JOURNAL OF GEOINTERFACE, Vol. 2, No. 2, December 2023, pp. 25–34 e-ISSN: 2583-6900

Mixed siliciclastic-carbonate sedimentation: A case study within Late Cretaceous Garudamangalam Sandstone Formation, Ariyalur, South India

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ABSTRACT

Treating siliciclastics and carbonates as incompatible entities is a misleading practice in sedimentology. However, the fact is, in spite of being compositionally and genetically different; siliciclastic and carbonate sediments are not compartmentalized. Rather, several modern and ancient (shelf) deposits enclose a continuum of sediments that are mixed in composition. The nature of sedimentation patterns in heterolithic settings is usually more complex than in pure systems. Understanding the mixing mechanisms of these two end members therefore seeks special attention. Moreover, mixed deposits are valuable in the context of hydrocarbon exploration. Late Cretaceous Garudamangalam Sandstone Formation is a mixed siliciclastic-carbonate deposit exposed in and around Ariyalur, Tamilnadu within the hydrocarbon producing Cauvery Basin. The paleogeography of this unit, a highstand system tract, is associated with a shore parallel wave dominated deltaic river mouth bar in a marginal marine setting. A wide spectrum of mixing took place within this formation depositing in a narrow zone of nearshore regime. Sedimentary facies analysis followed by petrography identifies the depositional mixing of both components. Chemical staining of thin sections, cathodoluminescence (CL) imaging, and limited application of SEM plus EPMA decode mixing intricacies in the diagenetic domain resulting from compositional variability of carbonates.

ARTICLE HISTORY

Received 8 December 2023

Accepted 30 December 2023

KEYWORDS

Siliciclastic-carbonate mixed sediments

Depositional and diagenetic mixing modes

Garudamangalam Sandstone Formation

Late Cretaceous, Ariyalur, India

1. BACKGROUND

A general misconception in sedimentology is siliciclastic and carbonate sediments should not mingle to each other and carbonate production does not take place in areas of terrigenous input. The outcome is a general trend of treating sediments as siliciclastic versus carbonates. Perhaps, this partitioning approach is imposed by the way the chapters in most of the sedimentology textbooks are organized for siliciclastic and carbonate sediments; no separate segments are allotted for mixed siliciclastic-carbonate systems (with the feeble exception of Nichols 2009). Moreover, classification schemes for sediments are focused upon pure end member components (e.g. Folk, 1959; Dunham, 1962; Pettijohn, 1975) although siliciclastic and carbonate sedimentation are part of a spatial and/or temporal continuum (Doyle and Roberts, 1988). It is not incorrect that there are some fundamental differences in the genesis, deposition, and diagenesis of siliciclastics and carbonates; considering climatic, physic-chemical, and biological constraints over the hydraulic regime and sedimentation dynamics (Wilson, 1975; Walker and James, 1992). Also, it is established that continuous siliciclastic influx hampers carbonate production in shallow-shelf environments. No carbonates are visible along the extensive east coast of India in recent times. Possibly, a huge siliciclastic supply by a number of large rivers: Ganga, Mahanadi, Godavari, Krishna,

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Cauvery, Vaigai, etc. inhibits carbonates to boom on the east coast. On the other hand, less number of major rivers (Narmada and Tapti) along the west coast of India results in the curtailment of siliciclastic input probably allowing carbonates to flourish, at least on a local scale. For example, a coral colony is visible along the Jamnagar-Dwarka stretch, Saurashtra (Gujarat). Lakshadweep and Minicoy Island together form the coral islands of India in the Arabian Sea. A similar argument may be raised for Andaman and Nicobar Island too where perennial rivers are almost nil except for five small rivers: Alexandera, Amrit Kaur, Danes, Dogmar and Galathea (longest, of 40 km length) in Great Nicobar Island and only one river named Kalpong (of 35km length) in Andaman Island. Well-developed carbonate sand beaches and coral reefs, fringing type on the eastern side and barrier type on the western side, prevail on the island.

Conversely, in nature, both modern and stratigraphic deposits contain a spectrum of sediments that are mixed siliciclastic-carbonate in composition (e.g. Holmes and Evans, 1963; Larsonneur et al., 1982; Roberts, 1987; Belperio and Searle, 1988; Larcombe and Woolfe, 1999; Dunbar and Dickens, 2003; Wright et al., 2005; Ryan-Mishkin et al., 2009, Longhitano et al., 2012; Sarkar et al., 2014; D'agostini et al., 2015 among others). These mixed sediments typically occur in shallow marine settings, especially the inner shelf. Depositional settings of siliciclastic and carbonate sediments are not compartmentalized rather their mixing is quite a common phenomenon. Pettijohn (1957) coined the term "calc-arenaceous orthoquartzite" for sandstone consisting of sub equal proportion of detrital carbonate and quartz. Dunbar and Rodgers (1957) proposed the terms "quartzose calcarenite" and "quartzose sandstone" for the intermediate varieties dominated by calcite and quartz respectively. The name "calcarenaceous sand" was proposed by Pettijohn (1975) to define sandstone containing an appreciable amount of detrital carbonaceous particles and was later adopted by Tucker (2003) for sediments that contain up to 50% of carbonate grains. Zuffa (1980) referred to the mixed sediments as "hybrid arenite". Mount (1984) identified four sedimentary processes of depositional mixing for compositionally and genetically different siliciclastic and carbonate components. Kidwell and Holland (1991) pointed about the association of bioclastic sediments with non-carbonate (siliciclastic) matrix, usually described as coquina or by using the adjective 'fossiliferous'. The Great Barrier Reef (GBR) is located on the world's largest mixed siliciclastic-carbonate passive margin along the continental shelf of northeastern Australia, which is believed to be an ideal place to study coral reef framework development as well as terrigenous sediment transportation in response to sea-level fluctuation (Webster et al., 2012; Lin et al., 2023).

The mixing of siliciclastic and carbonate sediments takes place through the interaction of both end members under different depositional processes in the same sedimentary environments. The result of such an interface is a heterolithic deposit comprising a mixture of siliciclastic and carbonate grains and their alternations with varied proportion and scales. Hence the sedimentation pattern of the mixed systems is usually more complex than more familiar pure siliciclastic and carbonate systems (Lubeseder et al., 2009; Chiarella et al., 2017). The spectrum of siliciclastic-carbonate mixing mechanisms, especially the diagenetic one in rock records, is still paid less attention. Moreover, mixed deposits are valuable in the context of hydrocarbon exploration as siliciclastic and carbonate components play different roles in characterizing the petroleum system (Chiarella et al., 2017; McNeill et al., 2004). The goal of the present study is to put light on mixed siliciclastic-carbonate sedimentation taking into account the modes operating in the depositional as well as diagenetic realm citing a case study from Late Cretaceous Garudamangalam Formation, Ariyalur, India.

2. CASE STUDY IN LATE CRETACEOUS GARUDAMANGALAM SANDSTONE FORMATION

2.1. Geological context

Oil and natural gas producing Cauvery pericratonic failed rift Basin formed as a consequence of late Jurassic to early Cretaceous rifting of the east Gondwanaland (Powell et al., 1988; Watkinson et al., 2007; Nagendra and Reddy, 2017; Chakraborty et al., 2021a) (Fig. 1A). Atop the fluvial Basal Siliciclastic Formation (upper Gondwana; Chakraborty et al., 2017), unconformity bound marine Uttatur Group comprises three formations: inner shelf originated Dalmiapuram (limestone) at the base followed by outer shelf/shelf margin derived Karai Shale, and Garudamanglam Sandstone of near shore realm at the top with gradational contacts in between them (Chakraborty et al., 2021b) (Fig. 2). The limestone-

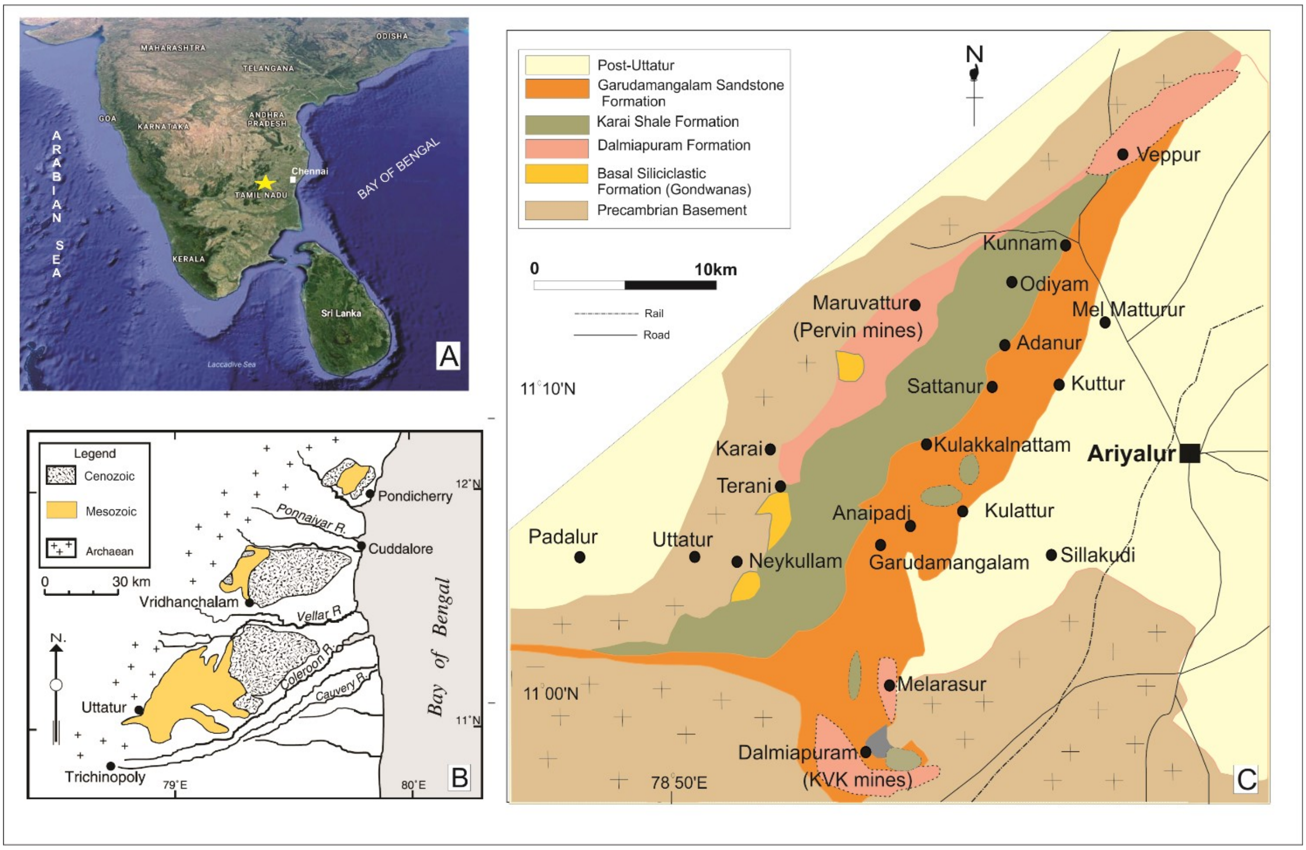

Fig. 1. Part of the Indian Map, the yellow star pointing to the study area (A). Three Cretaceous onshore outcrops near Pondicherry, Vridhanchalam and Ariyalur within the Ariyalur–Pondicherry sub-basin within the Cauvery Basin (modified after Watkinson et al., 2007) (B). Geological map showing spatial distribution of the Basal Siliciclastics and the three formations of the Uttatur Group (modified after Chakraborty et al., 2018) (C).

shale transition comprises a transgressive systems tract (TST) up to the level of the maximum flooding surface (MFS) (Chakraborty and Sarkar, 2018; Chakraborty et al., 2018). Further above, the coarsening-upward part of the Karai Shale grades into the Garudamangalam Sandstone characterizing a highstand systems tract (HST) before terminating against a regional unconformity (Sarkar et al., 2014; Sundaram et al., 2001). Present study deals with the Late Cretaceous Garudamangalam Sandstone Formation exposed along a NE-SW trending belt in the Ariyalur outcrop (Fig. 1B,C), which is considered as coeval to the offshore Kudavasal Formation (Govindan et al., 2000) (Fig. 2). The Garudamangalam Sandstone is a mixed siliciclastic-carbonate formation, abundant in marine macrofossils (ammonites, bivalves including encrusting oysters, gastropods and brachiopods); planktonic foraminifera, calcareous nannoplanktons and trace fossils (like *Glossifungites-Thalassinoides, Ophimorpha, Planolites, Bergaueria, Gyrolithes; Skolithos* and *Cruziana* (Hart et al., 1996; Nagendra et al., 2010; Sarkar et al., 2014).

3. METHODOLOGY

Rock samples for microscopic studies were collected in plastic satche. Thin sections, probe slides, and polished sections were prepared from the rock samples. Chemical staining with alizarin red S plus potassium ferricyanide reveals a non-ferroan composition of this blocky spar. A Leica DMLP polarizing microscope attached to a Leica DFC320 digital camera and computers with higher configurations facilitated the work enormously. The various carbonate components were tested for their cathodoluminescence (CL) characteristics to have a better idea about compositional inhomogeneity among them, whether inherited or diagenetically acquired. Model CL8200Mk5-2 of optical cathodoluminescence system in the Sedimentology Laboratory of Jadavpur University, India, was used at 392–400 µA and 17.2 kV. To acquire a clearer idea about the extent and mode of introduction of diagenetic carbonates, EPMA was performed, with limited application, for higher resolution and better understanding. CAMECA Sx100 at the CPL Lab-

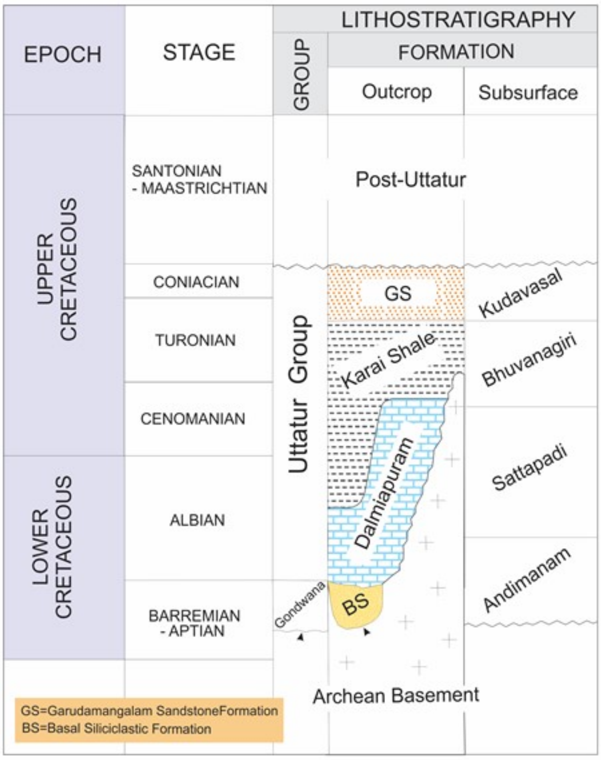

Fig. 2. Stratigraphic sub-division of the Cretaceous Uttatur Group in the study area in outcrop and sub-surface (modified after Chakraborty and Sarkar, 2018).

oratory of GSI, Kolkata Head Quarters, India were utilized for quantitative analyses of the carbonate cements of different generations. EPMA was carried out at 15 kV accelerating voltage, 12 nA current, and beam diameter of 1 micron.

3.1. Facies and Paleogeography

The Garudamangalam Sandstone Formation comprises four distinctive facies associations, viz. River-dominated deltaic bar, restricted bay or lagoon, tidal inlet, and marine (Sarkar et al., 2014). Each of these four facies associations are subdivided into two individual facies and one of the facies (3B) into two sub-facies. Facies and sub-facies are distinguished on the basis of lithology and structure with the prime objective to understand their sedimentary dynamics. Facies associations, on the other hand, highlight the paleogeography of deposition. Table 1 summarizes essential facies characteristics of the Garudamangalam Sandstone Formation. For further details, the reader is referred to Sarkar et al. (2014). The palaeogeographic reconstruction indicates that deposition took place in a narrow belt within the nearshore zone, and differed strongly in energy and active processes. Palaeoenvironmental conditions also differed widely. The presence of a shore-parallel river-mouth bar resulted in a restricted environment on its shoreward side, while its seaward side remained open marine. A connection between the two contrasting energy regimes was maintained by at least one tidal inlet. The western wing of the Mississippi bird-foot delta is considered to be a present-day analogy. The palaeogeographic model in Sarkar et al. (2014) has been utilized here with some modifications to represent the palaeogeographic distribution of different facies association (Fig. 3).

Fig. 3. Model for paleogeography of deposition of the GS (not to scale; modified after Sarkar et al., 2014).

3.2. Siliciclastic–carbonate mixing modes

Carbonates and terriginous clastics can co-exist under certain conditions. A wide range of siliciclastic-carbonate mixing modes is unveiled by the Garudamangalam Sandstone Formation. The mixing modes can be broadly grouped into two categories: a) depositional and b) diagenetic. In both categories, the mixing modes are biogenic as well as abiogenic.

4. DEPOSITIONAL MIXING

The most common mode of mixing is at the transition between two laterally adjacent facies of contrasting compositions. Due to the mixing of two heterolithic constituents, the contact between two indigenous facies is blurred. On the landward side of the bay-mouth bar (facies association 1) patchy growth of isolated mesoscale rudist colonies or other build-ups of calcium carbonate secreting organisms

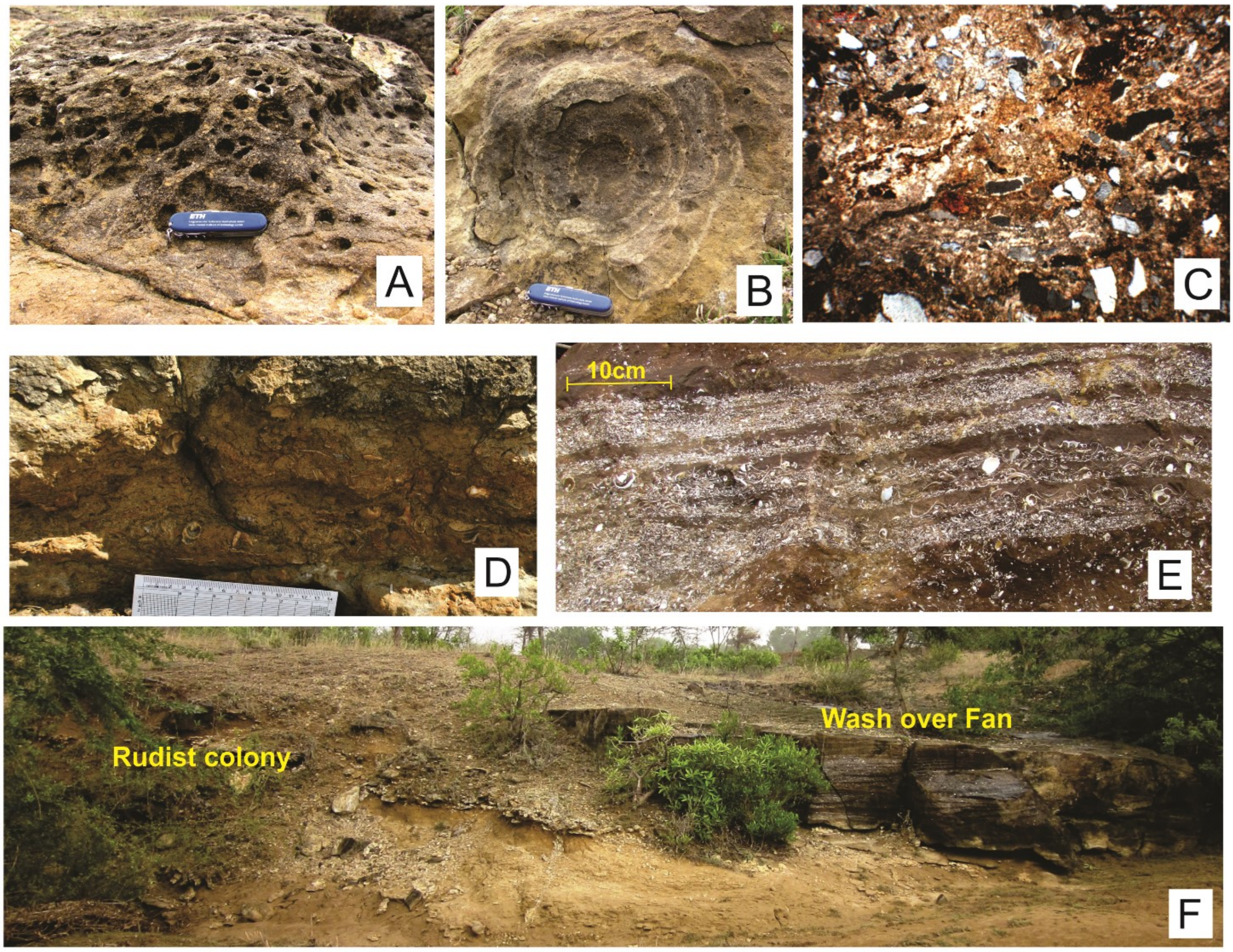

Fig. 4. Patchy growth of isolated rudist colonies (A) and a stromatolite-like convex-up biogenic build-up (B) within facies 2A; Microscopic red algae growth (C) within facies 2B; Reddish siltstone enriched in skeletal grains (D) characterizing facies 2B; Heterolithic unit comprising alternate sandstone and shell-rich limestone (E) within facies 3B; Low angle cross-laminae constituted by coupled shell-rich and mud laminae internally characterizing a washover fan (facies 4B) in close association of well-sorted calcareous sandstone with locally intense bioturbation and patchy build-ups of rudist bivalves growth of bioherms of some rudists (facies 4A).

(bioherms) amidst siliciclastic regime in facies 2A (Fig. 4A, B) is comparable to "facies mixing" of Mount (1984). Microscale mounds of red algae within sandstones (Fig. 4C) are the other examples. In facies 2B, the carbonate depositional components (skeletal and non-skeletal) are indigenous while the siliciclastic components are not (Fig. 4D). The Hydraulic regime of them was definitely different. Mixing took place when extraneous aeolian loess used to be dropped from the air onto an indigenous carbonate mudflat.

An admixture of siliceous and carbonate clastics took place due to simultaneous transport of both the components by the same current. Different settling behaviours, however, generally segregated the two components in two different parts of the beds. Preferred accumulations of carbonate shells at the bottom of the beds both as traction as well as suspended loads within the facies associations 3 and 4 respectively are examples. Heterolithic units in facies association 3 comprising alternate sandstone and shell-rich limestone beds (Fig. 4E) may result either from inter-fingering between two facies deposited in spatially apart contrasting energy spectra or from temporal variability in carbonate productivity. In facies 4A, depositional mixing was limited but occurred mostly to the growth of bioherms of some rudists, in the seaward side of the mouth bar (Fig. 4F), resistant enough to overcome prevailing siliciclastic influx. Within facies 4B, the siliciclastic and carbonate components were supplied by the same current, but segregated during the deposition because

Table 1. Facies constituents of the Garudamangalam Sandstone Formation.

Facies Association	Facies	Description	Trace fossil	Interpretation
FA 1	1A	Entirely siliciclastic, distinctly coarser than the other, cross-sets thickness up to ∼25 cm, siliciclastic mud fills interstitial spaces among framework grains; wood fragments with lengths of up to 81 cm; quartz, feldspar and biotite comprise the framework population, decomposed feldspar grains preferably along cleavage planes, bleached biotite grains preferably along their margins; recrystallization of mud matrix along the margin of framework.	Glossofungites association, Thalassinoides, oblique Ophimorpha, suspected Arenicolites in 1A and sponge - liomorpha in 1B	River-dominated deltaic bar
	1B	Flat bases convex-up geometry, internally trough cross stratified (set thickness ∼12 cm) and sigmoidal cross-strata (∼15 cm) at the flanks oriented at high angles to the trough cross-strata, calcareous sandstone beds (∼1 m) alternating with planar or ripple-laminated siltstonesor silty shales (∼6 cm), comparatively finer grained, interstitial spaces filled by dirty calcite spar, sand crystals present, overall poorly sorted.		
FA 2	2A	Internally characterized by trough co-sets (individual cross-sets thickness up to 11 cm), wood fragments (max 10 cm) present, local growth of convex-up organic buil up (rudist colony/bioherm) and irregular patches of thick-cemented shells of bivalves; moderately sorted, usually fresh feldspar grains replaced by carbonates along cleavage planes and quartz grains nibbled at their margins, specks of glauconite, opaque grains of pyrite scattered within the groundmass.	Very limited burrowing activities	Restricted bay or lagoon
	2B	Reddish well-sorted siltstone with skeletal grains and silt-sized siliciclastic grains floating within carbonate mud, minuscule red algae growth, micritic rims are present on many shells, abundance of glauconites (greater than in facies 2A), small specks of pyrite.		
FA 3	3A	Cross-stratified, planar at places and troughs elsewhere, dune-like bedforms (average height 42 cm) with substantial shell concentration at their toe, well-defined mud drapes, framework elements often found floating within the carbonate groundmass made of blocky calcite crystals, sand grains present, carbonate crystals are generally dirty in appearance, pyrite crystals present, Glauconite grains, both fresh and oxidized, locally present.	Glossifungites including Planolites, Bergaueria and Gyrolithes	Tidal inlet
	3B 3B1	Well sorted, thinner bodies (not exceeding 6-7 cm), internally cross-stratified or planar-laminated, but may also be massive, frame -work grains here also float within the car-bonate groundmass made of blocky calcite, sand crystals present, dirty carbonate crystals contain relict grains, quartz and feldspar grains having nibbled margins, feldspar grains preferably replaced by carbonates along cleavage planes, both fresh and oxidized glauconite pellets are present.		
	3B2	Dominance of carbonate skeletal material concentrated preferably along bases of foresets (av. thickness 4 cm), characteristically draped by reddish mud; vertical burrows (diameter ∼3 cm, length 15 cm) with fuzzy boundaries, burrow-fills are characterized by sand-mud alternations with almost absence of shell, feldspar grains are characteristically fresh in nature, quartz and feldspar grains are nibbled and replaced by carbonates along their margins, drusy growth present only within some mouldic pores.		
FA 4	4A	Medium-grained, moderate-to well-sorted, trough cross stratified sandstone (up to 10 cm thick), local intense bioturbation and small patchy bioherms of rudists bivalves, numerous polygonal cracks and minute borings, small blebs of glauconite in fairly high frequency, framework population includes quartz, feldspar and numerous skeletal fossils, feldspars are generally fresh, interstitial spaces between framework elements are filled by clear blocky calcite spar.	Thalassinoides are and sponge borings	Marine
	4B	Heterolithic facies, found only in small patches (not exceeding 3 m) in lateral extent and 1.5 m in thickness, presumably erosional, concave-up base and a slightly convex-up top, internally being characterized by repeated alternations between thicker shell-rich beds and thinner internally massive reddish mud beds, shell bands have a somewhat irregular geometry because of lateral pinching and swelling, load casts present at the base of shelly beds, locally normal grading, authigenic glauconite globules are common, minute crystals of authigenic pyrite, interstitial spaces between framework grains are filled by blocky calcite shells commonly retaining their primary fabric.		

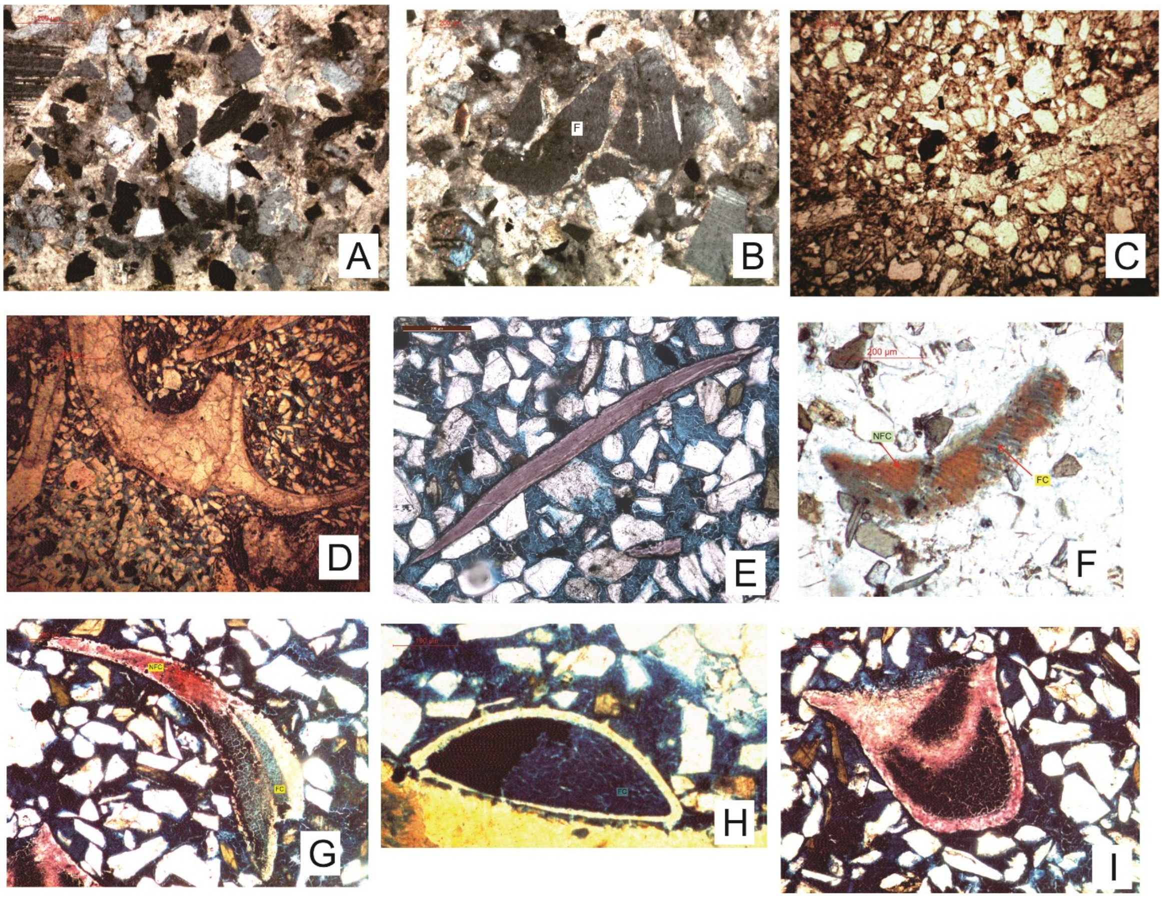

Fig. 5. Replacement of finer-grained matrix by carbonate within siliciclastic sediments (A) within facies 3A; Carbonate-replaced feldspars (F) along cleavage planes (B) in facies 2A; carbonate cement filled veins (C) and drusy growth of carbonate cement filling within dissolution cavities (D) in facies 3B; skeletal grains retaining primary fabric shows non-ferroan composition, note the ferroan micritic rims around shell (E) in facies 2B; Secondary ferroan calcite replacing primary non-ferroan calcite (F) in facies 3B; Ferroan calcite filling the intercrystalline spaces, note primary non-ferroan shell and secondary ferroan cement within the dissolution cavity (G); Intraparticle pore filled up by ferroan calcite (H) and Non-ferroan mouldic cement (I) within facies 3A.

of size- and shape-dependent grain-settling behaviour (Sarkar et al., 2014).

5. DIAGENETIC MIXING

Spectral variation in diagenetic mixing can, indeed, be comparable with that of depositional mixing. The most frequent is perhaps the preferred replacement of finer-grained matrix by carbonate within siliciclastic sediments (Fig. 5A). The replacement is likely to initiate at grain-margins, most readily penetrable to the replacing solution. During further progress of the replacing front into the grain interstices, the solution may undergo compositional transformation. Although fine-grained matrix is preferred, replacement has affected the framework siliciclastic grains too (Fig. 5B). Another common mode of diagenetic mixing arises from carbonate cement filling the veins (Fig. 5C). Carbonate filling within intraparticle pores and dissolution cavities also led to diagenetic mixing (Fig. 5D). Filling of dissolution cavities within and without shells may not be entirely abiogenic.

In the long term, the carbonate components acquire strongly variable compositions, especially in trace element content inherited or acquired, and add a different dimension to the compositional mixing through subsequent alterations in composition during different stages of diagenesis. Variability in crystal growth rate, temperature, salinity, redox potential, porewater composition, and biogenic influence, especially that of microbiota comes into play (Tucker and Wright, 1990; Bathurst, 1975).

Among the skeletal grains, some retain their primary fabric, others do not. The skeletal calcite crystals are almost without exception nonferroan in composition (Fig. 5E); ferroan calcite occurs within

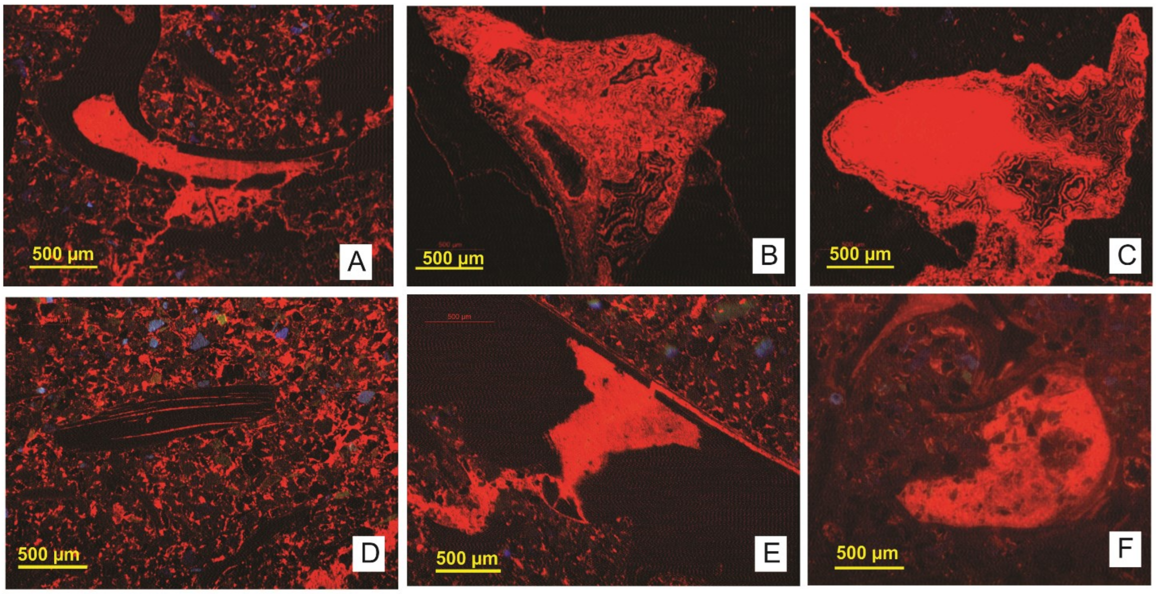

Fig. 6. Partially altered shell showing sectoral zoning (A); Mouldic cement showing concentric zoning (B); Pore fill cement showing sectoral and concentric zoning (C); Fabric selected replacement within a shell (D); Carbonate-cement filling within fractures and fracture-induced dissolution veins (E); Differntial luminescence shown by shell and sediment within shelter pore (F).

small dissolution cavities replacing the primary non-ferroan fabric (Fig. 5F). The interstitial spaces between framework grains are often filled by ferroan calcite. Ferroan calcite also occurs along the growth lines of some shells and fills the intercrystalline spaces (Fig. 5E,G) and also in parts of the micritic rims around shells (Fig. 5E). Intercrystalline pores are filled by ferroan calcite (Fig. 5H). Drusy growth of clear ferroan calcite crystals is present only within some moldic pores (Fig. 5I).

Under CL, the bright rings apparently owe to the abundance of Mn, presumably in a bivalent state, having also Pb and Ce as additional sensitizers. Contrastingly the dull rings alternating with them have much reduced content of Mn and Pb against richness in Fe, presumably again in a bivalent state, along with Ni and Co present as luminescence quencher. Shells that retained their primary fabric are generally non-luminescent, although some have thin interbands that are slightly luminescent. Bright luminescence is also found in cement within intercrystalline pore spaces and dissolution voids (Brand et al., 2012). The micritic rims around the shells are non-luminescent, irrespective of facies. Similar non-luminescence even in the altered parts of the micritic rims suggests the copious presence of Fe^{2+} in the diagenetic environment (Dromgoole and Walter, 1990; Machel et al., 1991; Machel, 2000; Boggs Jr. and Krinsley, 2006). Moldic pores always dominantly display bright luminescence; dull luminescence may, nevertheless, be present within intercrystalline spaces. Within the skeletal moldic pores, concentric alternations between zones of dull or non-luminescent and bright illumination are characteristic. Concentric zonation is found also within intraparticle pores apparently without biogenic influence. Blocky carbonate crystals either forming a groundmass as products of replacement or aggrading neomorphism show a mixed nature because of patchy alternations of bright and dull luminescence. Carbonate cement-filling within fractures and putatively fracture induced dissolution veins across both the framework elements and the groundmass show bright orange luminescence. Cathodoluminescence Characteristics of various carbonate components of the rocks in their different parts are shown in Fig. 6. EPMA within a skeletal mouldic pore shows elevated value of MnO at bright bands while at dull bands higher value of FeO plus NiO have been noticed (Fig. 7).

6. CONCLUSION

- The occurrence of mixed carbonate and siliciclastic sediment appears to be quite common in both modern and ancient deposits
- The late Cretaceous Garudamangalam Sandstone Formation at Ariyalur, India, a high-stand systems tract, unveils a wide range

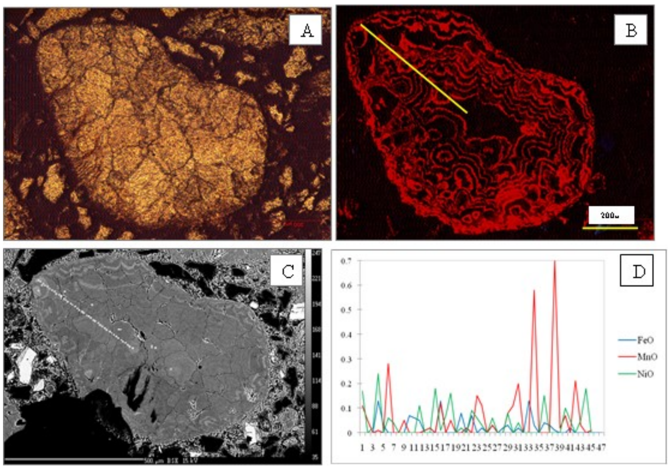

Fig. 7. Drusy growth of cement within a skeletal mouldic pore under PPL (A), under CL showing concentric zoning (B), under SEM (C), EPMA plot along the marked line in (C) showing fluctuation of FeO, MnO and NiO (D).

of siliciclastic-carbonate mixing modes in a nearshore marine realm associated with a river-mouth bar.

- Mixing took place to a comparable extent within both realms: depositional and diagenetic.
- The entire depositional realm of the Formation witnessed mixing between siliciclastic and carbonate components in all the palaeogeographic sectors.
- Possible modes of depositional mixing were a lateral transition between siliciclastic and carbonate facies, calcareous organic build-up within the siliciclastic depositional system, aeolian sand spray on carbonate depositional system, flow segregation, and temporal variation in biogenic carbonate production.
- Under the diagenetic domain too, mixing took place in various modes: cementation by carbonate crystals, replacement of matrix by carbonate, receiving precipitation of carbonate cement within voids, vugs, shelter pores, intraparticle veins, and intercrystalline pores, and replacement of metastable shells.

ACKNOWLEDGEMENTS

The author sincerely thanks the Department of Geological Sciences, Jadavpur University for providing instrumental facilities and acknowledges CPL Laboratory of GSI, Kolkata for SEM-EPMA analysis. The manuscript has been improved by the critical comments of the reviewers. The author is thankful to KJRGGDC for the infrastructural help.

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