Oxygen-isotopic composition of nautiloid *Cymatoceras*? sp. from the lower Albian of Madagascar shows that its investigated portions were secreted at palaeotemperatures of 16.4–17.2 °C (Figs. 15 and 16). Somewhat similar results have been obtained from ammonoids *Cleoniceras besairei* (16.4–19.4 °C) and *Desmoceras* sp. (15.5–21.1 °C). All sixteen samples, taken from the ammonoid *Douvilleiceras* sp. show comparatively high palaeotemperatures, which might be explained by their secretion during summer or inhabitation this ammonite with unusually strong sculpture at most shallow part of the shelf. Lowest palaeotemperatures (13.3–16.4 °C) were shown by ten samples taken from the ammonoid *Eotetragonites umbilicostriatus* shell, which might be caused by secretion of the mentioned parts of the shell during winter or ability of this ammonite to migrate in the water column, reaching sometimes colder upper bathyal waters (Figs. 15 and 16).

Palaeotemperatures estimated from oxygen isotopic analyses on Albian cephalopods from southern India and Madagascar consistent with known palaeotemperature data obtained from Albian cephalopods from the Pas-de-Calais area (21.9–22.8 °C) and Normandy (19.3–22.8 °C) (Fig. 17) (Zakharov et al., 2006d). However, these

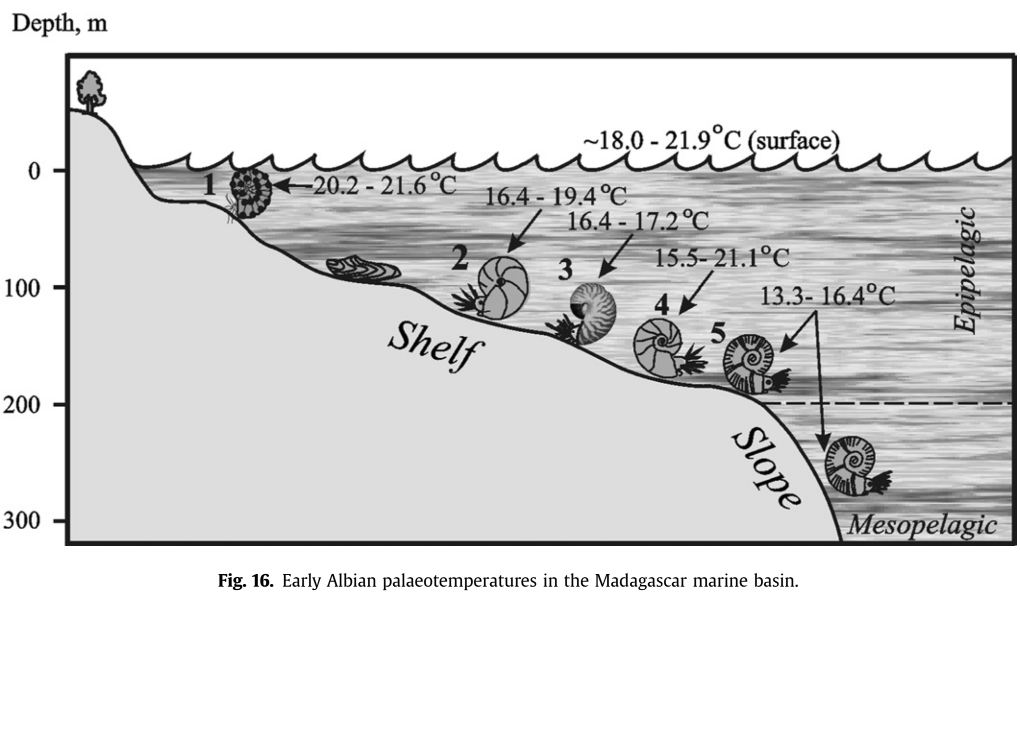

Fig. 16. Early Albian palaeotemperatures in the Madagascar marine basin.

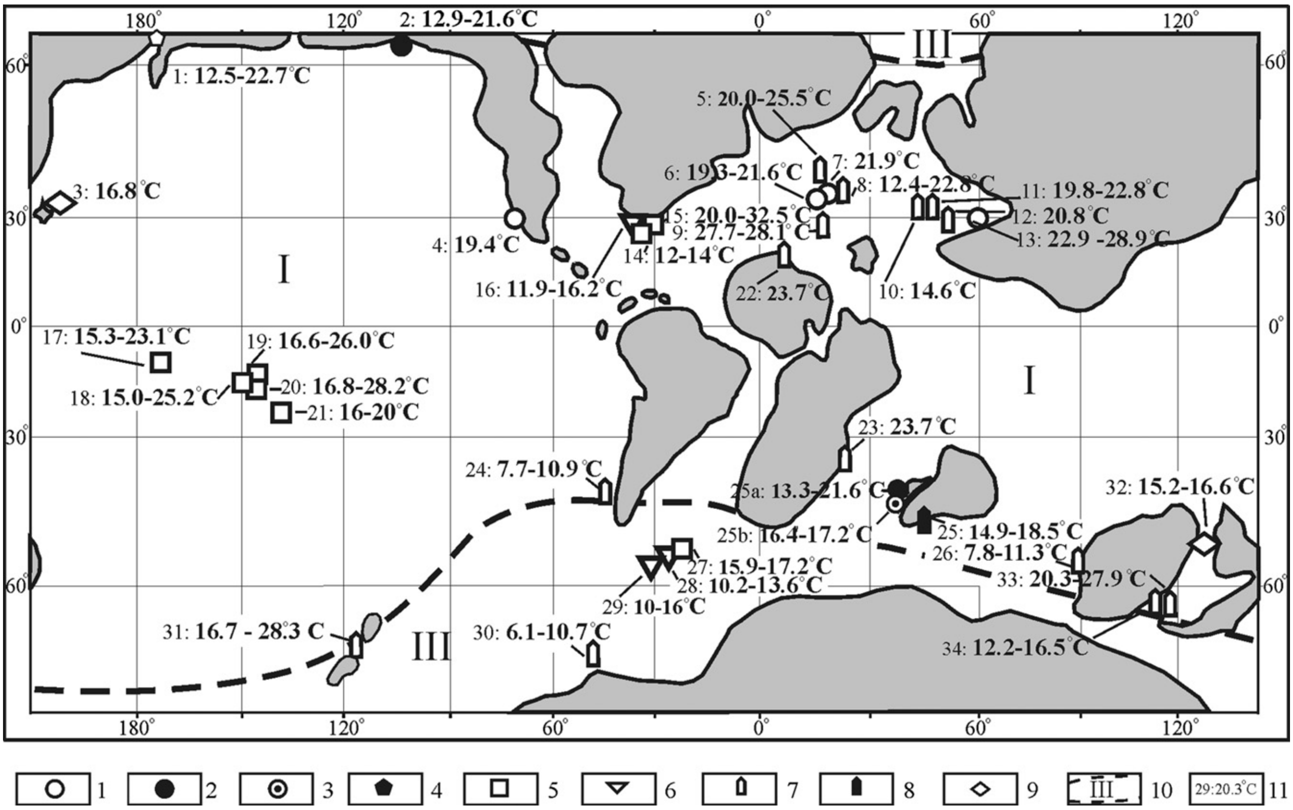

Fig. 17. Map showing isotopic palaeotemperatures for the Albian. 1 and 2 – from ammonoid shells: 1 – original data, 2 – published data, 3 – from nautiloid shells (original data), 4 – from brachiopod shells (published data), 5 – from planktic foraminifera (literary data), 6 – from benthic foraminifera (literary data), 7–8 – from belemnite rostra: 7 – literary data, 8 – original data, 9 – from bivalve shells (literary data), 10 – climatic zones (I – tropical-subtropical, II – warm-temperate), 11 – locality number and palaeotemperature. Localities: 1 – Melkaya River – late Albian (Zakharov et al., 2006d), 2 – South Alaska – early Albian (Zakharov et al., 2011), 3 – Horokanai area, Hokkaido – late Albian (Zakharov et al., 2006d), 4 – Shaeta county, California – Albian (Lowenstam and Epstein, 1959), 5 – England – Albian (Bowen, 1961b), 6 – Northern France, Normandy – Early Albian (Zakharov et al., 2006c), 7 and 8 – Northern France, Pas-de-Calais – middle Albian (Zakharov et al., 2006d): 7 – from ammonoid shell, 8 – from belemnite rostra, 9 – Southern France Albian (Bowen and Fontes, 1963), 10 and 11 – Crimea (Teiss and Naidin, 1973): 10 – early Albian, 11 – late Albian, 12 – Kheu River, North Caucasus (Teiss and Naidin, 1973), 13 –Mangyshlak – late Early and Late Albian ammonoids (Zakharov et al., 2006d, 14–16 – Blake Nose (Erbacher et al., 2001; Norris and Wilson, 1998; Huber et al., 2002): 14 – Early Albian planktic foraminifera, 15 – Late Albian planktic foraminifera, 16 – Late Albian benthic foraminifera, 17 –Hole 305 – Albian (Douglas and Savin, 1975), 18–20 – Hole 463 (Price and Hart, 2002): 18 – Early Albian, 19 – Middle Albian, 20 – Late Albian, 21 – Hole 167 – Late Albian (Douglas and Savin, 1973); 22 – Algeria – Albian (Lowenstam and Epstein, 1954); 23 – Mozambique – Albian (Lowenstam and Epstein, 1954); 24 – Lago San Martin, Argentina – Early Albian (Pirrie et al., 2004); 25 – Karai, India (original data); 25a – b – Madagascar Early Albian (original data): a – ammonoids, b – nautiloid; 26 – Carnnarvom, Australia – late Early–early Late Albian (Pirrie et al., 1995); 27–29 – Hole 511 (Huber et al., 1995, 2002): 27 – Albian planktic foraminifera, 28 – Early Albian benthic foraminifera, 29 – Late Albian benthic foraminifera; 30 – James Ross, Antarctic – Early Albian (Pirrie et al., 2004); 31 – New Zealand – Middle and Late Albian (Stevens and Clayton, 1971); 32 – Queensland, Australia – Albian (Bowen, 1969); 33 – Fossil Creek, Southern Australia – Albian (Dorman and Gill, 1959).

palaeotemperature are higher than those calculated from Albian belemnites from Lago San Martin, Argentina (7.7–10.9 °C), James Ross Basin, Antarctica (6.1–10.7 °C) and Carnarvon Basin, Australia (7.8–11.3 °C) (Pirrie et al., 2004), but lower than Cenomanian–Turonian values, calculated from benthic foraminifera (21–29 °C) (Gupta et al., 2007) and a belemnite rostrum (judging from its oxygen isotope composition (Ayysami, 2006), about 20.7 °C) of southern India, as well as palaeotemperatures calculated from oxygen isotopes measured on Late Bathonian brachiopod shells from the Kachchh Basin, northwestern India (19.6–24.2 °C) (Fürsich et al., 2005) and Oxfordian bivalve (19.5–23.1 °C) and ammonoid (17.1–29.9 °C) shells from Madagascar (Lécuyer and Bucher, 2006). Our interpretation of the new isotopic palaeotemperature data suggests that southern India and Madagascar were in middle latitudes during Albian time locating at the same time within the tropical–subtropical climatic zone, which is consistent with data on crocodiliform osteoderms, common for the Upper Cretaceous Maevarno Formation of the Majunga Basin, northwestern Madagascar (Ravelson and Whatley, 2009). Besides, we suggest that the mentioned Jurassic–Cretaceous temperature fluctuation at the India–Madagascar area is connected first of all with the Oxfordian global warming, somewhat cooler conditions during Albian time and next increasing of global warming at the beginning of the Late Cretaceous.

Based on maximal $\delta^{18}O$ values (from −2.2 to −1.9‰) in investigated bivalve shells from the Kallankurichchi Formation of the Trichinopoly area, the palaeotemperatures of the south Indian shallow water basins probably ranged between 19.8° and 21.2 °C during the early Maastrichtian. However, our knowledge of Maastrichtian palaeotemperatures in southern India remains limited.

5.3. Carbon-isotope results

One can see that $\delta^{13}C$ values of calcite formed during the admittedly second life year of the belemnite In-10a (*Parahibolites blanfordi*) from the Albian of southern India are markedly lower than those of belemnite portions created during its early ontogenetic stage of life (Fig. 10), which is apparently related with the intermittent reduction of biological productivity of the late Albian seas. Recently, we undertook the first attempt to show a possible correlation between Recent *Nautilus* $\delta^{13}C$ value changes and solar activity (Zakharov et al., 2006b). Our preliminary results indicate

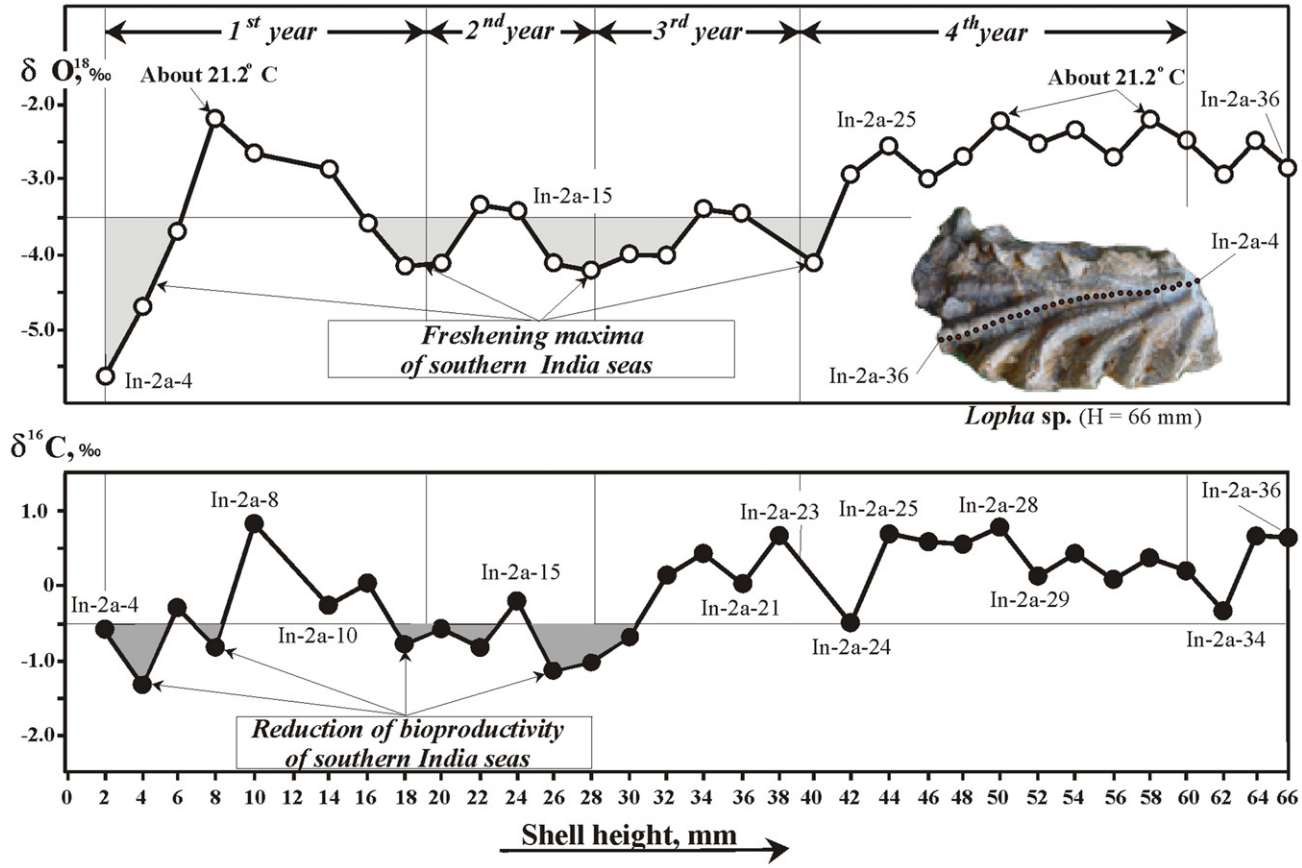

Fig. 18. Intended seasonal freshwater inputs and reconstructed raining seasons for the Southern India area during about 4–5 year interval of the Early Maastrichtian (on the basis of data from *Lopha* sp. shell In-2a from the Kallankurichchi Formation of the Cauvery Basin, southern India (interpretation from 35 samples).

that a direct relation exists between the solar activity at the beginning of cycle 23 (1996–1999) and the carbon isotope values in the septa of the investigated *Nautilus* shell from the Tangan area, Philippines (Zakharov et al., 2006b). This was confirmed by the results of analyses of living brachiopods from the same area. It is not inconceivable that the reduction of biological productivity of the late Albian marine basin during the end of investigated belemnite *Parahibolites blanfordi* life is also related with the intermittent reduction of solar activity of that time.

In contrast to the late Albian nectonic fossils, isotope results of well-preserved early Maastrichtian oyster *Lopha* shells from the Ariyalur Group of the Trichinopoly district in southern India are characterised usually by very low $\delta^{18}O$ values (up to −5.8‰) but "normal" $\delta^{13}C$ values, fluctuating from −2.2 to +2.6‰ (the $\delta^{18}O$–$\delta^{13}C$ cross-plot demonstrates a positive correlation – $r = 0.74$) (Figs. 12 and 18). This might be a result of influx of freshwater in the marine environment, probably locally. Similar change in the rainfall pattern towards higher humidity took place in India earlier, during the Callovian–Oxfordian (Fürsich et al., 2005).

Mook and Vogel (1968) attempted to find a criterion for determining of whether conditions were truly oceanic or not, based on isotopic composition of Recent bivalves *Mytilus, Cardium, Mya* and *Macoma* from two estuaries of the North Sea area in which the ratio of freshwater to seawater slowly varies. At least for the shells they investigated, there was a state of isotopic equilibrium between carbonate and solution, not only for the oxygen but also for the carbon isotopes (analysis of the relative abundances of ^{18}O and ^{13}C in the shell carbonates showed a linear relation between the two). At the same time they noted that for different regions, different $\delta^{18}O$ and (possibly) $\delta^{13}C$ values of the freshwater contaminant are to be expected, so that a straight carbonate line can only be expected in a restricted area. A gradual increase in the $\delta^{13}C$ of the freshwater contaminant they ascribed to isotopic exchange with the atmosphere. Such a situation apparently occurred in the Trichinopoly area during Maastrichtian time. Our hypothesis is supported by fact that living oyster bivalves usually prefer brackish water conditions. If the detail investigated bivalve *Lopha* sp. was more than one year old (we have dated it, though questionably, as four years old due to presence of about four sinusoidal cycles in both $\delta^{18}O$ and $\delta^{13}C$ diagrams, see in Fig. 18), then, apparently, there were annual rainy seasons in the southern India area during the early Maastrichtian. This scenario may possibly account for the freshwater input. The maxima of freshwater influence based on $\delta^{18}O$ data from the Trichinopoly area agrees with a reduction of biological productivity in the Cauvery Basin apparent from the carbon-isotope data (Fig. 18).

Our data on carbon-isotope composition of Cretaceous molluscs indicate that biological productivity of Indian and Madagascar marine basins during the Cretaceous was very variable.

6. Conclusions

1. New evidences show that Albian palaeotemperatures interpreted as summer values for near-bottom shelf waters in Madagascar (20.2–21.6 °C) are somewhat higher than those calculated for southern India (16.3–18.8 °C), but their winter values are very similar (13.3–16.4 °C and 14.7–16.1 °C,

respectively). However, the winter values are higher than those calculated from early Albian fossils from northern and southern high latitudes. New isotopic data suggest that Madagascar and southern India were in middle latitudes during Albian time, locating at the same time within the tropical–subtropical climatic zone.

2. Albian palaeotemperatures, obtained for the Madagascar–southern India area, are similar with those, calculated from isotopic composition of cephalopod shells from middle palaeolatitude area of Pas-de-Calais in northern France (Zakharov et al., 2006d), but significantly lower than mainly Cenomanian–Turonian values, calculated from benthic foraminifera of southern India (Gupta et al., 2007). It seems to be connected with increasing of global warming in the beginning of Late Cretaceous time.
3. Isotopic records, based on isotopic composition of Maastrichtian bivalve shells from the Ariyalur Group of the Cauvery Basin, allow to assume that this middle latitude region remained a part of tropical–subtropical climatic zone during the early Maastrichtian, but with tendency in increasing of humidity.

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