Microfacies analysis and depositional environments of the upper Cretaceous (Campanian-Maastrichtian) succession in the Cauvery Basin, southern India

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The Cauvery Basin of south India is an ideal reference section for the study of the marine Cretaceous (Aptian-Maastrichtian) sediments. The basin received more than 5500 m thick mixed siliciclastic and calcareous sediments in the course of intermittent phases of marine transgressions/regressions during Aptian-Maastrichtian time. The three microfacies-grainstone, packstone, and wackestone - have been broadly identified in the Campanian-Maastrichtian sediments of the Ariyalur Group of the Cauvery Basin. An attempt has been made here to use the distinctive features of these three microfacies and contained diverse bioclasts for the reconstruction of the physicochemical conditions to unravel the depositional history of this part of the Cauvery Basin, southern India. The facies analysis depicts a shallow marine (maximum depth 10 m) environment with an uninterrupted deepening from the Campanian to Middle Maastrichtian terminating into a basinal conditions during the Late Maastrichtian. The basin was well oxygenated with an average temperature (26°-28°C) of the Cretaceous sea and normal palaeosalinty range (30‰-35‰). These Campanian - Maastrichtian sediments are deposited on a carbonate ramp setting extending from the inner ramp to the marginal outer ramp.

ARTICLE HISTORY

INTRODUCTION

The microfacies analysis is regarded as one of the most important tools for the disclosure of the composition of biotic debris by studying the shell microstructures. Flügel (2010) defined the microfacies as the 'total of all sedimentological and palaeontological data' which can be described and classified from the thin sections, peels, polished sections, or rock samples. It provides subjective information with the integration of the fields of palaeontology and sedimentary petrography. It is basically related to skeletal microstructures *i.e.,* internal characters of the shells/skeletal walls documented as the geometry of skeletal architecture (Horowitz and Potter, 1971). It has an additional advantage of recording the presence of such fauna as bioclasts/skeletal fragments which are otherwise megascopically invisible or not recovered. Usually, these occurrences have notable applications in the chronostratigraphy or even in the elucidation of the depositional environment in view of the adaptation of a diverse group of organisms to a range of environments. The systematic study of the petrographical characters of the fossils has been long in practice and was earlier done under the carbonate petrography. The precise knowledge of the fossil petrography came through the coveted book of Horowitz and Potter (1971), which contains an elaborate review of the earlier classic works and detailed petrographic descriptions of various Phanerozoic fossil groups with well expressive photographs. The microfacies analysis of the Late Cretaceous (Campanian - Maastrichtian) carbonate sediments of Ariyalur region of south India records the presence of skeletal microstructures of numerous skeletal/shell fragments of foraminifers, bivalves, brachiopods, gastropods, cephalopods, echinoids, scleractinian corals, ostracods, bryozoans, and dasyclad algae. Although the diagenetic solution/recrystallization has frequently affected the geometry of skeletal architecture but in many cases, it is possible to allocate them at least to the broader categories of invertebrate fossil hierarchy. The main objective of the present study is to use these bioclasts/skeletal grains as the principal ingredient to identify and classify the different microfacies of the Ariyalur Group and to formulate a broad depositional history for Campanian - Maastrichtian of this part of the Cauvery Basin.

GEOLOGIC SETTING

The Cauvery Basin (Lat. 08°30' and 12° 30' N: Long. 78° 30' and 80° 30' E) occupies the south-eastern part of the

eastern coast of India and is spread over 25,000 km^2 onshore area (Kumar, 1983). The disintegration of primordial eastern Gondwana during the Late Jurassic - Early Cretaceous culminated into basement separation between India, Antarctica, and Australia (Veevers *et al*., 1991). This tectonic event configured the present NE - SW trending peri-cratonic Cauvery Basin with half-graben morphology having a regional dip of 5-10° E and SE directions (Ramkumar, 2015). The present-day tectonic setup of the Cauvery Basin reveals an initial block faulting and the deposition of Upper Jurassic - Lower Cretaceous sediments. However, the overall sedimentary history of the Cauvery Basin appears to be more controlled by sea-level fluctuations as a consequence of global sea-level changes (Ramkumar, 2004). The Cauvery Basin consists of Sivganga, Thanjavur, Ariyalur, Vriddachalam, and Puducherry sub-basins (Fig. 1A, after Banerji, 1972), altogether contains a near-complete stratigraphic record (both marine and non-marine sediments) from Barremian to Maastrichtian.

The fluvial non-marine sediments perhaps represent rift stage sediments. Later, the Cauvery Basin experienced continuous deepening with the deposition of basinal sediments with the peak of transgression during Cenomanian. The end-Cretaceous was marked by phases of uplift and erosion. These tectonic activities could have strongly affected relative sea-level changes in the basin resulting in episodes of transgression, regression, erosion, and deposition (Prasannakumar *et al*., 2016). Throughout the sedimentary history, the basin fills show textural immaturity.

The marine Cretaceous successions of the Cauvery Basin has been extensively explored for its rich invertebrate and microfossils, which have been later used for establishing the biostratigraphic framework (*e.g.,* Banerji, 1973; Sastri *et al*., 1977; Ayyasami, 1990; Venkatachalapathy and Ragothamanmi, 1995; Gale *et al*., 2002; Prasad and Pundeer, 2002; Ayyasami, 2006; Bragina and Bragin, 2013; Rai *et al*., 2013). The Cauvery Basin has a close resemblance in tectonic evolution, stratigraphy, and sea-level trends with the central European basins *viz.,* Danish, North Sea, North Germany, and Northern Gulf of Mexico (Nagendra *et al*., 2011). The global Cenomanian sea-level rise (Gignoux, 1943) which reached its maxima during Turonian (Hancock and Kauffman, 1979) has also affected the Indian subcontinent and deposited a thick pile (more than 5500 m) of siliciclastic and calcareous sediments during Aptian - Maastrichtian interval along the eastern coast of southern India (Sundaram *et al*., 2001). These shallow marine successions laden with well preserved invertebrate fauna are popularly called 'Cretaceous of Tiruchirapalli' and globally established as a reference sequence for the various Cretaceous horizons. Blanford (1862) classified these marine Cretaceous sediments into Uttatur Group, Trichinopoly Group, and Ariyalur Group in ascending order (Fig. 2). Later workers (*e.g.,* Bhatia and Jain, 1969; Banerji, 1972; Sastry *et al*., 1972; Sundaram and Rao, 1986; Ramasamy and Banerji, 1991; Tewari *et al*., 1996; Sundaram *et al*., 2001; Verma, 2015; Gautam *et al*., 2019a,b) retained the three-fold classification of Blanford (1862) with few modifications, which has been followed in the present work (Fig. 1B).

The sediments of the Ariyalur Group are exposed in the Ariyalur Sub-basin and occupy the northern part along the western margin of the Cauvery Basin. The Ariyalur Group has earlier been classified by Tewari and Srivastava (1967) into three formations: Sillakkudi, Kallankurichchi, and Cullamood (Kallamedu) in the order of superposition. Later Sastry *et al*. (1972) demarcated two litho units Ottakkovil and Kallamedu Formations within the Kallamedu Formation. This lithostratigraphic scheme was further revised by Sundaram *et al*. (2001) by retaining the three-fold classification of Tewari and Srivastava (1967) by clubbing Ottakkovil and Kallamedu formations under Kallamedu Formation with the remarks that the usage of two separate units was 'not supported by distinct lithological attributes'. Tewari *et al*. (1996) believed that the Ottakkovil Formation is a locally developed regressive marine facies and non-mappable unit. However, Ottakkovil and Kallamedu Formations are found faunastically quite distinct. Pteriomorphs, rudist heterodonts, heteromorph ammonoids, etc are persisting in the Ottakkovil Formation, but in the Kallamedu Formation only vertebrate remains (considered as drift carcasses by Sundaram *et al*., 2001) and fossil woods are found; none of the invertebrates have been so far recorded from this unit. These two formations have dominant siliciclastic lithology. The Ottakkovil Formation consists of fine to medium-grained sediments while Kallamedu Formation is mostly medium to coarse-grained. Facies wise, the shallow marine Ottakkovil Formation is separated from the underlying Kallankurichchi Formation by a non-depositional surface and overlain by Kallamedu Formation of fluvial origin (Ramkumar, 2004). Henceforth, as also pointed out in early works (Madhavaraju and Ramasamy, 1999 a, b; Jaitly and Mishra, 2001, 2011), the four-fold classification proposed by Hart *et al*. (1996) and Ramkumar (2004) with a few modifications has been followed here (Fig.1C).

Globally, the Maastrichtian was a period of widespread marine regression (Fischer and Germann, 1987; Haq *et al*., 1988), yet in the Cauvery Basin, the sea level started rising during the Early Campanian and continued at least up to the latest Middle Maastrichtian. The evidence of the transgressive conditions during Maastrichtian has been recorded from several parts of the globe *e.g.,* Oman, which experienced upward deepening transgression (Alsharhan and Nasir, 1996; Gameil, 2005), however, most of the workers attributed it to local subsidence at a place exceeding the rate of supply of sediments (Altmeyer, 1982; Negendank, 1983; Gullentops, 1986, etc.). The depositional model of Ariyalur Group has been vividly discussed by Ramkumar, 1996 a, b 1999, 2001, 2004, 2006; Ramkumar and Chandrasekaran, 1996 and Ramkumar *et al*., 2004a, b. They portrayed a distally steepened carbonate ramp for this part of the Cauvery Basin. Ramkumar (1996a, b, 2004) has also discussed in detail the various aspects of the Ariyalur Sub-Basin including the microfacies analysis by using the bioclasts in general *e.g.,* molluscs, echinoderms, corals, and others especially for the Kallankurichchi Formation (Maastrichtian). However, the present authors could identify these bioclasts at least up to the generic level and in some cases even at species level while attempting to infer the various depositional parameters of the Ariyalur Sub-basin. The distribution pattern of these benthic communities is basically controlled by sediment supply, water energy, oxygenation, light, and nutrient, where relative deepening of sea and nutrient supply are thought to be motivating factors (Gotz *et al*., 2005).
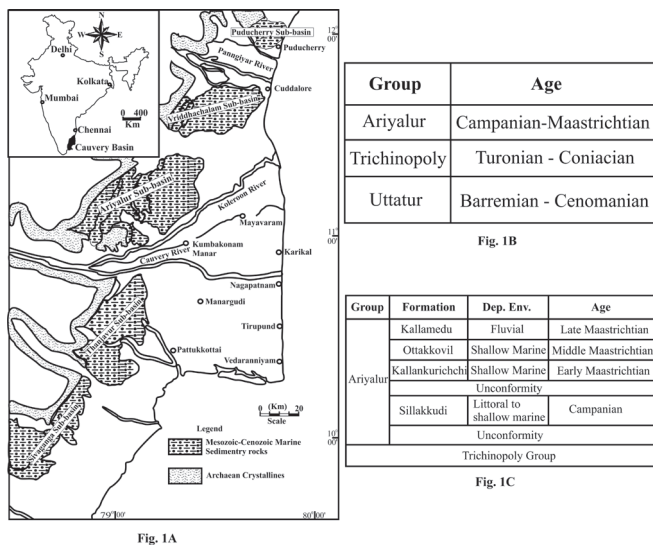
Group	Age
Ariyalur	Campanian-Maastrichtian
Trichinopoly	Turonian - Coniacian
Uttatur	Barremian - Cenomanian

Fig. 1B

Group	Formation	Dep. Env.	Age
Ariyalur	Kallamedu	Fluvial	Late Maastrichtian
	Ottakkovil	Shallow Marine	Middle Maastrichtian
	Kallankurichchi	Shallow Marine	Early Maastrichtian
	Unconformity		
	Sillakkudi	Littoral to shallow marine	Campanian
	Unconformity		
	Trichinopoly Group		

Fig. 1C

Fig. 1. A. The five sub-basins in the Cauvery Basin (modified after Banerji, 1972), B. General stratigraphy of the Cretaceous of the Cauvery Basin, south India (modified after Sundaram *et al.*, 2001) and C. Lithostratigraphy of the Ariyalur Group (modified after Hart *et al.*, 1996; Ramkumar, 2004).

The basal part (Sillakkudi Formation) witnessed the beginning of the transgressive phase with the deposition of coastal conglomerates which experienced further deepening in the latest Campanian-Early Maastrichtian as evidenced by the gradual reduction of the size of siliciclastic sediments followed by deposition of carbonates (Kallankurichchi Formation). Deposition of Kallankurichchi Formation took place in a carbonate ramp setting under normal saline, warm, and well mixed open sea conditions with low to moderate depositional rate and energy. Thereafter, there was a pause in sedimentation due to receding sea level exposing the fossiliferous middle shelf carbonates for erosion and subsequent re-sedimentation into biostromal deposits (Fürsich and Pandey, 1999; Ramkumar, 2004). There was a drop in the sea level as evidenced by the deposition of shallow marine siliciclastic in Ottakkovil Formation (Late Maastrichtian) immediately above the carbonates (Kallankkurichi Formation) followed by fluvial sediments of Kallamedu Formation of the latest Maastrichtian which establishes the gradual regression during the end-Cretaceous (Rai *et al.*, 2013). Such changes in this part of the Cauvery Basin have been ascribed to the global sea-level fluctuations, which have played a major role in the deposition of sediments of the Ariyalur Group (Raju *et al.*, 1993; Hart *et al.*, 2000; Ramkumar *et al.*, 2004b). On the whole, the matrix is composed of carbonate mud, very fine skeletal fragments, very fine quartz, silt, and argillaceous materials. These fine skeletal fragments are considered intrabasinal in origin. The fibrous cement spars are formed at or near the sediment-water interface under the marine regime (Ramkumar, 2004). Grainstone with micritised bioclasts is usually formed in agitated warm water at shallow depth. The low micrite matrix represents shoreface areas with shoals affected by fair-weather waves developed in inner ramp settings and also influenced by storm waves and coast parallel bottom currents (Flügel, 2004).
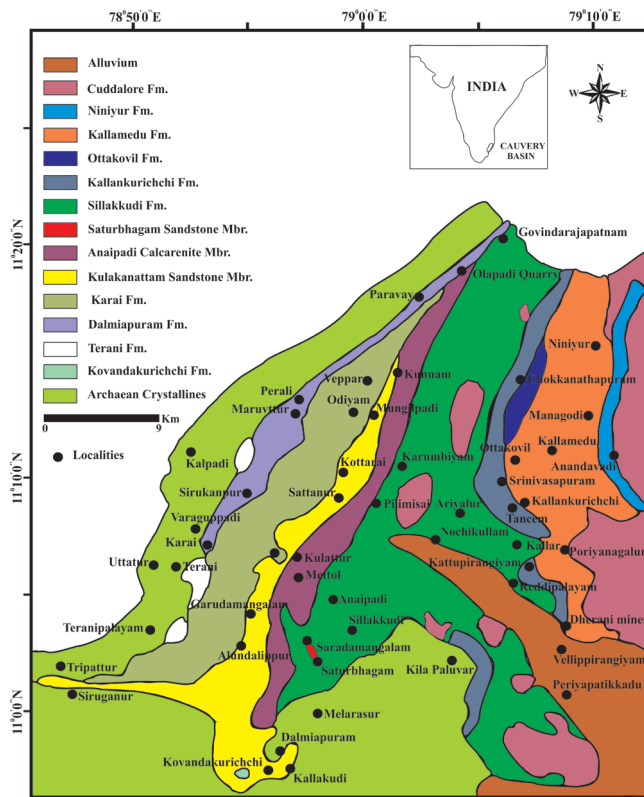

Fig. 2. Geological map of the Ariyalur Sub-basin (modified after Sathish *et al.*, 2017).

MATERIALS AND METHODS

The thin sections of only calcareous lithic units have been used for the microfacies analysis as shell fragments are sparsely distributed in the siliciclastic lithic units. The recognition of the microfacies follows the classification of Dunham (1962), which has been later elaborated by Embry and Klovan (1971) and revised by Wright (1992). It helps in the characterization of microfacies, especially when the quantification of individual allochem has not been attempted. For categorizing the bioclasts, mainly Horowitz and Potter (1971) and Majewske (1974) have been broadly followed. In most of the cases these microfacies are affected by diagenetic solutions and are exceedingly recrystallised and impregnated by ferruginous material. The skeletal material (sensu Kidwell, 1991) is recrystallised up to the extent that the shell microstructures are obliterated and often difficult to identify.

All the photomicrographs are of the same magnification. For the purpose of the field description of the fossiliferous calcareous horizons, the basic palaeontological observations have been made as recapitulated by Gold ring (1991) for the carbonate sediments.

MICROFACIES ANALYSIS

Three microfacies namely grainstone, packstone and

wackestone have been broadly identified in the Ariyalur Group. The carbonate microfacies are not found in younger Ottakkovil and Kallamedu formations of the Ariyalur Group. The grainstone microfacies is present in the upper part of the Sillakkudi Formation (Campanian) and continues up to the basal part of the Kallankurichi Formation (early Early Maastrichtian). The succeeding mid Early Maastrichtian is dominated by packstone microfacies sometimes. It is difficult to separate grainstone from packstone when allochems are coarse and unsorted present in siliciclastic material. In grainstone and packstone microfacies, due to variations in the water energy thin layers of grainstone/packstone are frequent in occurrence. Higher up in the section of Kallankurichi Formation (late Early Maastrichtian), the wackestone microfacies is present. On the whole, three types of grainstone microfacies, five types of packstone microfacies and one type of wackestone microfacies have been recognised in the Campanian - Maastrichtian sediments. Each of them has been broadly christened on the basis of the dominating bioclasts and/or their associations. For further authentication, these identified microfacies of the Ariyalur Group have been compared to Standard Microfacies (SMF) of Flügel (2010) and accordingly ramp environment has been deciphered (Table 1).

Grainstone microfacies

This microfacies consists of tightly packed peloids along with sub angular quartz and a little feldspar (albite) grains. Some quartz grains are polycrystalline and exhibiting undulose extinction. The containing bioclasts of various shapes and sizes are extensively affected by neomorphic processes. The percentage of quartz grains is decreasing upward in the section. The identification of most of the bioclasts is tentative as in many cases these have been compared to their macro - representatives.

Foraminifer bioclastic grainstone-In this microfacies foraminifers are the most dominating bioclasts. Most of these are basically rounded to sub rounded and accompanied by inconsistent proportions of bioclasts of other invertebrate fossils. In some cases, the bioclasts represent complete shells, but due to the effect of diagenetic solution/and or may be due to winnowing process by waves and tides most of its microstructural features are lost and could only be broadly identifiable. It is also marred by the encrustation of other bioclasts concealing the microstructures of the host bioclast as seen in the transverse section of the cup coral-encrusted by bryozoa (on the lower right side, Plate 1: 4a) and losing most of its original microstructure due to recrystallisation and impregnation of ferruginous material in the central part of the cup (Plate 1, Fig. 4a). It is partly encrusted by an incomplete *Heterohelix* foraminifer, whose microstructure has also been destroyed due to recrystallisation (Plate 1, Fig. 4b).

The most abundant allochem is of larger foraminifer shells constituting about more than 40% of the allochems along with a few smaller globular foraminifers. Barring a few, most of the foraminifers are represented by incomplete shells/shell fragments, so that their generic identification has been tentative. The recognizable foraminifers belong to the genera *Lepidorbitoides*, *Pseudorbitoides*, *Pseudotexularia*, and *Heterohelix*. The *Lepidorbitoides*is is represented by a vertical section with fairly preserved flat lateral chambers on both sides of the median zone (Plate 1, Fig. 5a). The microspheric *Pseudorbitoides* present in the central-vertical section show a sudden increase in pseudorbitidlayers (Plate 1, Figs. 6 b,c). The bioclast of *Pseudotexularia*is fragmentary and only outer surface is visible in the thin section (Plate 2, Fig. 3a). *Heterohelix*is seen in an oblique vertical section within a complete apical part and as remnants of shell fragments (Plate 2, Figs. 3c, i). Besides, a keeled globotruncanid fragment (Plate 2, Fig. 3e) and some other unidentifiable foraminifer bioclasts are also present. The accompanying bioclasts belong to an assorted group of invertebrates like brachiopod represented by a shell fragment (Plate 1, Fig. 5b) and a spine (Plate 2, Fig. 3b); poorly preserved tangential section of a bryozoon (Plate 1, Fig. 5c); crinoid stem (Plate 1, Fig. 5d); a fragment of echinoid shell (Plate 2, Fig. 3h); attached valve (AV) of *Vaccinites* represented by dorsal part (Plate 1, Fig. 5e), longitudinal section (Plate 2, Fig. 3f) and side upper view (Plate 2, Fig. 3j); a shell fragment of pycnodontid bivalve *Phygraea* with relics of vesicular microstructures (Plate 1, Fig. 6a); dorsal part of an unidentifiable thin bivalve shell (Plate 2, Fig. 3d); a poorly preserved articulated ostracode? *Cytherella* (Plate 1, Fig. 5f); transverse section with the remnant of septa of a scleractinian coral (Plate 1, Fig. 4a); a coral cup with multiple bivalve boring (Plate 2, Fig. 3g) and evidence of bivalve borings (Plate 2, Fig. 3i). Additionally, there are other unrecognizable bioclasts intermixed with sparry calcite matrix-forming biotic debris. The effect of recrystallisation and ferrugination is conspicuous. Few subrounded, polycrystalline quartz grains are present as terrigenous material. This microfacies is found equivalent to SMF 18 of Flügel (2010) representing high energy (storm) inner ramp environmental conditions (Table-1).

Bryozoan grainstone microfacies-The dominant allochem of this microfacies is bryozoa, categorized by transverse, longitudinal, and tangential sections of the shell fragments. The bryozoan bioclasts are diagenetically less altered and retain some of their original microstructures as evident in the longitudinal section of a cyclostome bryozoa? *Osculipora*. Traces of the interzooecial tissues and paucity of diaphragms in the outer part of the zooecium is visible near the zooarial surface. The outer zooarian is thick while the inner zone is thin and the boundaries of adjacent zooecia mark zooaria with numerous transverse partitions (Plate 3, Fig. 3a). It is superficially resembling *Osculipora carolinensis* Taylor and Mckinney (2006, p. 46, Pl. 26) recorded from the Maastrichtian of Albama (U.S.). Other recognizable bryozoa belong to cerioporid genus *Tetrocycloecia* (Plate 3, Fig. 1a). It could be compared with *Tetrocycloecia tennesseensis* (Canu and Bassler, 1926) described by Taylor and McKinney (2006, Pl. 30, p.51, fig. 4a) from the Maastrichtian of North Carolina (U.S.). Few shell fragments of rounded to subrounded, moderately well-sorted bivalve bioclasts are also present (not seen in the present thin section as its resolution has been amplified to show the microstructures of bryozoa). All these bioclasts are present in the sparry calcite matrix. It is correlatible to SMF 4 (Flügel, 2010) of mid-ramp depositional setting (Table-1).
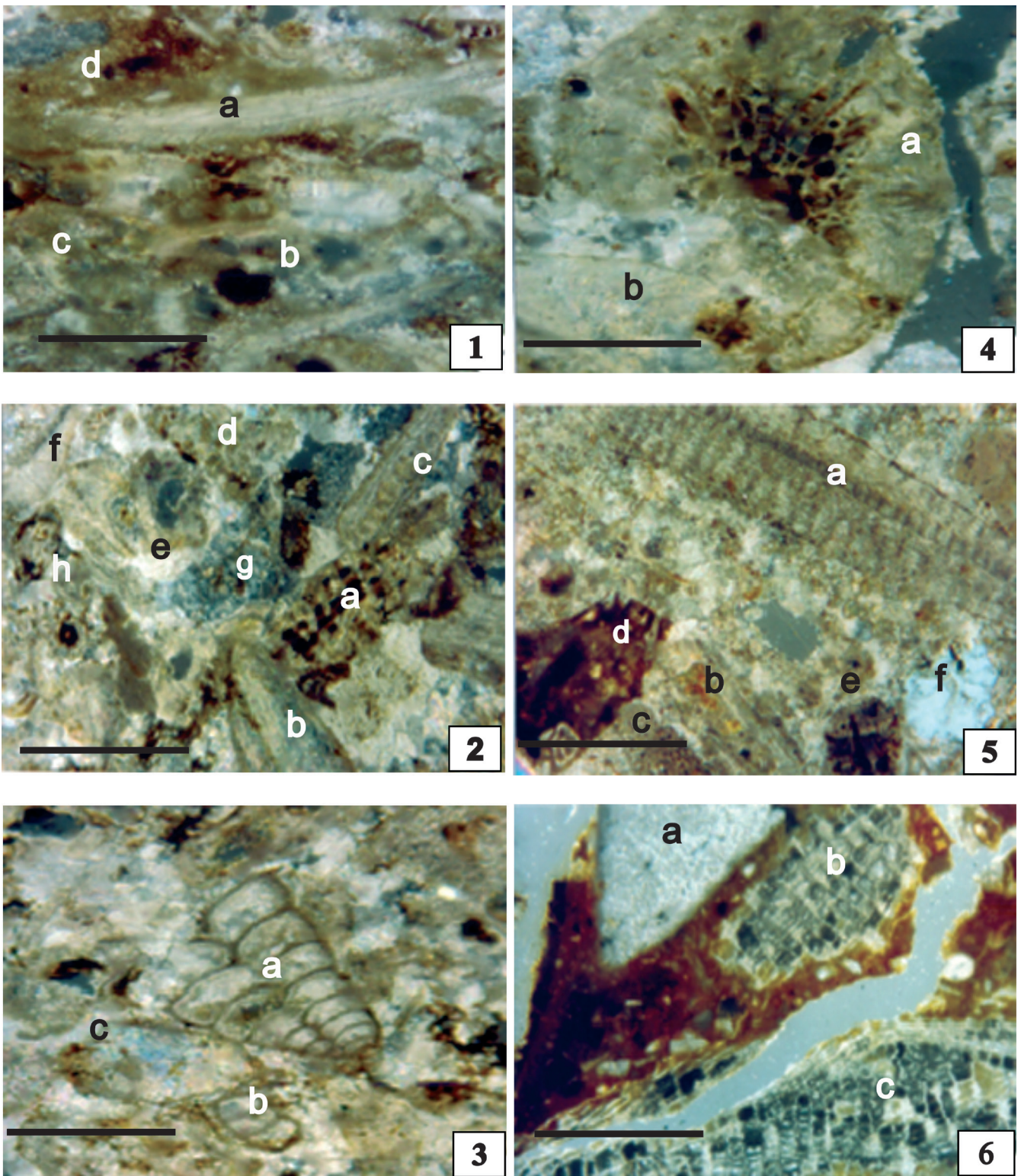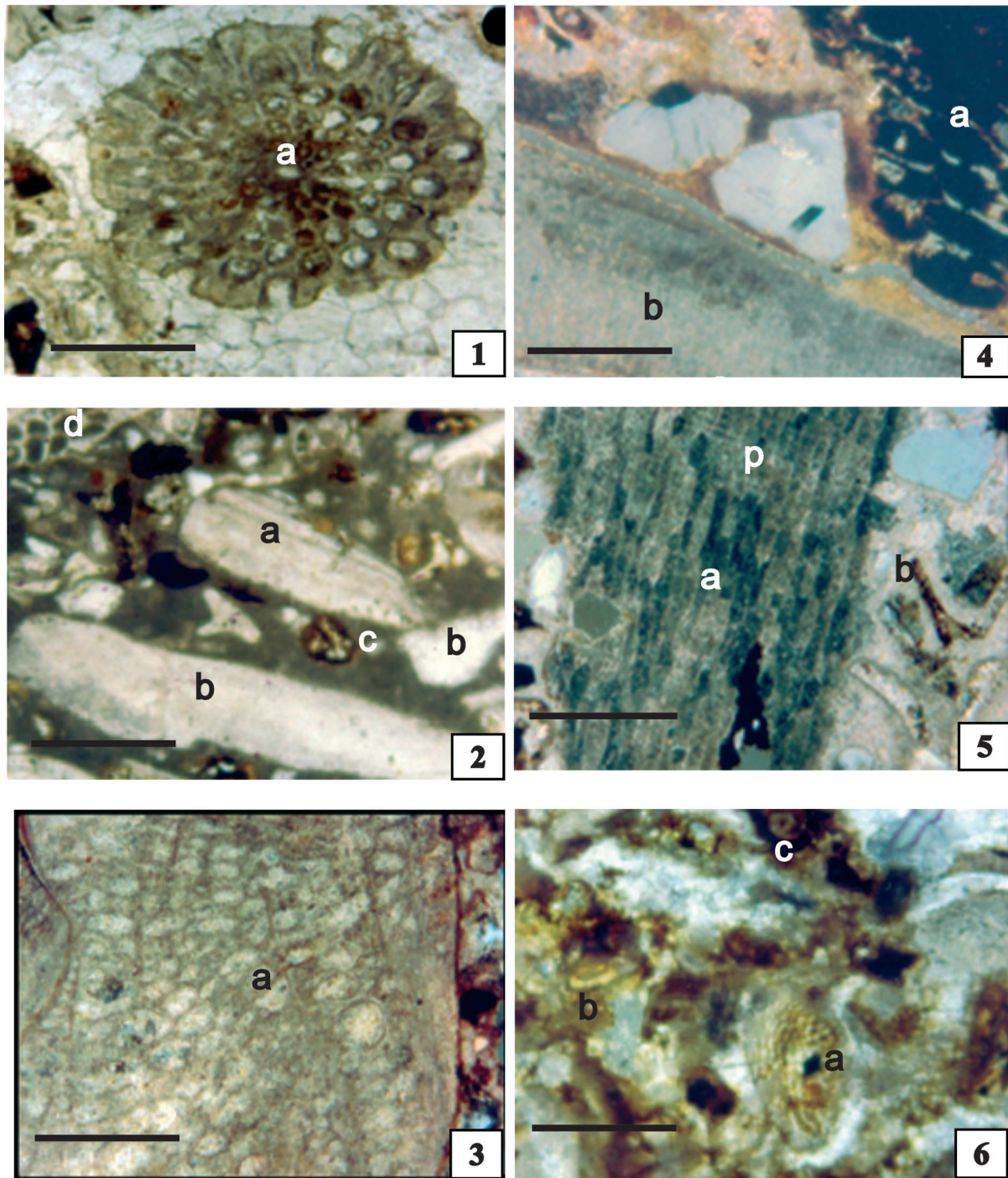
EXPLANATION OF PLATE I

1. Shell fragment of a gastropod (a) and axial sections of pseudorbitoidid foram (b, c, d); **2**. large bolvinoidid foram, chambers obscured by ferruginous mud (a), bivalve shell with x- lamellar microstructure (b), side views of *Bolvinoides* (c, d), transverse section of the attached valve of a hippuritid bivalve (e), shell fragment of pycnodontid bivalve (f), bryozoans zooecia (g) and axial section of a small foram (h); **3**. Side view of *Heterohelix rajagopalani* (a), oblique equatorial section of an orbitoidal embryo with three chambers (b), and a crinoid stem (c); **4.** Transverse section of a coral cup with remnants of septa (a) and an incomplete shell of *Lepidorbitoides* (b); **5.** vertical section of *Lepidorbitoides* (a), brachiopod shell fragment (b), tangential section of bryozoan with remnants of walls (c), crinoidal stem (d), oblique section of attached valve of *Vaccinites* (e), and obscurely preserved ?*Cytherella* (f); **6**. *Phygraea* (*P.*) *vesicularis* with a relic of vesicular microstructure (a) and central - vertical sections of a microspheric test of *Pseudorbitoides* (b, c).
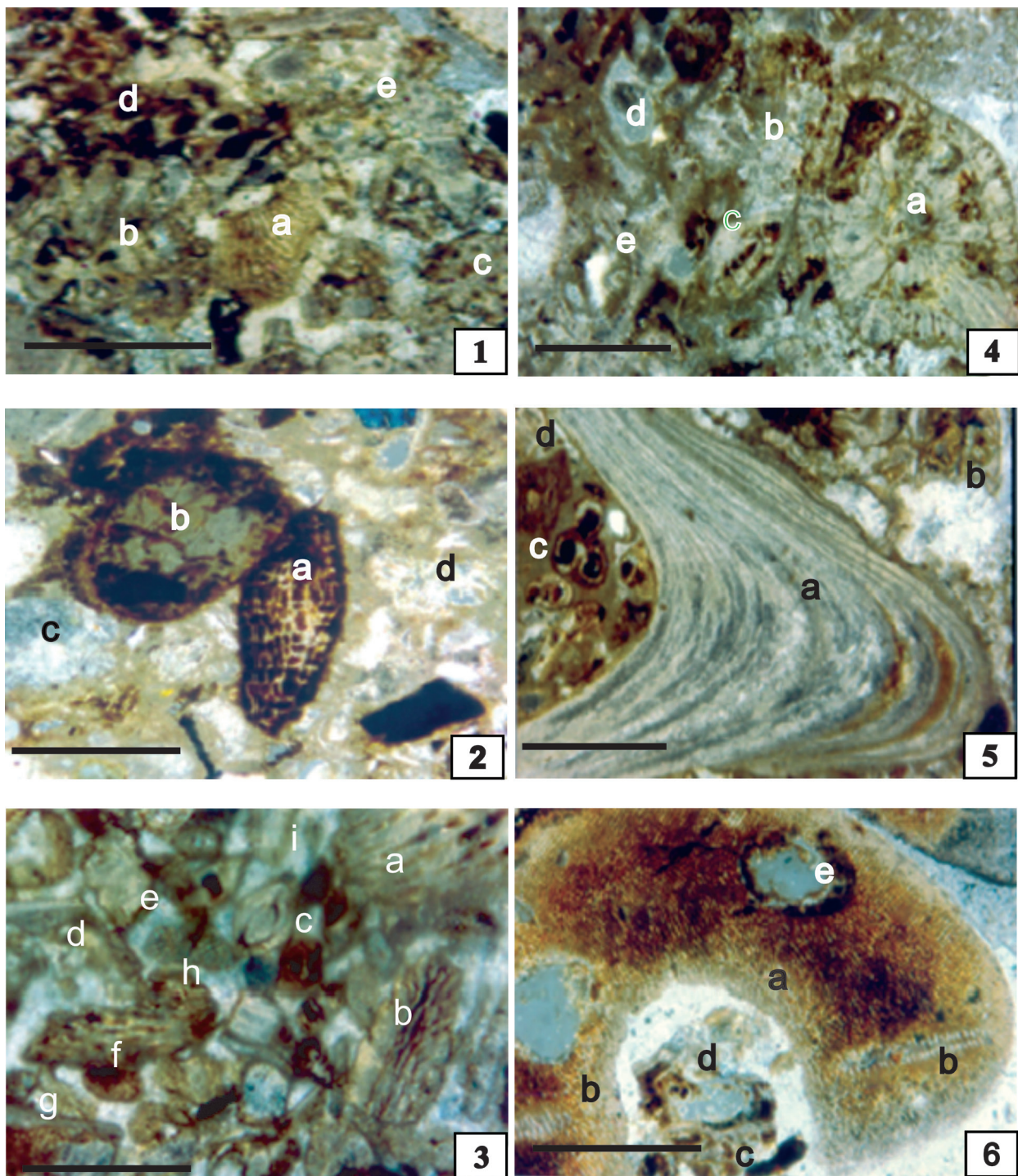
EXPLANATION OF PLATE II

1. Fragmentary axial part of *Orbitoides* (a), transverse sections (b, c) of *Neocoenia*, obscured by bryozoan encrustations (d), and a high spired gastropod shell, chambers obliterated (e); **2.** Recrystallized oblique axial section of a *Pseudorbitoides* (a), recrystallised and ferruginised large ostracode with overlapping walls (b) and coral cups, details lost due to reworking (c, d); **3.** Part of the outer surface of a *Pseudotexularia* (a), longitudinal section of a fragment of a brachiopod spine (b), oblique vertical section of a small *Heterohelix*, apical cells destroyed (c) and an incomplete shell (i), dorsal part of a thin shell fragment of a bivalve (d), keeled globotruncanid foraminifer (e), longitudinal sections of fragments of the attached valve of rudist bivalve (f) and side upper view (g) and poorly preserved shell fragment of an echinoid (h); **4.** Axial section of a large *Siderolites* with chambers and pillars (a) and oblique section (b,) and axial sections (c, d, e) of a large *Orbitoides;* **5.** Foliaceous shell fragment of *Phygraea* (*P.*) *vesicularis* with intervening vesicular microstructures in alternate folia (a), longitudinal section of a bifoliate bryozoan zooecium (b), and fragment of a zooecium (d), and longitudinal, transverse sections of a gastropod shell (c); **6.** Cross-section of an echinod column with a series of radial pores (a), vertical section of a *Lepidorbitoides* (b), moderately high spired gastropod with broad base (c), centrally bored and encrusted by a small heterohelixid foraminifer (d), and poorly preserved cross-section of the attached valve of a ?*Biradiolites* (e).

EXPLANATION OF PLATE III

1. Transverse section of a ceriopodbryozoa ?*Tetrocyclioecia* (a); **2**. Longitudinal section of brachiopod spine (a), shell fragment of *Phygraea,* most of vesicular microstructures eradicated due to recrystallisation (b), attached valve of a small rudist bivalve, details of tooth and sockets destroyed due to recrystallisation (c) and a part of the bryozoans colony of *Theonoa* with autozooids within the fascicles, irregularly polygonalin cross section (d); **3.** Longitudinal section of a cyticid cyclostomes bryozoa ?*Osculipora* along zoarial surface showing remnants of interzooecial tissues and paucity of diaphragms in the outer part of zooecia. Outerzone thick, inner zone thin, boundaries of adjacent zooecium with numerous transverse partitions (a); **4.** Longitudinal section of a fragment of ?*Pycnoporidium* having branching and partitions in filaments obscured by secondary deposition of ferruginous mud (a) and a *Phygraea (P.) vesicularis* with remnants of vesicular microstructures (b); **5.** A shell fragment of the attached valve of *Vaccinites*, original rudist microstructures partially obscured due to recrystallization (a), in upper part radial pores visible (p) and a fragment of agglutinated foraminifer *Placopsilina*, chambers destroyed due to recrystallisation and deposition of secondary material (b); **6.** Trasverse section of a megalospheric foraminifer ?*Sirtina* having micritic walls indistinguishable from muddy matrix of finally communited fossil debris (a), a small foraminifer ?*Gavelinella* in an oblique peripheral view (b) and a recrystallised globotruncanid foraminifer shell filled with ferruginous mud (c).

Table 1. The comparison of the identified microfacies of the Ariyalur Group with Standard Microfacies of Flügel (2010) and inferred depositional environment.

| Group	Formation	Age		Dominent Lithology	Dominent Bioclast	Microfacies	Equivalent standard Microfacies (Flugel, 2010)	Inferred Depositional Enviornment
A R I Y A L U R	Kallankurichchi	late Early	M A A S T R I C H T I A N	Fragmented shell bedded shelly limestone	echinoids, ostracodes & corals	Wackestone	SMF 12	Outer ramp
		mid Early		Inoceramid argillaceous limestone	foraminifera, bryozoa, algae, echinoids & gastropods	Packestone	SMF 4/SMF 5	Mid ramp
		early Early		Arenaceous fossiliferous limestone	foraminifera, bryozoa & hippuritid bivalves	Packestone/ Grainstone	SMF 11/ SMF 16	Shelf lagoon / Inner ramp / shelf lagoon
	Sillakkudi	Campanian		Medium to fine calcareous sandstone & conglomarate	foraminifera, *Phygraea*, corals & bryozoa	Grainstone	SMF 18 / SMF 5	Inner ramp / lagoon

Rudist bivalve-foraminifer grainstone microfacies-The main bioclasts are hippuritid bivalve and foraminifers. The former belongs to *Vaccinites* represented by a longitudinal fractured section of the outer layer of the attached valve. This outer surface has remnants of longitudinal ribs separated by furrows with elongate rectangular cells. The ridges and furrows present on the exterior of the shell are affected by recrystallisation and are somewhat recognizable, however, reticulate pores are visible (Plate 3, Figs. 5a,p). The foraminifer belongs to the genus ?*Placopsilina*. Its chambers are partially destroyed due to recystallization and subsequent deposition of secondary material (Plate 3, Figs. 5b). There are a few more foraminifer fragments and other unrecognizable bioclasts (not seen in the present thin section due to amplification to show the microstructures of the above two clearly). All these bioclasts are present in the sparry calcite matrix intermixed with other unrecognizable bioclasts forming debris. These microfacies correspond well to SMF 11 (Flügel, 2010) deposited within shelf lagoon (Table-1).

Packstone microfacies

This is the most common microfacies of the Ariyalur Group. The allochems occur in a matrix having silty quartz, calcite spars, subordinate mud mixed with peloids, and shell fragments. At places, the micritic filling is evidenced in the interspaces in the pores of bioclasts. The effect of recrystallisation/ferrugination is conspicuous. By and large, the foraminifers are the dominating bioclasts and coexist in uneven proportion with skeletal fragments of echinoid, bivalves, corals, gastropods, etc.

Foraminifer packstone microfacies - The foraminifer bioclasts are represented by different types of preservation. The psuedorbitoidid foraminifers are the most dominating (Plate 1, Figs. 1b,c,d). Most of them are recrystallised and generally, the shell microstructures are destroyed. The other foraminifers are megalospheric ?*Sirtina*, represented by transverse section having micritic walls indistinguishable from the muddy matrix of finally communted fossil debris (Plate 3, Fig. 6a),?*Gavelinella*, a small foraminifer in an

oblique peripheral view (Plate 3, Fig. 6b), planispirally coiled *Deriellina*, most of the characters of the chambers razed due to recrystallisation (Plate 4, Fig. 1a), a small ?*Pseudotexularia* represented by a side view with a few chambers filled with secondary ferruginous material (Plate 4, Fig. 1d). The *Siderolites* is both small (represented by axial section, details much lost due to reworking, Plate 4, Fig. 2e) and large (Plate 2, Fig. 4a) in size as observed in lateral views. The *Orbitoides*, which is also common in occurrence in this packstone microfacies is represented by the axial part of a large (Plate 2, Fig. 1a) and oblique, axial sections of the small fragments (Plate 2, Fig. 1a; Plate 2, Figs. 4b,c,d,e). It is also represented by embryo apparatus as seen in the equatorial sections with three broad chambers (Plate 1, Fig. 3b). *Heterohelix* is by far the best-preserved foraminifer bioclast and can be identified with *Heterohelix rajagopalani* recorded by Govindan (1972) from the Puducherry area, South India (Plate 1, Fig. 3a). The other *Heterohelix*is tentatively identified as *Heterohelix punctata* by Abramovich *et al*. (2003), present as a cross-section of recrystallized wall of a shell (Plate 4, Fig. 2c). *Bolvinoides* is represented by a large shell with chambers obscured by ferruginous mud and also seen in inadequately preserved side views (Plate 1, Figs. 2a,c,d). In addition a biserial *Dorthia* (Plate 4, Fig. 2a), a recrystallized globotruncanid shell filled with ferruginous mud (Plate 3: 6c) and unrecognizable small foraminifer bioclasts (Plate 1, Figs. 2g,h) are also present. The associated bioclasts are crinoids, bivalves, corals, and gastropods. The crinoids fragments are present both as crinoidal brachial filled with syntaxial cement (Plate 4, Figs. 1b,c) and recrystallised stem (Plate 1, Fig. 3c). The bivalves mostly belong to *Phygraea* (*P.*) *vesicularis* showing prismatic microstructure (Plate 4, Fig. 1e), cross lamellar microstructure (Plate 1: 2b), and relics of vesicular microstructure (Plate 1, Fig. 2f). The other bivalve bioclasts are of hippuritids represented by a transverse section viewed towards commissure of the attached valve (A.V.) of *Hippurites* (Plate 4, Fig. 2b); cross-section of A.V. of a small *Petalodontia* consisting three sockets and part of anterior myophore filled with ferruginous mud (Plate 4, Fig. 2d) and a highly recrystallised transverse section (Plate 1, Fig. 2e). The coral *Neocoenia* is present in transverse sections (Plate 2, Figs. 1b,c) and encrusted
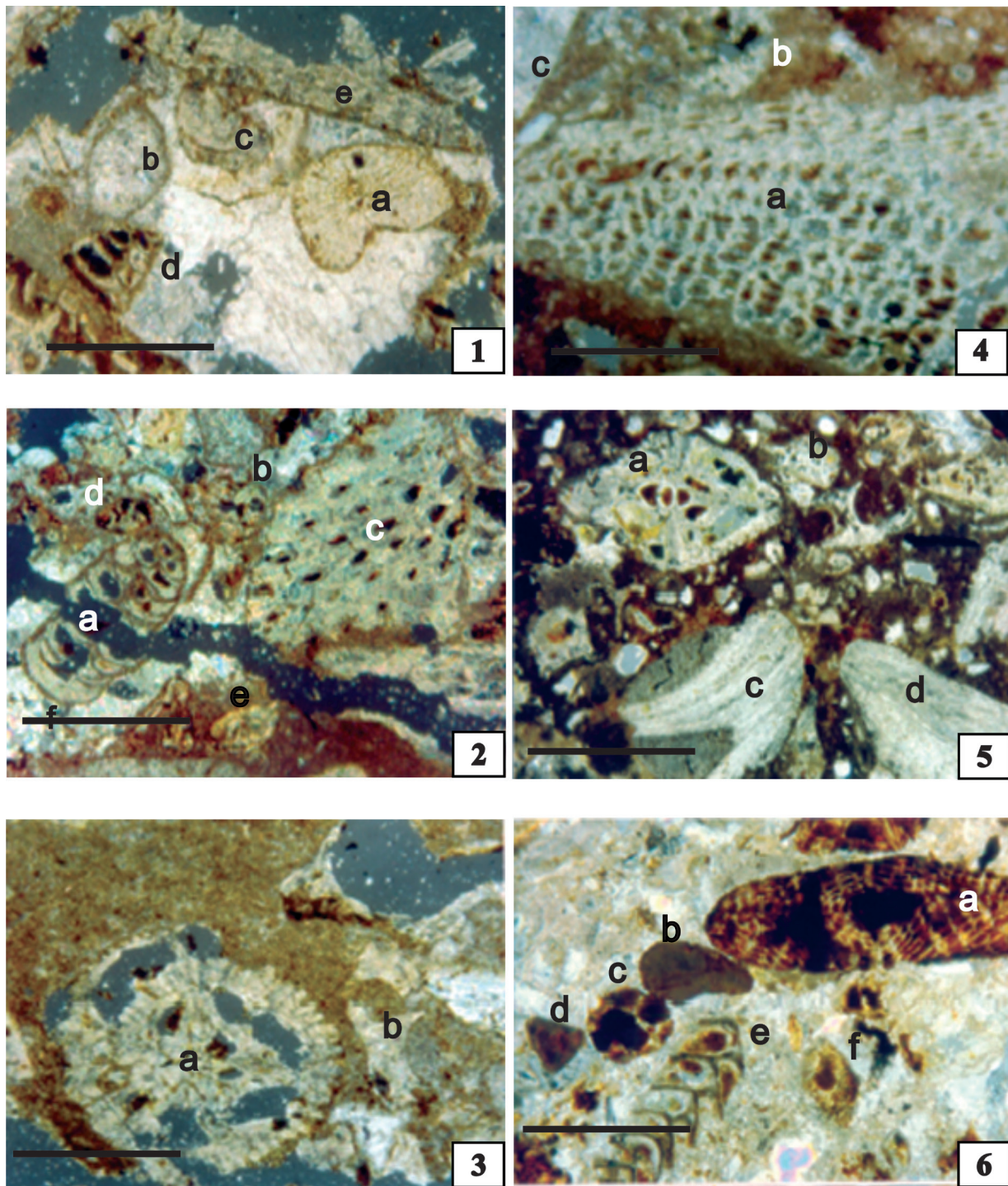
EXPLANATION OF PLATE IV

1. Planispiral foram *Deriellina* (a), fragments of crinoidal brachial filled with syntaxial cement (b, c), side view of *Pseudotextularia* (d), and a bivalve shell fragment with prismatic microstructure(e); **2.** Side view of a biserial benthic foram *Dorthia* (a), transverse section, viewed towards commissure of an attached valve of *Hippurites* (b), cross-section of recrystallised wall of *Heterohelixpunctata* (c), cross-section of an attached valve of a small *Petalodontia* with three sockets and part of anterior myophore (d), axial section of a small *Siderolites*, details much lost due to reworking (e), foraminifer attached to poorly preserved bryozoan colony (f). All these are present in shell debris with secondarily deposited calcareous and ferruginous material. Bioclasts have thin micritised crust of coralline algae; **3.** Equatorial section of a *Praesiderolites* with some chambers affected by diagentic solution(a) and fragment of an echinoid spine (b); **4.** External view of the encrusted outer surface of *Psuedosiderolites* showing details of canal openings (a), recrystallised coral cup of *Neocoenia* (b), and a recrystallised small bivalve shell fragment (c); **5.** Axial section of *Sirtina* (a), a globotruncanid shell (b), pycnodontid oyster with alternating thick fibrous and thin vesicular layers (c) and a reworked fragment (d); **6.** Transverse section of *Orbitoides* (a), obscurely preserved ?*Nanionella* (b), internal surface of free valve of *Mitrocaprina* (c), a highly ferruginised bryazoan zooecia (d), side view of *Bolivinopsis* (e) and cross section of an echinoid spine (f).
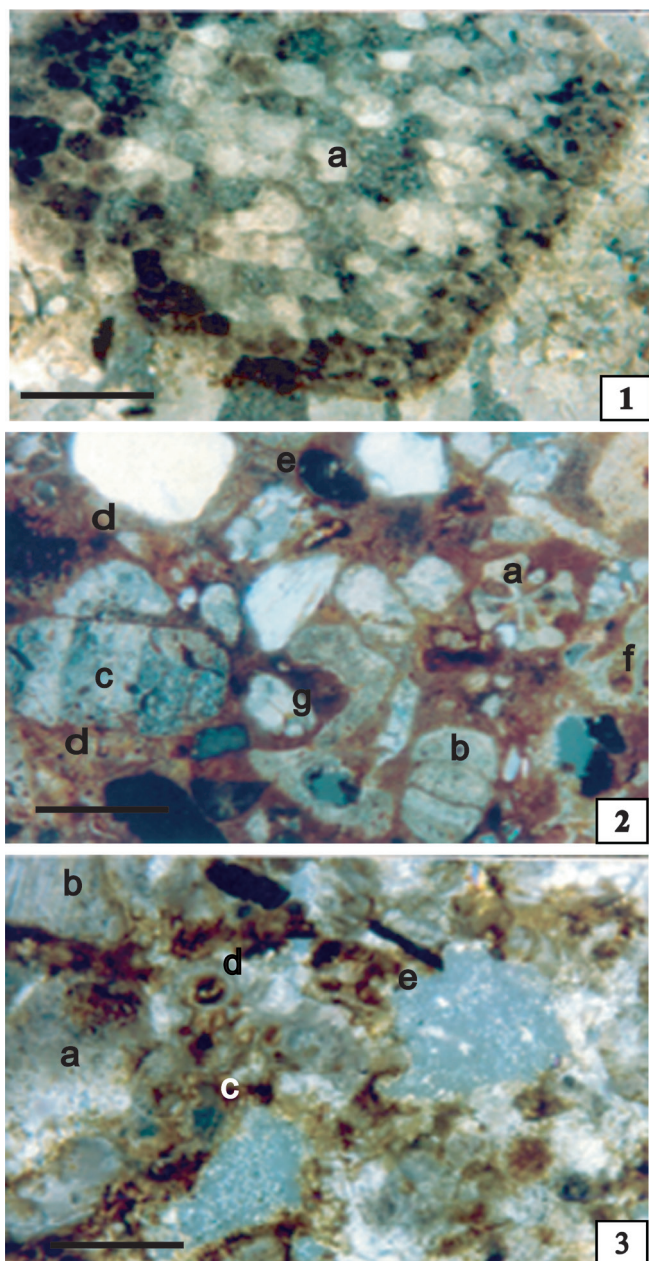
EXPLANATION OF PLATE V

1. Bryozoan zooaria encrusting another bryozoa (*?Membranipora* displaying sheet-like honeycomb structure, zooaria recrystallised and replaced by sparry calcite. The host bryozoa is diagenetically altered). The entire zooaria has a peripheral micritised crust of coralline algae (a); **2.** Calyx of *Neocoenia* with relics of radial septa, other features obscured by recrystallisation (a), megalospheric embryo apparatus of an orbotoitid foraminifer in equatorial section with three broad chambers (b, c), a bryozoan zooecia impregnated with ferruginous mud (d), an articulated ostracode filled with ferruginous mud (e), a moderately high spired gastropod with broad base (f) and a cross-section of *Biradiolites* (g); **3.** A pseudorbitoidid encrusted by bryozoa and both recrystallised (a), fragment of attached valve of a rudist bivalve displaying longitudinal folds and bryozoans encrustation (b, c), transverse section of a hollow brachiopod spine (d), and an extremely recrystallized globotruncanid foraminifer (e).

by bryozoans (Plate 2, Figs. 1d). The gastropods too are fragmentary and exhibit crossed-lamellar microstructure but whorls are indistinguishable due to recrystallisation (Plate 1, Figs. 1a; Plate 2, Fig. 1e). The foraminifers *Deriellina* and *?Pseudotexularia*, crinoidal stems, and the bivalve fragments are partially or completely bounded by a thin crust of coralline algae (Kroh and Nebelsick, 2010). All these bioclasts are present in heterogeneous shell debris. This microfacies is similar to SMF 5 (Flügel, 2010) of the shallow inner ramp environment (Table-1).

Bioclastic packstone-In this type of microfacies assorted bioclasts of foraminifers, bivalves, bryozoa, corals, gastropods, etc. are present. Overall most of these bioclasts are inadequately preserved so that a broad and tentative identification is done. The foraminifers belong to orbitoidal megalospheric embryo apparatus as seen in the equatorial section with three broad chambers (Plate 5, Figs. 2b,c); pseudorbitoidid foraminfer encrusted by bryozoans and both recrystallised (Plate 5, Fig. 3a); *Psuedosiderolites* with canal opening (Plate 4, Fig. 4a) and a ferruginised globotruncanid foraminifer (Plate 5, Fig. 3e). The rudist bivalve *Biradiolites* is represented by a cross-section of recrystallised A.V. valve (Plate 5, Fig. 2g) and a fragment of A.V. showing longitudinal folds on a bryozoan colony (Plate 5, Fig. 3b). A completely recrystallised bivalve skeletal fragment is also present (Plate 4, Fig. 4c). The bryozoans are represented by incomplete colonies which are recrystallised (Plate 5, Fig. 3c) and ferruginised (Plate 5, Fig. 2d). The coral *Neocoenia* is represented by its calyx with the remnant of radial septa (Plate 4, Fig. 4b, Plate 5, Fig. 2a). The other broadly identifiable associated bioclasts are articulated ostracode completely filled by ferruginous mud (Plate 5, Fig. 2e), a moderately high spired gastropod with a broad base and indistinct chambers (Plate 5, Fig. 2f), and a hollow brachiopods spine in transverse section of (Plate 5, Fig. 3d). These along with other unidentifiable bioclasts are found in shell debris mixed with sparry calcite matrix. At places, the bioclasts are engulfed by thin coralline algal crust (micritised). It represents SMF 4 (Flügel, 2010) of mid-ramp depositional environment (Table-1).

Bryozoan-oyster packstone microfacies - The bryozoans are the dominating bioclasts represented by incomplete zooecium (Plate 2, Fig. 5d), longitudinal section of a bifoliate zooecium (Plate 2, Fig. 5b), and a portion of the colony of *Theonoa* with autozooids within the fascicles exhibiting irregular polygonal shape in cross-section (Plate 3, Fig. 2d) and a *?Membranipora*de, showing sheet-like honeycomb structure, whose zooaria is completely recrystallised and replaced by sparry calcite and engulfed by a micritised peripheral crust of coralline algae (Plate 5, Fig. 1a). The oyster is represented by *Phygraea* (*P.*) *vesicularis* with alternate thick fibrous and thin vesicular layers (Plate 4, Fig. 5c), and at places, its original vesicular structure is lost due to recrystallisation (Plate 4, Fig. 5d; Plate 3, Fig. 2b). The characteristic vesicular structure is also observed in another foliaceous shell fragment in the intervening parts of folia (Plate 2, Fig. 5a). The other accompanying bioclasts are rudist bivalve represented by a small attached valve, whose

details of teeth and sockets are lost due to recrystallisation and subsequent deposition of ferruginous material (Plate 3, Fig. 2c); axial section of foraminifer *Sirtina* (Plate 4, Fig. 5a); unrecognizable globotruncanid shell (Plate 4, Fig. 5b); longitudinal and transverse sections of gastropod shells (Plate 2, Fig. 5c) and longitudinal section of a brachiopod spine (Plate 3, Fig. 2a). These are present in the sparry calcite matrix intermixed with shell debris. The present microfacies correspond well to SMF 10 (Flügel, 2010) of mid-ramp setting (Table-1).

Echinoid-foraminifer packstone microfacies- The echinoids are one of the dominant macrofossils in the area but not so well represented in thin sections except for isolated plates and spines fragments. Occasionally column of plates is visible in cross-section with a series of radial pores. In a micritised corona, the radial pores of the plates are strongly leached due to pressure solution (Plate 2, Fig. 6a). It is encrusted by a small *Heterohelix* (Plate 2, Fig. 6d) and a *Lepidorbitoides* seen in the vertical section (Plate 2, Fig. 6b) in the central part. The other associated bioclasts are moderately high spired gastropod with broad base (Plate 2, Fig. 6c) and an A.V. of a rudist bivalve superficially resembling *Biradiolites*d (Plate 2, Fig. 6e) especially those described by Caffua and Plenicer (2004). It is equivalent to SMF 5 (Flügel, 2010) of shallow inner ramp environment (Table-1).

Algae-bivalve packstone microfacies-The algae are represented by an algal fragment having filaments and septa (Plate 3, Fig. 4a). Most of the characters of the filaments are not visible due to the deposition of ferruginous mud. This algal fragment may belong to the genus *Pycnoporidium*, particularly to *P. Sinuosum* recorded by Jonshon and Konishi (1960) from the Late Cretaceous of Guatemala. In these microfacies coralline algae are also present and commonly occurs as a thin micritised crust surrounding the bioclasts of other invertebrates. The bivalve is represented by a large fragment of *Phygraea* (*P.*) *vesicularis* with remnants of prismatic, x-lamellar, and vesicular microstructures. Most of these microstructures, especially the vesicles are destroyed due to recrystallisation (Plate 3, Fig. 4b). It is well correlatable to SMF 18 of Flügel's (2010) standard microfacies of protected low energy inner ramp environment (Table-1).

Wackestone Microfacies

This microfacies is relatively less developed in comparison to grainstone and packstone microfacies. It is present immediately after the hard ground surface in the upper part of Kallankurichchi Formation. This microfacies is characterized by the bioclasts of foraminifers, echinoids, hippuritid bivalves, ostracods, bryozoan, and corals, which are unevenly distributed in calcareous/ferruginous mud. These bioclasts are less diverse than those of packstone microfacies. The foraminifers are relatively better preserved and identifiable at least up to the generic level. The echinoids could be differentiated into echinoderm plates exhibiting fine porous structures and echinoid spines with characteristic

internal fine radial patterns. The ostracods, corals, and bryozoa are broadly identifiable. Few angular to subangular, mono- as well as polycrystalline quartz, are irregularly distributed in the mud (Plate 4, Fig. 3). This microfacies has been named bioclastic wackestone microfacies. The foraminifer bioclasts are represented by a highly ferruginised transverse section of *Orbitoides* (Plate 4, Fig. 6a); a small ?*Nanionella* lacking ornamental details due to ferrugination (Plate 4, Fig. 6b); equatorial section of a *Praesiderolites* with chambers, some part of the inner chambers destroyed due to recrystallisation (Plate 4, Fig. 3a); side view of a biserial foraminifer *Bolivinopsis* (Plate 4, Fig. 6e); highly recrystallised and ferruginised oblique axial section of a *Pseudorbitoides* (Plate 2, Fig. 2a). The bivalve is represented by a hippuritid genus *Mitrocaprina*as seen in the internal view of the fixed valve (Plate 4, Fig. 6c). The other bioclasts correspond to a highly feruginised portion of zooecia of bryozoa (Plate 4, Fig. 6d); cross-sections of echinoid spines (Plate 4, Figs. 3b, 6f); a large ostracode with characteristic overlapping walls, recrystallised and ferruginised (Plate 2, Fig. 2b) and a coral corallite lacking details of septa due to recrystallisation (Plate 2, Figs. 2c,d). This sole wackestone microfacies corresponds to SMF 9 of Flügel, (2010) of the shallow lagoonal depositional environment (Table-1).

DISCUSSION

The foraminifers are practically present throughout but for bryozoan grainstone, oyster-bryozoan packstone, and algae-bivalve packstone microfacies. The foraminifers (both planktic and benthic) constitute more than 40% of the total bioclasts. The abundance of benthic forams is inversely proportioned to depth and is a more function of food and nutrient supply than temperature, palaeosalinity, and nature of the substrate (Zwaan *et al.*, 1990). Some of these foraminifers are characteristic of a particular type of carbonate environment of the Cretaceous sea throughout the globe. Double keeled *Globotrunca* and *Heterohelix* indicate an open marine deep shelf depositional environment. While single-keeled globotruncanid foraminifers occur in the Late Cretaceous only. The planktic forams occupy the upper zones of pelagic realms of oceans (Flügel, 2010). Likewise, *Pseudosiderolites* is a larger foraminifer genus that was widespread in the Campanian - Early Maastrichtian of the central regions of the Tethys, including the northern and southern Mediterranean and southeastern Asia. These *Pseudosiderolites* are confined to shallow-water conditions and have an arrow stratigraphic range (Zakrevskaya, 2009). *Orbitoides* and *Lepidorbitoides* have a more flattened, lenticular morphology and probably lived in even deeper water environments. *Orbitoides* genus is considered a cosmopolitan one, with a worldwide distribution in the open shelf sediments of Late Cretaceous (Zambetakis-Lekkas 2010). Disc-shaped *Orbitoides* occur in a shallow marine shelf below the wave base (Gameil, 2005). *Siderolite* has robust spines, found in relatively shallow water, high-energy environments, probably in seagrass meadows (Renema, 2010; Renema and Hart, 2012). The *Siderolites*-dasyclad algae association is common during the

Late Cretaceous time in open marine shelf margin facies. Overall, the benthic forams dominate over the planktic in the lower (Campanian) and upper part (late Late Maastrichtian) of the studied unit. The planktic forams are more common in the middle (Early to Middle Maastrichtian). It indicates a shallowing-deepening-shallowing trend of the palaeosea in this part of the Cauvery Basin.

The bryozoans, the next dominant bioclasts, commonly occur as encrusting other bioclasts or suitable substrates, mostly unidentifiable. Only four genera *Tetrocyclioecia, Osculipora*, *Theonoa,* and *Membranipora* and have been tentatively identified. The former three genera occur in grainstone microfacies, while the last one is in packstone microfacies. However, the zooecial fragments are irregularly distributed in all the three microfacies of the Ariyalur Sub-basin. These bryozoans are found in the intertidal to subtidal zones with relatively strong wave action (Zágorśek and Kroh, 2003) and in shallow water warm temperate conditions (McKinney and Jackson, 1989).

The echinoderms are quite frequently occurring as an ecological ingredient and played important role in the accumulation of both macrofossils and skeletal fragments in the Campanian - Maastrichtian calcareous sediments of the Ariyalur Sub-Basin. It may be due to their moderate diversity, sturdy calcareous shells, and easy identification (Kroh and Nebelsick, 2010). These are mostly represented by the fragments of spines, ossicles, and crinoidal stems. Each of the skeletal grains of these echinoids is made up of a single impure calcite crystal. The diagenetic alteration of the ossicles could have played important role in further lithification of these carbonate sediments. In the microfacies of the Ariyalur Group, these echinoderms are more common in packstone microfacies and less frequent in the other two grainstone and wackestone microfacies.

Although in the microfacies of the Ariyalur Group, coral, algae, and rudists do not occur in reefal mode, but these three are quite prolific in occurrences at different levels and as also seen elsewhere. These have complex biotic relationships pointing towards their adaptation to a relatively stable, predictable environment (Scott, 1981). Rudist bivalves are represented by both hippuritids and radiolitids. The rudists are an extinct group of peculiar shape, heavily calcified heterodont bivalves. It is a sessile gregarious bivalve and common in outer to mid-shelf environments. They evolved in the Late Jurassic and radiated during Cretaceous to high diversity occupying shallow water niches. Due to their high diversity (yielding more than 1000 species) in the Late Cretaceous, rudists became the most important benthic carbonate producers. After modifying their hinge and ligament system, allowing uncoiled growth of their inequivalve shells, they became the most important shallow-water dwellers in the Tethyan carbonate platforms and settled in a wide range of lagoon to shallow marine shelf environments (Skelton, 1976). They are common in the inner shelf environment of carbonate ramps. The shell fragments of rudists are well transported as evidenced from their random pattern of distribution. Texturally, they have more perseverance in packstone and wackestone microfacies. Typical shallow marine conditions at the upper part of the Kallankurichchi Formation led to the deposition of silty limestone with abundant fossils of corals, bivalves, gastropods, echinoids, rudistid bivalves, and bryozoans. These fossiliferous beds were deposited in extremely shallow water conditions in a protected lagoon or inner self-setting (Smith *et al*., 1994; Madhavaraju *et al*., 2017). The rudists dominated upper beds could have been deposited on stable shoals above the active wave base (Smith *et al*., 1994). The co-occurrence of corals and rudists may be due to environmental overlap (Skelton, 1976; Scott, 1988, 1995; Smith *et al*., 1994; Sanders and Baron-Szabo, 1997; Skelton *et al*., 1997; Sanders and Pons, 1999; Gotz, 2001; Gameil, 2005). In such environmental overlap, either corals or rudists or both were under ecological stress (Baron-Szabo, 1997; Sanders and Pons, 1999; Gotz, 2003). The Late Cretaceous mixed coral/rudist assemblages are restricted to the outer shelf environment. The thick shells of rudist presumably protected them from the corals.

The bivalves' shell fragments are irregularly distributed in all the three microfacies of the Ariyalur Group. *Phygraea* (*P*.) *vesicularis*in a packstone microfacies is the only identified bivalve species in the thin section. Megascopically ratio of infaunal/epifuanal bivalves is high in the lower and middle parts of Kallankurichchi Formation. The high density of infauna/semi-infauna macro-organisms may be due to the high nutrient supply (Cataldo *et al*., 2013). The suspension feeders dominated throughout in both Sillakkudi and Kallankurichchi formations also indicate sufficient nutrient supply. Along with the local changes, the persisting global ocean water chemistry has also appreciably affected the environment in which these bivalve shells were formed (Winter *et al*., 2017).

There are few occurrences of dasyclad algae in the Maastrichtian microfacies of the present area and only one belonging to the genus *Pycnoporidium* could be tentatively identified. The algae genus *Pycnoporidium* was earlier placed in the family Solenporaceae has been transferred to the family Siphonocladaceae by Jonshon and Konishi (1960). A new species of *Pycnoporidium sinousum* has been recorded from the Late Cretaceous of Guatemala by Jonshon and Konishi (1960) and they estimated a maximum depth of 10 m with a temperature of more than 20^{0}C for its habitat. Two closely allied genera *Solenpora* and *Parachaetetes* belonging to the family Solenporaceae have been earlier described from the older Uttattur Group (Aptian - Turonian) of Cauvery Basin by Mishra *et al*., (2009) in a sublittoral environment with high to moderate energy conditions. Normally the calcareous dasyclad algae and encrusting organisms flourish in the shallow subtidal zone (Flügel, 2010). Micrite rims produced by algal borings are common on rudist bivalves especially in petalodontid rudist. Since the preservation is poor, it is difficult to identify their exact origin. Golubic *et al*. (1975) pointed that it is difficult to distinguish between algal and fungal borings. Since these organisms experienced a wide range of depth and environment, they were much more affected by the process of shell margin micritization (Friedman *et al*., 1971). Such processes of the borings and formation of micrite rims usually took place in the shallow-shelf where organisms lived within the photic zone (Golubic *et al*., 1975).

On a Carbonate ramp, environmental changes are gradual, not abrupt. The intertidal zone is characterized by alternate flooding and exposure i.e. alternate erosion and deposition with rapid change in current and wave velocity. The intertidal environment is exemplified by very low diversity, rare well preserved fossils, and dominance of the

remains of a few groups like benthic foraminifera, bivalves, ostracods, dasyclad algae, and others. while in the subtidal zone normal marine biota is present and accompanied by shell debris composed of highly diverse shell/skeletal fragments. The association of algae with ostracode/gastropod in the wackestone also points towards well illuminated shallow upper part of the subtidal zone. The packstone and wackestone or even grainstone fabric could be products of diagenetic processes e.g. micritisation, cyrtocrystalline calcite crenulations, or neomorphism (Flügel, 2010, p. 350). There sedimented bioclastic packstone may represent a deeper outer ramp. Bathymetry of these deposits is interpreted to be less than 25 m based on bivalve microboring and algal micritization. The recent analog of inner ramps ranges from sea level to fair weather wave base in most of the cases in between 5-10 m in depth (Cataldo *et al*., 2013).

The above microfacies-based observations can be further supplemented by the megascopic characters of fossils and the sediments. Throughout the Kallankurichi Formation, the shell fragments are frequent in occurrence, which may be due to repeated reworking in high energy conditions. The presence of complete articulated shells of bivalves and brachiopods point towards a more distal quieter environment (Fürsich and Pandey, 1999). The life habits of bivalves can also be related to energy conditions. The suspension-feeding infaunal bivalves occur more in medium energy conditions in Kallankurichchi and Ottakkovil formations (Jaitly and Mishra, 2007). In the lower part (Sillakkudi Formation) the calcareous fine-grained sandstone contains low-level suspension feeder infaunal bivalves (*Protocardia*, *Crassatella*, *Frenguelliella*, *Glycemeris,* etc.) which commonly occur in relatively low energy conditions.

High energy communities are usually not found in situ and occur as reworked shell beds and shell pavements of *Phygraea vesicularis* and *Ceratostreon pliciferum*. In the middle part of the Kallankurichi Formation, *Phygraea* exists as a nest and colonized in the shifting high energy substrate. Some of these shell beds with dominant oysters are associated with tempestites deposited in the inner-middle ramp. The occurrence of shell beds intercalated with fine siliciclastics experienced shifting from the middle to the outer ramp (Puga-Bernabéu and Aguirre, 2017). The distribution of these bioclasts, especially planktic organisms are also controlled by temperature (Fürsich, 1995). The larger forams like *Lepidorbitoides* and *Siderolites,* which frequently occur with the bivalve bioclasts are well adapted to low latitude carbonate-rich shallow water environments (Hart *et al*., 2000) in a carbonate ramp setting of Kallankurichi Formation (Early to early Late Maastrichtian). Based on the trace elements along with carbon and oxygen isotopes measurements in the three rudist bivalve species *Vaccinites vesiculosus, Torreites sanchezimilovanovici* and *Oscillopha figari,* a mean annual sea surface temperature of $\pm$ 28°C has been predicted for the Late Campanian south eastern Tethys Ocean on the seasonal scale (Winter *et al*., 2017). Further Zakharov *et al*. (2011) based on the isotopic composition of the bivalve shells of the Ariyalur Group affirmed that this middle latitude area corresponds to the tropical-subtropical climatic zone during the early Maastrichtian. Most of the recorded bivalves of the Ariyalur Group show a wide range of temperature tolerance so that they could have easily survived

in the average temperature (26^0-28^0C) of the Cretaceous sea (Otto-Bliesner *et al*., 2002). The distribution pattern of the macrofauna and their associations provided a fluctuating paleosalinity range from brachyhaline (30‰) to euryhaline (35 ‰) for Sillakkudi to Ottakkovil formations (Campanian - Late Maastrichtian) with the possibility of some hypersaline conditions at a certain level of Kallankurichi Formation (Jaitly and Mishra, 2007). In the Late Maastrichtian, oysters, rudists, dasyclad algae, and echinoderm clasts are common in occurrences that infer near-normal salinity conditions. The concentration of echinoderm bioclasts in some of the packstone microfacies of Early and Middle Maastrichtian also indicates a stenohaline condition (Nichols and Currey, 1968). The occurrence of these clasts as compactly packed mass may be due to the impact of strong current affected by intermittent storms (Madhavaraju *et al*., 2017). The reduced diversity of bivalve clasts in certain beds of Early, Middle, and late Late Maastrichtian may be due to fluctuations in the normal palaeosalinity conditions.

CONCLUSIONS

In the present microfacies analysis, the textural parameters depict the presence of grainstone microfacies in the lower part (Sillakkudi Formation), followed by the prevalence of packstone microfacies (in most of the Kallankurichi Formation) and terminating with wackestone microfacies (uppermost of the Kallankurichi Formation) altogether indicating a continuous deepening of the sea in this part of the Cauvery Basin. Deposition of grainstones took place in comparatively higher energy conditions under well-circulated waters. The substrate is oxygenated and loose due to wave influx. Grainstones received source materials from bank facies limestones and the grains experienced noticeable transport and sorting. The associated conglomerates were formed during brief episodes of strong bottom current generated from storm waves which eroded and redeposited layers of carbonate mud. The packstone microfacies consist of a diverse proportion of bioclasts of foraminifers, bryozoans, bivalves, brachiopods, gastropods, echinoderms, ostracods, and others associated with coarse monocrystalline quartz grains indicating deposition in fairly deeper water conditions with adjoining relatively higher energy conditions. In the higher up the section (Late Maastrichtian) presence of mud-dominated argillaceous wackestone, microfacies represent a basinal condition of deposition. These wackestones are finely laminated and contain fewer bioclasts and could be a basinal extension of sediments deposited below storm weather wave base in the Kallankurichchi Formation. Such wackestones are formed in a well-oxygenated, clear, turbid-free, normal saline, and warmer water environment. Wackestones with large foraminifers indicate mixed ramp position.

Overall, this region of the Cauvery Basin was shallow (up to 10 in-depth), well-oxygenated with an average temperature (26^0-28^0C) of the Cretaceous sea and normal palaeosalinty (30‰-35‰). These Campanian - Maastrichtian sediments were deposited in a carbonate ramp setting and extended from shallow lagoonal to inner ramp to marginal outer ramp.

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