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ORIGINAL ARTICLE

Facies analysis and depositional environments of the early Eocene Naredi Formation (Nareda locality), Kutch, Western India

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Abstract The early Eocene Naredi Formation in the southwestern Kutch represents the initial marine sedimentation in Kutch area during Tertiary period. The 22 m thick succession of Naredi Formation, exposed along cliffs (N 23°34′36.8″, E 68°38′38.1″ and N 23°34′3.1″, E 68°39′7.8″) of the tributary of the Kakdi River in and around Nareda village, is dominantly composed of argillaceous member (also known as gypseous shale member) in the lower part and dominantly biochemically precipitated carbonate member, including newly identified algal and coral reef facies, in the upper part. A total of eight lithofacies have been identified based on sedimentological and micropaleontological attributes; those are alternate green- and brown shale facies, comprising the argillaceous member followed by bioclastic wackestone, *Assilina* packstone, organically bounded framestone (bioherm), clayey limestone, bioclastic packstone–wackestone alternation and ferruginous coralline limestone in ascending order, which constitute the upper carbonate member. The green as well as brown shale facies are splintery in nature and show horizontal interlamination with gypsum layers. Both these facies contain glauconites with circular to elliptical outline and radial fractures, thus suggesting deposition on a mid- to outer-shelf or restricted lagoonal depositional setting. The overlying horizontally bedded wackestone facies and sparitic packstone facies containing fossil shells of larger benthonic foraminifera, including *Assilina spinosa, Assilina* and *Nummulites burdigalensis* with some planktonic forms such as *Globigerina* and *Globorotalia* in association to rotalids, ostracods, bivalve and gastropod shells, whose presence depict their deposition in mid- to inner-shelf marine realm under normal seawater salinity. The abundance of peloids, calcispheres and limestone fragments are the major non-biogenic allochems in these facies. Replacement of the ostracods, bivalve and gastropod shells by sparry calcite is also the common feature. The overlying organically bounded algal framestone (bioherm) is characterized by slightly undulatory tabular form in the lower part to concentric undulatory mounds in the upper part showing reef growth at outcrop section whereas framework of curvi-radial concentric growth of carbonate layers under thin section indicates reef formation on shallow marine depositional setting in warm and clear tropical water under normal seawater salinity. The thinly bedded brownish white clayey limestone indicates deposition during deepening of the lagoon. The overlying bioclastic packstone–wackestone alternation facies studded with fragments of algal reef and stromatolitic limestone along with various fossil shells like bivalves, echinoids and gastropods, most of them are micritized, resembles its deposition under back-reef lagoonal environments during storm condition which is overlain by an intertidal coralline limestone deposit showing colonial growth and partial to complete replacement of some of the coral shells by ferruginous mineral along with secondary precipitation of the same within the pores during shallowing of the sea and/or due to late diagenetic changes. Based on shale-carbonate wackestone-packstone-reefal-coralline facies association along with the presence of some key minerals such as glauconite, pyrite, siderite and anhydrite and their genetic link to characteristic depositional milieu, authors have proposed fluctuating depositional environments from lagoonal-barrier ridge to lagoonal-tidal flat for the Naredi Formation.

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Keywords Eocene · Kutch basin · Naredi Formation · Facies · Glauconite · Depositional environment · Deepening-upward sequence

Introduction

Eocene epoch is largely characterized by carbonate build-ups and a large turnover of biota including larger foraminifera on Indian subcontinent. The Eocene sequences of India are significant from the viewpoint of energy resources as most of the petroliferous basins here belong to this epoch. In particular, early Eocene sedimentary successions of India are marked by the development of fossiliferous sediments and provide data on contemporary equatorial faunal and vegetational assemblages. The level of atmospheric carbon dioxide was higher during Eocene (~465 ppmV) than the modern value on the Indian subcontinent (Singh and Lee 2007). Further, the early Eocene was the warmest period in the Cenozoic era and is commonly known as Paleocene–Eocene Thermal Maximum (PETM). Eocene successions are exposed at a number of places in Sub- and lesser Himalaya, hills of Assam, Manipur, Meghalaya, Andaman, Rajasthan, Gujarat and Puducherry. They also occur subsurface on the east and west coasts of India (Saraswati 2011). Facies analysis provides important clues regarding vertical and lateral organizations and variations of the facies in a sedimentary succession and it allows to decipher depositional environments. This tool is being applied in the Eocene successions of SW Kutch, India for interpreting depositional environments.

A thick succession of the Paleocene–Eocene rocks, consists of laterites, lignites, shales, mudstones and carbonates with subordinate proportion of sandstones and siltstones, fringes the Deccan basalt in the western Kutch (Fig. 1) and shows its development on a stable shelf environment. Biswas and Raju (1971, 1973) subdivided the rocks of Tertiary period of Kutch into several formations and assigned their ages based mainly on microfossil association (see also Bhatt 1968; Guha 1968, 1974; Khosla and Pant 1989; Biswas 1992). The extensively developed shaly succession and carbonate platform of the Naredi Formation in Kutch have been variously interpreted for its stratigraphic position and age. The upper part of the Naredi Formation was assigned early Eocene age based on the presence of larger foraminifera such as *Nummulites burdigalensis*, *Nummulites acutus*, *Assilina* and *A. spinosa* (Biswas and Raju 1973; Biswas 1992) and the lower part was referred as late Paleocene based on micro- and macro-fossil assemblages (Tandon et al. 1980; Biswas 1992; Pandey and Ravindran 1988; Mukhopadhyay and Shome 1996; Pandey and Dave 1998; Chattoraj et al. 2009; Kachhara et al. 2011). Singh (1978) and Saraswati and Banerjee (1995) have studied glauconite-containing shales and have interpreted them to be deposited in shallow marine conditions. Srivastava et al. (2002) have recovered some fish remains of early Eocene age from the Gypseous Shale Member occurring in the lower part of this formation. Garg et al. (2011) reported dinoflagellate cysts assemblage from the lower part of the Naredi Formation and assigned early Eocene (Ypresian) age to it. Also, Saraswati et al. (2012) constrained the age of Naredi Formation as early Eocene based on *Nummulites solitaries–Nummulites burdigalensis* lineage. Further, Keller et al. (2013) have reported benthonic larger foraminifera, including *N. burdigalensis* along with some planktonic foraminifera and assigned early Eocene age to this formation.

A complete succession of the Naredi Formation is well exposed along the Kakdi River section (Fig. 2) situated nearly 0.8 km west of Nareda village across Naliya-Narayan Sarovar road. This formation is well developed only in Western Kutch. It occurs in a narrow semi-circular belt of outcrop from Lakhpat in the north to Jhulrai in the south through Umarsar, Nareda and Naredi around the structural nose of Narayan Sarovar (Biswas 1992). The studied localities (N 23°34′36.8″, E 68°38′38.1″; N 23°34′3.1″, E 68°39′7.8″) show around 22 m thick succession of predominantly argillaceous and calcareous sedimentary rocks that disconformably overlie the Deccan Traps (Fig. 2).

A number of invertebrate, vertebrate and microfossils have been reported from the Gypseous Shale Member occurring in the lower part of the Naredi Formation. Further, *Assilina, Nummulites, Rotalids* are recovered from the upper carbonate member here. Naredi Formation has been intensively worked for its biostratigraphic aspects and hence less attention had been paid over its sedimentological characteristics. The present study incorporates results of the facies analysis of the Naredi Formation, exposed in the cliffs along Kakdi River, to infer its depositional environment. In this investigation, a detailed study of lithology, sedimentary structures, texture, fossil content and bioturbation supported with petrography and X-ray diffraction analysis of the selective shale samples from the Gypseous Shale Member was carried out. Reefal limestone build-ups have been discovered during the present investigation. Relative sea-level changes (Fig. 2) have been established based on microfossils found in individual facies, facies association in vertical sedimentary succession supported by the presence of some key minerals such as glauconite, pyrite, siderite, gypsum and anhydrite.

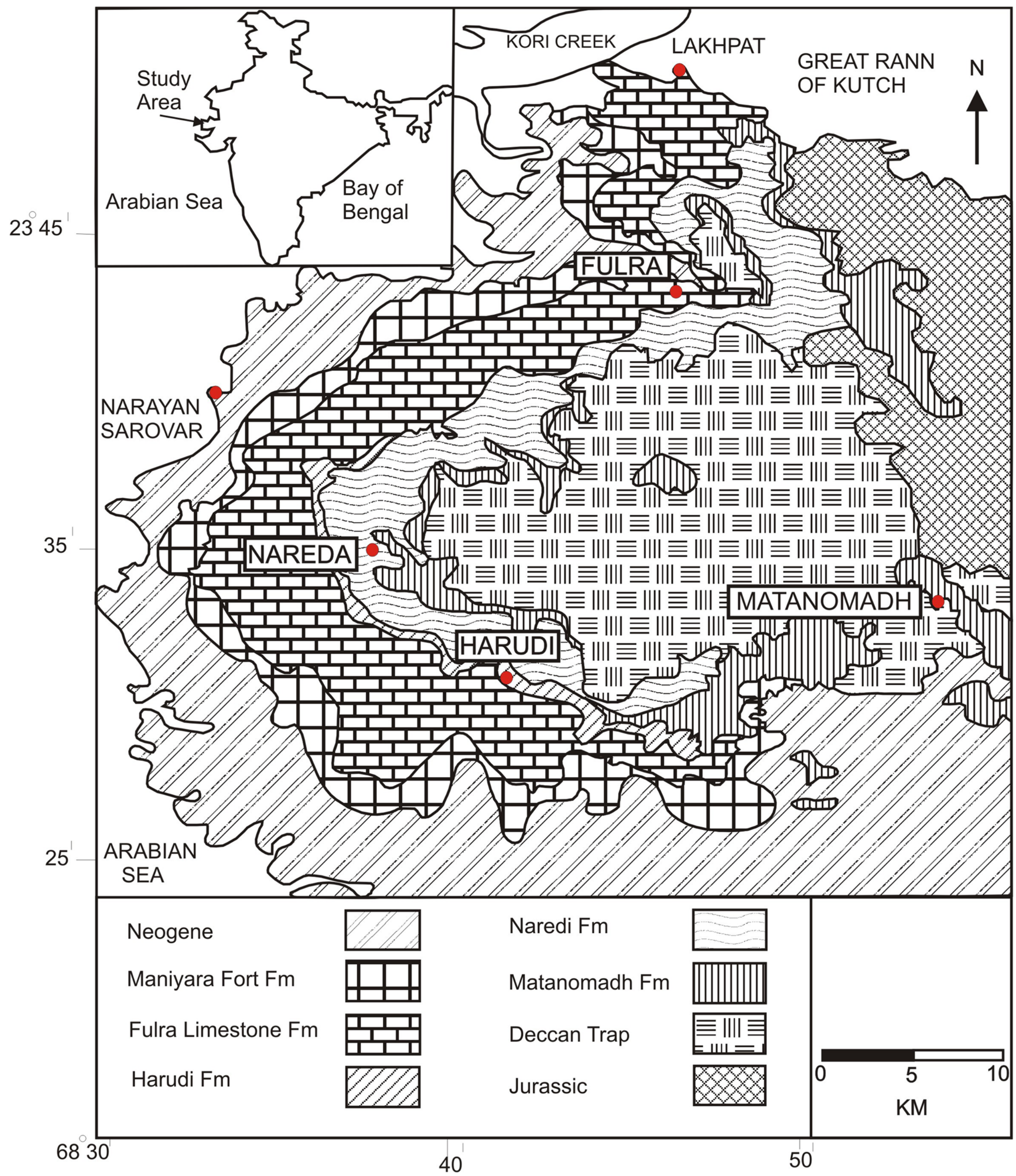

Fig. 1 Geological map showing Paleogene outcrops in the western Kutch (after Biswas 1992). *Inset* India in the outline map. Here *arrow* indicates study area

Geological setting

Kutch basin (KB) is an E–W oriented western margin pericratonic rift basin of western India that extends between latitudes 22°30′ and 24°30′ N and longitudes 68° and 72° E and evolves due to sequential rifting and repeated movements in relation with the northward drift of Indian plate after the breakup of the Gondwanaland during late Triassic-early Jurassic period (Norton and Sclater 1979; Koshal 1984; Biswas 1982, 1987, 2005). This basin shows its evolution into a passive margin basin during the Paleogene (Biswas 1987). It is bounded by the Nagar-Parkar fault in the North, Radhanpur-Barmer basement arch in the east and North Kathiawar fault towards the south (Biswas 1982). There are extensive exposures of Mesozoic and Cenozoic rocks both on mainland and on-shore areas of Kutch. The Paleogene sequences overlie the Cretaceous rocks in many areas in the eastern part also.

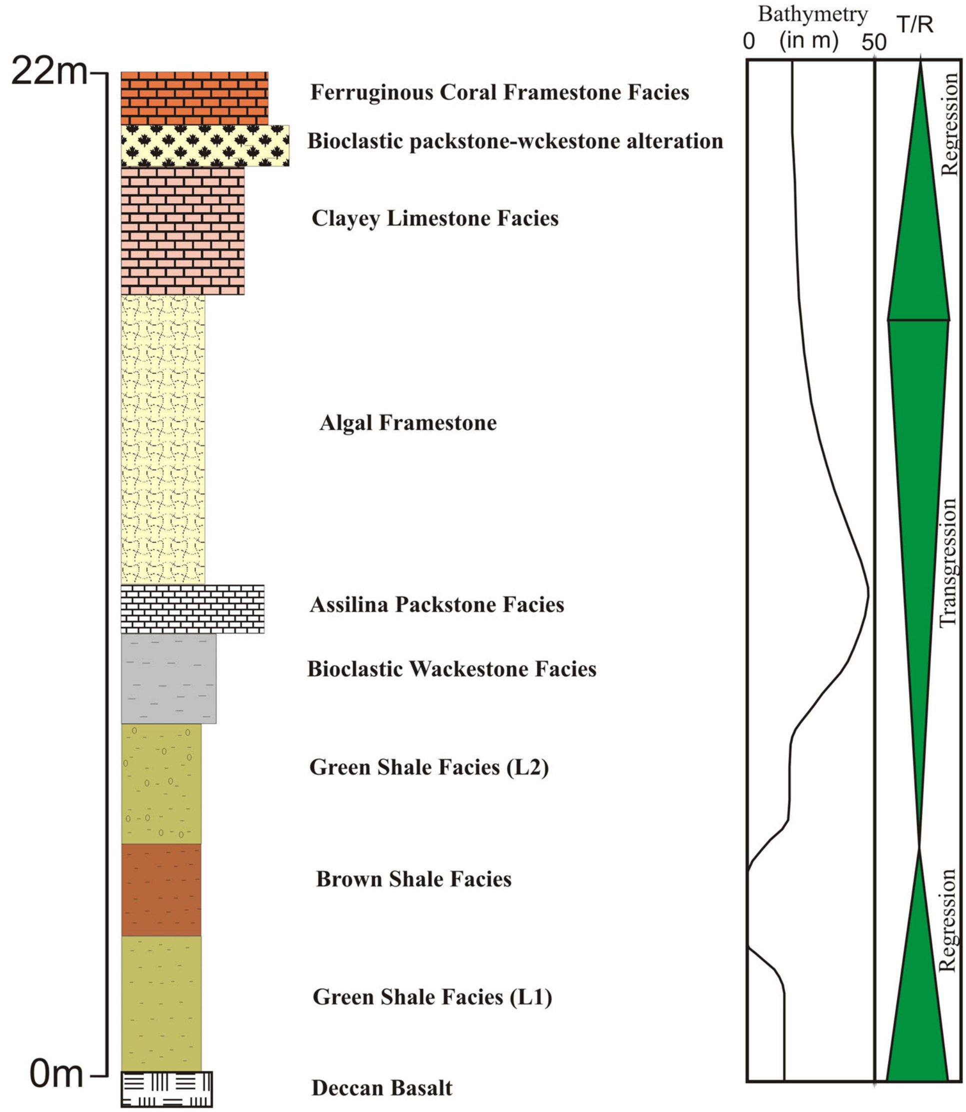

Fig. 2 Litholog showing Facies succession and change in bathymetry of the Naredi Formation exposed at the bank of Kakdi river near Nareda village. T/R model is drawn to represent transgressive and regressive phases of sea during deposition of Naredi Formation

The total area of the Paleogene basin is about 71,000 km^2 of which shoreline area is 43,000 km^2 and offshore area is 28,000 km^2 considering a depth of 200 m. The early Eocene Naredi Formation in the southwestern Kutch occurs fringing the Deccan Trap of Paleocene age in its type locality (present study area) and represents the inception of marine sedimentation in Kutch during Tertiary period. Elsewhere, it overlies the Matanomadh Formation with the presence of a thick basal lignite deposit. The Naredi Formation is disconformably overlain by the middle Eocene Harudi Formation that is exposed in the western and southern part of the study area.

The age of the Naredi Formation is a matter of controversy since long, where Biswas and Raju (1973), Tandon et al. (1980), Biswas (1992), Pandey and Ravindran (1988), Mukhopadhyay and Shome (1996), Pandey and Dave (1998), Chattoraj et al. (2009) and Kachhara et al. (2011) assigned a Paleocene age to the lower part of the formation and an early Eocene age to the upper part of the formation based on the occurrence of macro- and micro-fauna. However, recent workers such as Srivastava et al. (2002), Garg et al. (2011), Saraswati et al. (2012) and Keller et al. (2013) assigned an early Eocene age to the entire Naredi Formation based on the age marker dinoflagellate cysts assemblage and larger foraminifera.

Methods

Different facies were identified and demarcated in the field on the basis of color, sedimentary structures, grain size, composition, fossil content and acid test to ascertain carbonate facies. Thicknesses of the individual facies were measured with the help of measuring tape and a litholog was prepared incorporating characteristic features of the facies from base to top of the sections studied. Fresh samples from the early Eocene aged argillaceous and carbonate members, comprising of green shale and brown shale facies intercalation and bioclastic wackestone, *Assilina* packstone, algal reef (bioherm), clayey limestone, bioclastic packstone and coralline limestone, respectively, were collected from the exposed sections along Kakdi river in and around Nareda village and from the same locality along Naliya-Narayan Sarovar road section in the southern extension. Thin sections were prepared from representative shales, calcareous shale and various limestone samples. Petrography was performed on a LEICA DM 4500P microscope attached with image analysis software. The investigation is further supported by X-ray Diffraction analysis, for the gypseous shales member, performed on a PANalytical X'Pert Pro diffractometer fitted with a copper tube (CuK-alpha) and xenon detector at the Department of Geology, Banaras Hindu University, Varanasi.

Facies analysis

The early Eocene Naredi Formation has been broadly segregated into eight lithounits based on their sedimentological and biological composition. The carbonate facies were erected following Dunhum's classification of limestone (1962) and its modification by Embry and Klovan (1971). Limestones can be studied by comparing them with the Standard Microfacies (SMF) types, which is a system, put forward by Wilson (1975) from Flügel's (1972) concept. Wilson (1975) identified 24 SMF types based on the petrographic characteristics of the Phanerozoic limestones, and put a generalized model of carbonate sedimentation assignable to nine standard facies belts. Distinctive composition of each facies indicates towards a particular environment, but some of the SMF types may not be restricted to only one facies belt (Wilson 1975; Flügel 1982). Description of the microfacies criteria using the Dunham's classification scheme (1962) is the basic requirement for recognizing SMF types, as designated by Wilson (1975). The clastic and carbonate facies identified in the present study are as follows:

Green shale facies

This facies marks the beginning of the Naredi Formation at the type locality. It is characterized by horizontal interlamination of clay and gypsum layers. Two levels of this facies are identified with major variation in the glauconite pellets maturity, nodules and/or concretions composition and sandwiched brown shale facies occurrence between them (Fig. 3a). Both the levels of this facies are splintery in nature and constitute 2.8–3 m thick succession individually. Yellowish green colored, circular to elliptical glauconite pellets with radial fractures and relics of feldspar laths are observed from the lower green shale (Fig. 3b) and most of them found occurring along the lamina planes. Very thin layers of gypsum occur within the shale that shows platy euhedral crystals of selenite in thin sections (Fig. 3c). Glauconite pellets occurring in the green shale also show pyrite inclusions in thin sections (Fig. 3d, e). Thin sections of anhydrite nodules in the lower green shale facies show the presence of bivalve, gastropod and echinoid shells with remarkable bioturbation filled with secondary calcite (Fig. 4a–c). Highly mature brownish green colored glauconite pellets with elliptical to irregular grain boundaries are recorded from the upper green shale which contains the sideritic nodules with framboidal pyrite (Fig. 4d).

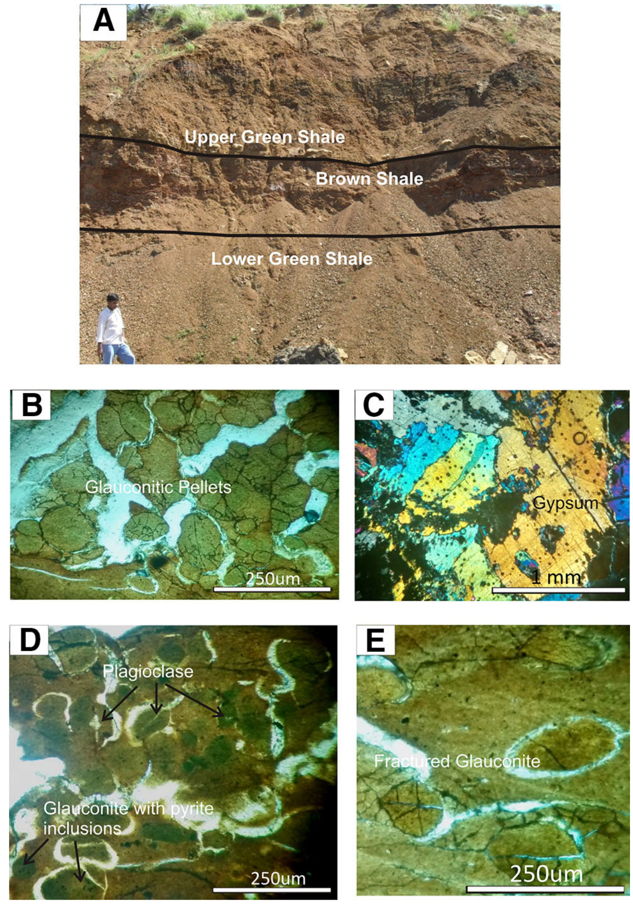

Fig. 3 **a** Field photograph of the constituent facies of the gypseous shale member of Naredi Formation. Note here the *brown* shale facies is sandwiched between two levels of *green* shale facies. **b**, **d** Photomicrographs exhibit the *yellowish green color*, fractured, circular- to elliptical glauconitic pellets surrounded by clayey groundmass. **c** Photomicrograph shows the presence of large, platy and euhedral grains of gypsum (selenite). **e** Relics of plagioclase feldspar and inclusions of pyrite marked by *arrow* in the *brownish green color* glauconitic pellets

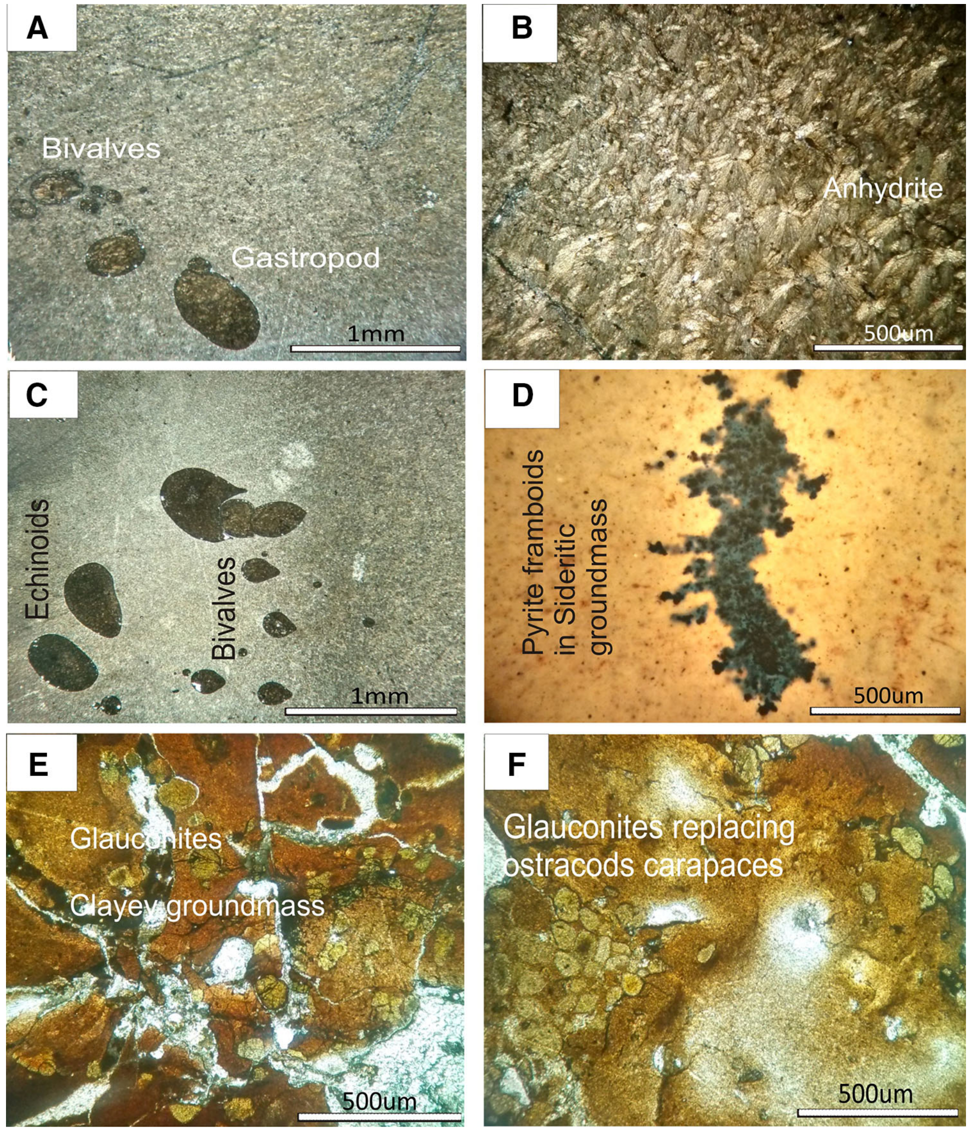

Fig. 4 **a**, **c** Photomicrographs show the presence of fossil groups such as bivalves, echinoids and gastropods recovered from the anhydrite nodules. Calcite crystallization in the voids produced through bioturbation (*Top central and right side*). **b** Photomicrograph of the anhydrite nodule. Note the crystallized mass of anhydrite mineral showing prismatic nature of the crystal. **d** Photomicrograph shows pyrite framboids in the sideritic groundmass recovered from sideritic nodules of the *upper green* shale. **e** Photomicrographs show randomly oriented *brownish green* glauconitic pellets among clayey groundmass under PPL view. **f** Photomicrographs show replacement of carapaces of ostracods' shell by brownish green glauconite floating in clayey groundmass under PPL view

Interpretation The presence of thin-horizontal inter-lamination of gypsum and very fine-grained clay layers suggests that the sedimentation took place in a low energy condition may be in a lagoon. Thin layers of gypsum precipitate from a saline groundwater through evaporative pumping in a coastal depositional environment (Warren 1986; Singh 2010). The presence of gypsum layers in the green shale suggests an evaporative condition during their precipitation may be from the saline groundwater. The anhydrite nodules possessing relics of gypsum formed during surface desiccation or during burial diagenesis (e.g., Singh et al. 2006). The presence of bivalve, gastropod and echinoid shells suggests marginal marine ecological conditions. Where there is a good connection with the open sea, normal salinities will occur within the lagoon and a diverse and abundant fauna can be expected but where circulation is poor within a lagoon, then the fauna typically is impoverished and fossil diversity is low (Tucker and Wright 1990). The low diversity of the foraminifera in the green shale may be because the lagoon was not connected with the open sea during deposition of this facies. Glauconite pellets are known to occur in marine and lagoonal sedimentary environments ranging in age from Paleoproterozoic to Recent (Odin and Matter 1981; Dasgupta et al. 1990; Amorosi 1994; Chafetz and Reid 2000; Lee et al. 2002; El Albani et al. 2005; Meunier and El Albani 2007; Amorosi et al. 2007; Bandopadhyay 2007; Banerjee et al. 2008, 2012; Chattoraj et al. 2009). They form either as precipitates as pellets, in the form of cement or by the diagenetic alteration of host minerals like quartz, feldspar, calcite and micaceous minerals. Their presence also indicates a low rate of sedimentation and thus, they can be considered as one of the key factors in stratigraphy (Amorosi 1995, 1997; Amorosi and Centineo 1996;

Kitamura 1998; Banerjee et al. 2008). The nodules and concretions present in the green shale with anhydrite and sideritic composition were formed during diagenesis. The occurrence of framboidal pyrite suggests its formation in a marine environment with reducing conditions (e.g., Singh 2012). The presence of micro-laths of feldspar as relics in some glauconitic pellets from green shale facies (Fig. 3e) suggests formation of glauconite from precursor feldspar by partial or complete alteration during diagenesis.

Brown shale facies

It occurs in a 1.7 m thick succession between the green shale facies and is characterized by brown color, horizontal interlamination of clay and gypsum layers and relatively coarser silty layer that demarcates the gypseous layers from clayey ones. The facies has sharp and planar upper and lower contacts with green shale facies (Fig. 3a). This facies is also very fissile or splintery in nature but comparatively harder than green shale. It contains brownish green colored circular to elliptical pellets of glauconites (Fig. 4e). Some of them resemble replacing ostracod shells (Fig. 4f). The distribution of these pellets is random in the clayey matrix. This facies contain foraminifers, bivalves and ostracods in relatively lower proportion. Both benthonic and planktonic foraminifera occur in this lithofacies.

Interpretation The presence of horizontal interlaminated brown clay and gypsum layers suggest their sedimentation in a low energy lagoon similar to green shale. The brown color of the shale suggests oxygenated condition that might have achieved as a result of shallowing of the lagoon. The gypsum layers were precipitated in an evaporative condition from the saline groundwater adjacent to the lagoon. The replacement of the ostracod shells by glauconite indicates its generation during late diagenesis as it randomly occurs in this facies. Triserial planktonic foraminifera, *Guembelitria* shows unstability in the marine conditions that has been noted in modern oceans from embayments and areas of upwelling (Kroon and Nederbragt 1990; Ghosh et al. 2007). The presence of *Guembelitria* in the yellowish brown shale suggests fluctuating marine conditions during its sedimentation. The other biotic elements occurring in this facies also indicate the coastal ecological conditions.

Bioclastic wackestone facies

It is 1.6 m thick dirty yellow, thinly and horizontally bedded calcareous mudstone. It shows sharp lower contact with green shale facies (Fig. 5a). It mainly contains carbonate with sub-ordinate amount of clayey and silty mud. It possesses various larger benthonic foraminifera such as *Assilina* and *Nummulites* with some planktonic forms such as *Globigerina* and *Globorotalia* (Fig. 5b–d). These foraminifera occur within the micritic matrix forming a wackestone. Rotalid, ostracod, bivalve shells and algal matter are also found floating in the micritic matrix (Fig. 5b). A 15 cm thick nodular carbonate band also occurs near the base of this facies (Fig. 5a). Upper contact of this facies is sharp with *Assilina* packstone facies.

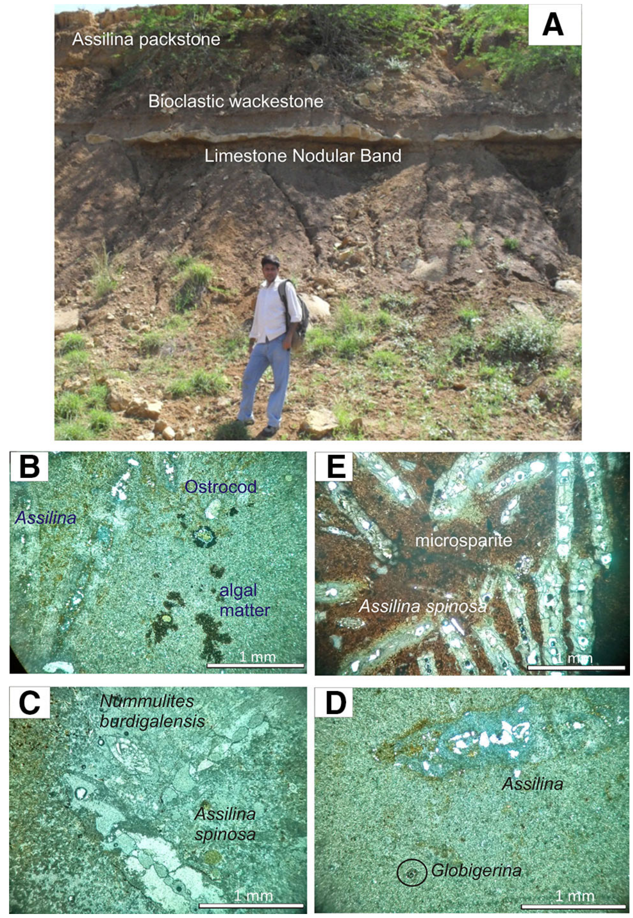

Fig. 5 **a** Field photograph of the bioclastic wackestone and *Assilina* packstone facies of the carbonate member of Naredi Formation. **b**, **c**, **d** Photomicrographs exhibiting shells of various larger benthonic and planktonic foraminifera floating in micritic carbonate groundmass (name mentioned against each foraminifera). Note here the presence of ostracods and algal matter. **e** Photomicrograph exhibiting unbroken entire shells of *A. granulosa* supported by micro-sparite cement

Interpretation The occurrence of the wackestone suggests low- to medium-energy depositional environment dominated by weak waves and currents. The presence of *Assilina* and *Nummulites* with some planktonic forms such as *Globigerina* and *Globorotalia* suggests open marine mid-ramp depositional setting. Lack of preferred orientation of bioclasts suggests the absence of current reworking and hence supports the idea of deposition below fair weather wave base and/or storm wave base around 30–45 m depth. This falls under the SMF type 9 of the

Wilson (1975) and Flügel (1982) standard microfacies types suggesting sedimentation in shallow water with open circulation condition close to wave base.

Assilina packstone facies

It is 0.8 m thick brownish yellow, thickly and horizontally bedded packstone (Fig. 5a) consisting predominantly of larger benthonic foraminifera mainly *Assilina* constituting 50–60 % of total rock volume (Fig. 5e). It is characterized by the presence of micro-sparitic matrix/cement constituting about 30 % of the bulk with low content of micritic mud. Original planar laminae are often noticed in places. The facies is non-repetitive and maintains approximately same thickness throughout the section. Besides *Assilina*, it also contains subordinate proportion of *Nummulites* and other biotic components such as fragments of irregular echinoids, oysters, bryozoa and ostracods. Among non-biogenic components calcispheres, pellets, sparitic cement and ferruginous coating around grains are common which gives brown hue to this facies (Fig. 5e).

Interpretation Abundance of *Assilina* and presence of a number of other foraminiferal species in this facies indicate deposition in the shallow marine environment with only moderate water circulation. The presence of foraminiferal association, including *A. spinosa, Assilina granulose* and *N. burdigalensis* is indicative of inner ramp environment. The sharp base of the packstone bed suggests sudden increase in the wave or current energy that may also be recognized by the entire to partially broken nature of the shells. Bathymetry of the facies appears to be in the range of 20–40 m. This falls under the SMF type 16 of the Wilson (1975) and Flügel (1982) standard of microfacies types and suggests shallow water depositional condition with moderate circulation may be on a beach ridge.

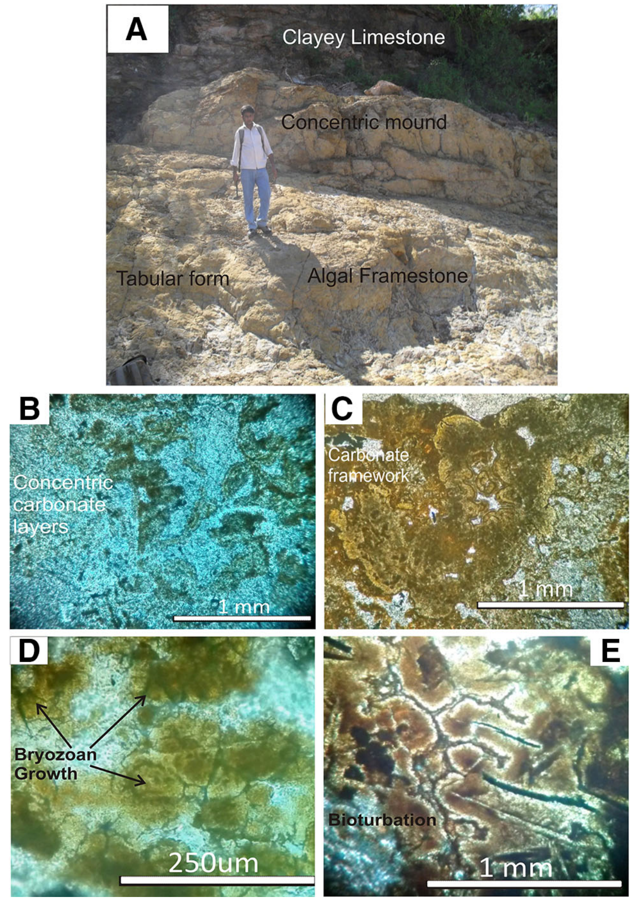

Fig. 6 **a** Field photograph of Algal Framestone and Clayey Limestone facies of the carbonate member of Naredi Formation exposed in the southern extension of Nareda village on the western side of the Naliya-Narayan Sarovar road section (~1 km away). **b**, **c** Photomicrographs of Algal framestone facies exhibiting concentric growth of algal framework. **d** Bryozoans in association with algae show colonial growth. **e** Extensive bioturbation leads to micritization. Note here the branching pattern of bioturbation

Algal framestone

This facies is 7 m thick with dirty yellow color and shows slightly undulated tabular form in the lower 5 m thickness whereas wavy and concentric undulatory growth in the upper 2 m thickness (Fig. 6a). This is calcareous in composition (confirmed after acid test in the field). It is highly bioturbated both in space and time as burrows, spur and groove structures are easily recognized in the field and shows a complete exposure from reef crest boundstone to reef front framestone (Fig. 6a). This facies shows framework of curvi-radial concentric growth of carbonate layers under thin section resembling growth of calcareous green algae and has needle-like aragonitic infillings in the pores between frameworks (Fig. 6b, c). Bryozoans are also recorded in association with algae forming a massive reef (Fig. 6d). Extensive bioturbation shows micritization of the carbonate in thin sections (Fig. 6e). Besides these biotic components, non-biotic component pellets and calcispheres are the most common.

Interpretation Algal reefs develop at a low rate of sedimentation under intense wave energy (James 1984). The tabular to slightly undulated algal growth in the lower part to strongly undulated or concentric growth in the upper part of this facies confirms it and suggests encrusting type of growth form of the reef that developed during intense wave energy and low rate of sedimentation. The presence of algal dominated framework throughout the thin section and also the presence of bryozoans corroborate to this argument. The bioturbation suggests that the sedimentation was intermittent with some breaks in it giving time for animals' activities. This facies falls under the SMF type 7 of the Wilson (1975) and Flügel (1982) standard of microfacies types and suggests reef growth on platform margin.

Clayey limestone facies

Clayey limestones overlie the organically bounded framestone (algal reef) with a sharp and irregular contact (Fig. 6a). It is around 3.5 m thick brownish white colored, fine-grained, thinly bedded and unfossiliferous limestone facies (confirmed after acid test in the field). It is hard and compact and shows horizontal bedding (Fig. 7a). It shows calcite crystals into crystalline form associated with patchy distribution of clay minerals in thin sections throughout this facies (Fig. 7b, c). It shows a sharp and planar upper contact with bioclastic packstone–wackestone alternation facies.

Interpretation Unfossiliferous, thinly and horizontally bedded clayey limestone with negligible bioturbation is the commonest feature of restricted (barred) back-reef/barrier lagoon which has no connection with seawater and where salinity is moderately high, waves and tidal influence are minimal and detrital input is low to moderate depending upon climate, sea-level and tectonics (Nurmi and Friedman 1977; Taylor 1990). Thus, the unfossiliferous clayey limestone facies with thin and horizontal lamination precipitated on the restricted back barrier zone or barrier lagoon and the deposition took place in anoxic condition through suspension and precipitation.

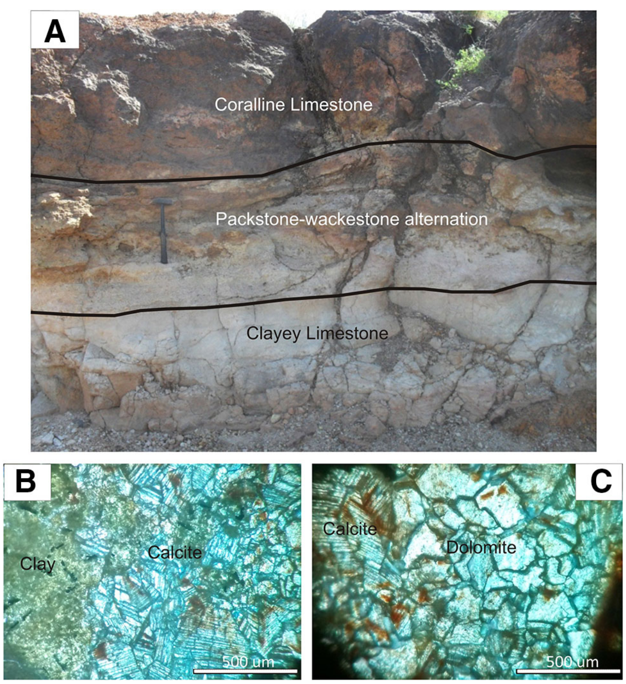

Fig. 7 **a** Field photograph of the *uppermost* carbonate sequence of Naredi Formation exhibits clayey limestone, bioclastic packstone–wackestone alternation and ferruginous coralline limestone facies that are exposed along the Naliya-Narayan Sarovar road section near Nareda village. **b** Photomicrograph of the clayey limestone facies showing calcite crystals with patchy clay minerals under ppl view. **c** Subhedral dolomite crystals observed in thin section along with calcite crystals

Bioclastic packstone–wackestone alteration

This facies is characterized by grayish white colored, relatively thicker cross-bedded packstone and thinner horizontally bedded wackestone alternation. Together they constitute 0.8 m thick succession. Individual bed thicknesses in the packstone range from 20 to 25 cm, while wackestone beds are 10 to 15 cm thick (Fig. 7a). Moderate to high bioturbation destroys the original laminae and cross-beds at many places. However, small-scale cross-beds are fairly observed in the field from the packstone beds. In thin section, packstone shows larger fragments of algal reef (Fig. 8a), bivalves, gastropods, echinoids, and some other not recognized fossil shells, found surrounded by few ferruginous limestone intraclasts (Fig. 8b, c). On the other hand, wackestone shows the occurrence of highly micritized bioclasts floating in the micritic groundmass along with pellets (Fig. 8d). Intraclasts of stromatolitic limestone are also recorded in the cross-bedded packstone facies (Fig. 8e).

Interpretation The association of packstone–wackestone alternation represents a largely low energy depositional environment such as back-reef flank facies that had experienced phases of weak influence of storm events. This is also supported by the presence of the NE directed paleocurrent pattern and the occurrence of larger bioclasts (>2 mm) of reef and fossil shells with subordinate proportion of limestone intraclasts and micrite. The bioturbation suggests that the sedimentation was intermittent with some breaks in it. This facies falls under the SMF type 5 of the Wilson (1975) and Flügel (1982) Standard microfacies types and suggests deposition on a reef flank.

Ferruginous coral framestone facies

This facies marks the end of the Naredi Formation in and around Kakdi River section overlying the bioclastic packstone–wackestone alternation facies. It is 0.8 m thick brownish yellow colored limestone facies (confirmed after 10 % conc. HCL acid test) having undulatory diffused lower contact with the underlying facies. It is hard and compact and shows moderate bioturbation in both space and time. The burrows are filled by ferruginous minerals (Fig. 7a). It shows horizontal to slightly wavy bedding planes and infillings of ferruginous material within the pores. Under the microscope, it shows well-developed colonial growth of corals (Fig. 9a, c) with pore infillings by other bioclasts such as bivalves, gastropods, echinoids and other fossil shells (Fig. 9b, d). Replacement of fossil shells by ferruginous material is common. Bioturbation produces micritic matrix that also occurs filling the pores. It has been considered as laterite or bauxite deposit because of its brownish yellow color by earlier workers, but the presence

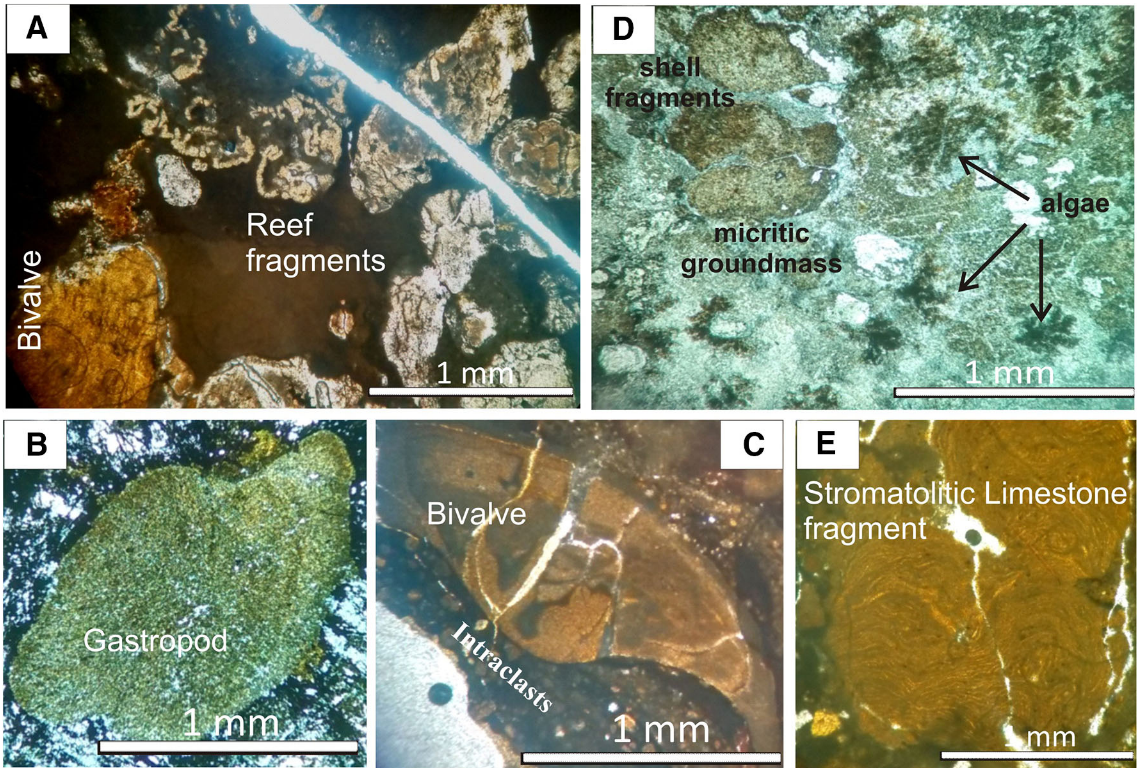

Fig. 8 **a** Photomicrograph of bioclastic packstone–wackestone alternation facies showing larger fragments of algal reef and bivalve shells. **b** Preserved entire shell of a gastropod. **c** Partially broken shell of a bivalve. **d** Micritized shells of various fossil groups along with algae are reported from bioclastic wackestone facies. **e** Fragments of stromatolitic limestone documented from cross-bedded bioclastic packstone facies

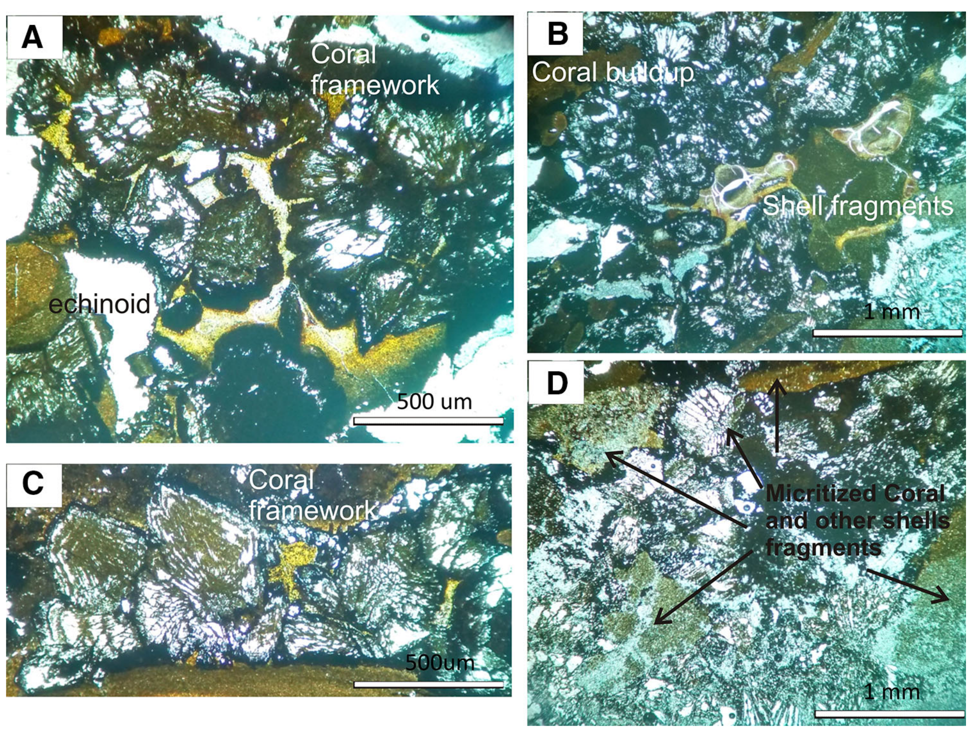

Fig. 9 **a**, **b** Photomicrographs of ferruginous coralline limestone facies showing colonial growth of coral incorporated by other organisms such as echinoid, bivalves and gastropods. **c** Typical representation of the coral colony. **d** Extensive bioerosion leads to micritization of shells fragments. Note here the ferruginous infillings in voids

of coral colonies as well as gastropods, bivalves, echinoids and other fossil shells and its calcareous composition help us to put it within the carbonate facies rather than the laterite or bauxite.

Interpretation The corals of the rusty brown hard limestones are predominantly characterized by the encrustating to fruticose growth forms that indicate moderate to high-energy conditions. These conditions are known to develop on shallow ramps may have ranged from middle to inner ramp environments in the lower photic zone. The moderate to high-energy conditions of middle to inner ramp environments is also supported by the presence of bivalves, gastropods and foraminifers in this facies. This facies falls under the SMF type 7 of the Wilson (1975) and Flügel (1982) standard of microfacies types and depicts reef growth on platform margin.

X-ray diffractometry

The samples of the gypseous shale member including green and brown shale facies were further studied on an X-ray Diffractometer for ascertaining mineral composition. The powdered dry samples were individually scanned over a range 4°–60° 2θ (theta) using a 0.4354 fixed divergence slit and 0.3800 mm in size receiving slit with a step size of 0.0250. Specifications are 1.20 s/step and a total run time of 42.02 min at 40 mA and 45 kV. The instrument was calibrated using a silica calibration standard and the mineral identification was carried out comparing the measured data to a reference database in PANalytical X'Pert High Score (Plus) v3.X database.

X-ray diffraction is a valuable tool in determining the mineralogy of sedimentary rocks, especially shales and carbonates. In case of cryptocrystalline and microcrystalline minerals, XRD is very useful for mineralogical determination. The presence of glauconite in green- and brown shale facies are confirmed by the peaks at 4.45, 2.57 and 5.06 Å, respectively. Gypsum shows its presence by the peaks at 7.60 and 3.05 Å in both the green and brown shale facies. The peaks at 7.19, 3.57 and 7.21 Å show the occurrence of kaolinite as a major clay mineral in shale facies. The presence of goethite is recorded by a peak at 4.18 Å in the brown shale facies. The occurrence of quartz is also recorded by a peak at 4.26 Å in the lower green shale (Fig. 10a, b).

Depositional environments

Late Paleocene has witnessed a widespread transgression on the Indian subcontinent (Singh et al. 2016). Sandstones, lignite and coals were deposited during this transgression. In Kutch basin also, this transgression was characterized by the presence of sandstones and lignite. This transgression was followed by a regression and sedimentation of the shale. The early Eocene Naredi Formation containing green and brown gypseous shale was deposited in a lagoon and marks the overall regression of 2nd order (e.g. Heckel 1986). Further, the brown shale sandwiched between the green shales also shows a short regressive phase of 3rd order (e.g. Heckel 1986). The upper carbonate member deposited during the transgression of 2nd order and the *Assilina* packstone carbonate represents a maximum flooding surface (MFS). The carbonates precipitated in a shallow water environment on barrier margins and as barrier reefs of a platform. Carbonate platforms develop in a wide range of geotectonic settings. Such as passive continental margins, intracratonic basins to failed rifts, and back-arc basins to foreland basins (Tucker and Wright 1990). The carbonates of the Naredi Formation developed in a peri-cratonic basin on the western margin of India.

The occurrence of glauconitic pellets in the green shale facies along the lamina planes suggests that it precipitated during recession in sedimentation from lagoonal water. The presence of pyrite inclusions in these pellets suggests a reducing condition during their formation. Glauconite suggests slow rate of sedimentation during green shale deposition and may act as a useful guide in sequence stratigraphic interpretations (Chattoraj et al. 2009). The overlying brown shale facies suggests deposition in a shallower basin from littoral to intertidal bathymetries. Again the deposition of green shale facies over the brown shale suggests repetition of the similar conditions and cyclicity. The presence of foraminifera, ostracods, bivalves, gastropods and irregular echinoids strongly favor the coastal/shallow marine depositional environment. Low diversity and density of marine fauna with moderate to low bioturbation in brown shale indicate deposition in a restricted basin such as lagoon or restricted shelf. Shales of the Naredi Formation containing larger benthonic and few planktonic foraminifera suggest two phases of transgression and a phase of regression (Keller et al. 2013). According to them, the regressive phase is characterized by the presence of root traces and bioturbation. The sediment supply was poor during clay-rich gypseous shales deposition that became negligible during the carbonate precipitation. It suggests that the gypseous shale member deposited during low-stand condition of sea and is overlain by an extensive upper carbonate member deposited during transgressive and highstand conditions of the sea (e.g. Burchette and Wright 1992).

Widespread shallow water carbonate precipitates within the vast epeiric seas in tropical and subtropical climatic zones (Edinger et al. 2002). Commonly, the absence of significant terrigenous sediment input favours a luxurious

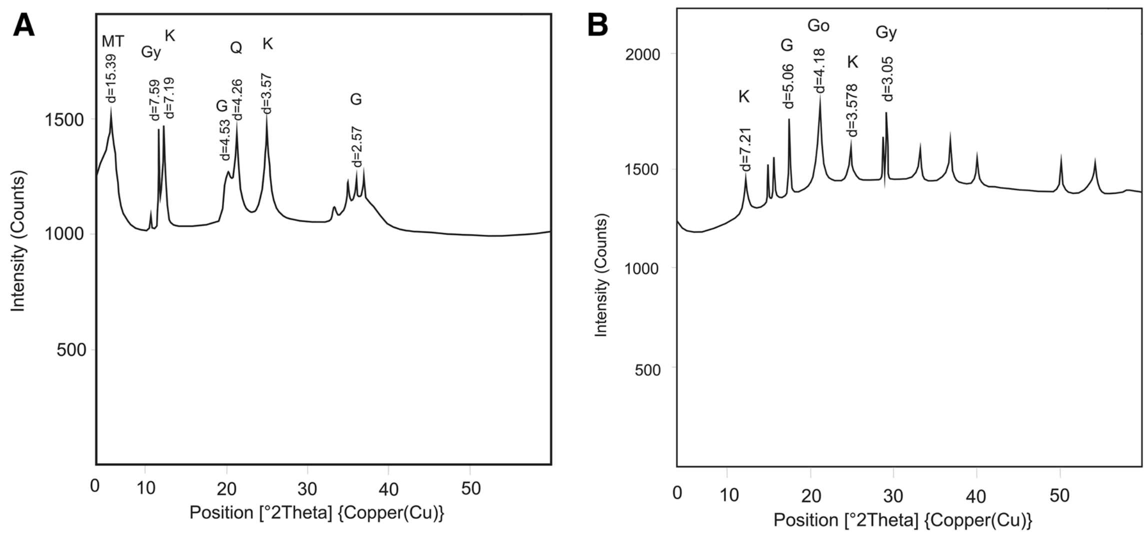

Fig. 10 **a**, **b** X-ray diffraction pattern of the samples from *green*- and *brown*- shale facies, respectively. Here MT, Gy, K, Q, G and Go are the abbreviated form used for Montmorillonite, Gypsum, Kaolinite, Quartz, Glauconite and Goethite, respectively. Note that the characteristic d-spacing values of the above-mentioned minerals are given in the adjacent *parentheses*

carbonate deposition. Occurrence of carbonate nodules within a carbonate mud matrix is a common feature of deposits that are formed above storm wave base on platforms and ramps (Burchette and Wright 1992). The calcareous nodular band at the base of the bioclastic wackestone suggests its formation above storm wave base on a platform or ramp. The most important controls on carbonate sediment production are temperature, salinity and light intensity; these determine the type and abundance of carbonate producing organisms (Lees 1975). The more density of the benthonic forms over planktonic forms of foraminifera suggests that the conditions were more favorable for the presence of benthonic forms. The bioclastic wackestone indicates that the deposition took place in shallow water environment on middle to inner part of the platform where water circulation might have been restricted (e.g. Flügel 2010; Boggs 2009). The abundance of *Assilina* and the presence of a number of sub-ordinate species in the *Assilina* packstone facies indicate deposition either on platform margin or in open marine conditions. The lack of abrasion on foraminifera and abundance of entire forms (Fig. 5e) suggest autochthonous accumulations below fair weather wave base in low wave and tidal processes similar to those reported from foraminiferal banks of Oman and Egypt (Aigner 1982a, b, 1983, 1985; Sinclair et al. 1998; Racey 1994; Adabi et al. 2008). Bioclastic limestones (wackestone and packstone) containing very large-sized *Assilina* and *Nummulites* suggest shallow marine/coastal depositional environment with adequate nutrition supply under the tropical climatic conditions.

The algal reef overlying the *Assilina* packstone facies with strong bioturbation suggests growth of the algal reef by calcareous green algae and incorporation of bryozoa under subtidal conditions that was subjected to faunal attacks. The irregular channels were formed in this limestone during early diagenesis and subaerial exposure. Overlying unfossiliferous clayey limestone facies deposited in a restricted lagoon. In higher-up, the bioclastic packstone–wackestone alternation facies with full of bioclastic fragments such as algal reef fragments, stromatolitic limestone fragments and fragments of bivalve, gastropod, ostracod and many larger benthonic foraminifera shells (not discernible) with fecal pellets indicates deposition behind barrier reef adjacent to lagoon margin (e.g. Tucker and Wright 1990). The NE directed paleocurrent pattern from the cross-beds of the packstone facies also suggests shoreward deposition of the facies on the lagoonal side of the reef. The wavy upper bedding also corroborates this idea. This wavy bedding acts as a substrate for the growth of coral colonies and development of a coralline limestone facies in subtidal to intertidal conditions (Fig. 11).

The carbonate factory is characterized in two ways: it represents the space where the carbonate sediment is produced; it also represents the processes that lead to carbonate production (Tucker and Wright 1990; James and Bourque 1992; Jones and Desrochers 1992; Wright and Burchette 1996; Patra and Singh 2015). Also, carbonate precipitation takes place chiefly on platforms such as; ramp platform, rimmed shelf platform, epeiric platform, isolated platform and drowned platform where carbonate factory involves interplay between the sedimentary environment and the intervening organisms (Kabanov 2009). Among them, the ramp and rimmed shelf platforms precipitation are mainly biotically controlled coupled with warm (20 °C)

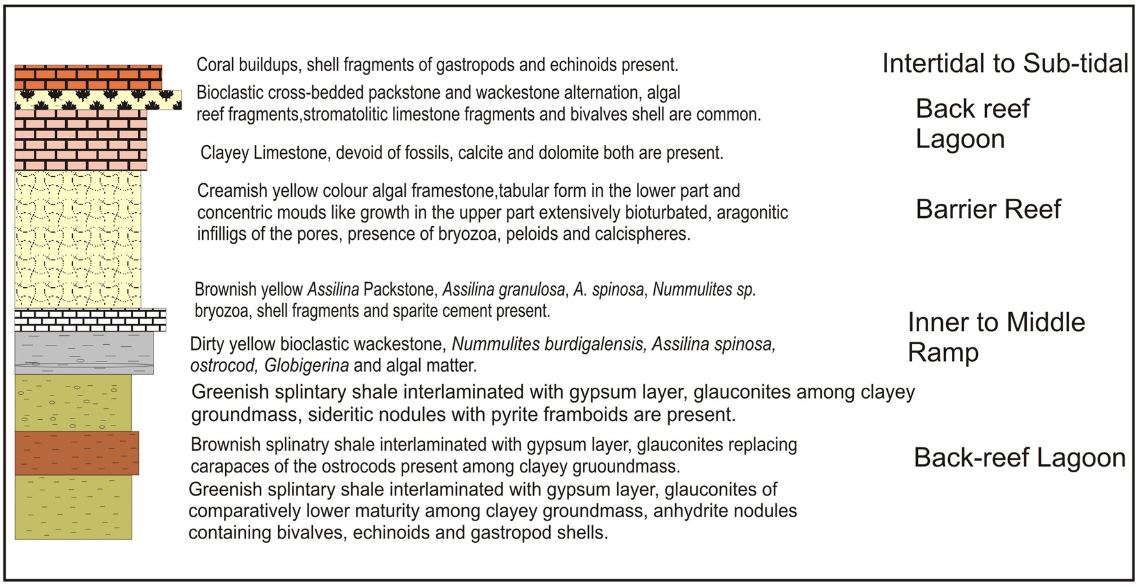

Fig. 11 Facies architecture represents the textural and compositional (biotic and non-biotic) characteristics of the individual facies and their respective depositional environments

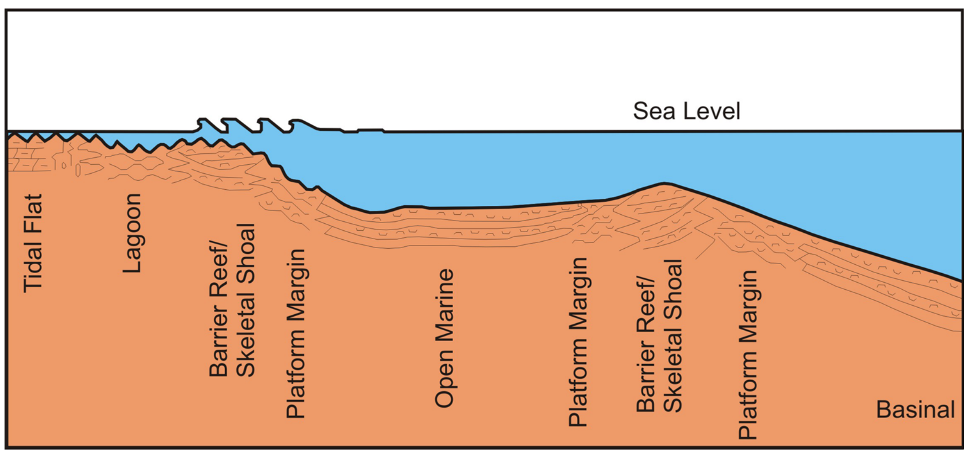

Fig. 12 Model represents association of marginal marine depositional environments such as lagoonal-barrier ridge–lagoonal-tidal flat setting (modified after Boggs 2009) responsible for the deposition of Naredi Formation during early Eocene

water, sunlight and high oxygen and nutrient conditions. They occur between 30°N and 30°S latitudes (Schlager 2005; Kabanov 2009). The studied limestones possess larger foraminifera, algae, bivalves, echinoids, ostracodes and gastropods, thus, suggesting that the biotic component played a larger role during carbonate precipitation. The paleogeographic reconstruction of the Kutch pericratonic rift basin suggests that it was between the equator and the 10°S latitudes during Eocene. This implies that the sea-water was warm with ample sunlight and high in oxygen content. Deposition on the platforms is characterized by three principal sedimentary environments reef, back-reef/barrier lagoon and slope. The back-reef facies or internal lagoonal areas are characterized by mudstone to grainstone depending upon the energy conditions (Schlager 2005). Since the limestones deposited in the Kutch basin during early Eocene time ranges from wackestone to rudstone through packstone, they most likely have been deposited in the back-reef and lagoons of a platform occasionally influenced by storms (Fig. 12).

Conclusions

Facies analysis of the early Eocene Naredi Formation is used in reconstruction of its depositional environments. Here the green and brown gypseous shales are deposited in a back-reef/barrier lagoonal environment and the brown shale shows shallowing of the basin during its deposition. The glauconite either precipitated in the lagoons during slow sedimentation or re-precipitated during diagenesis. The gypsum layers formed from the saline groundwater in both the shales as a result of evaporation. The overlying carbonate wackestone and packstone deposited on the beach ridge. The lagoonal condition is repeated again with the deposition of unfossiliferous clayey limestone. The back-reef bioclastic packstone–wackestone facies deposited on the reef margin by storms as the individual bioclast size crossed 2 mm and the coral reef formed during low- to medium-energy conditions on shallow ramps/platforms. Shallow-deep-shallow facies association suggests 2nd order sea-level change where lagoonal condition was changed to barrier reef and platform margin environment. Also, the 2nd order regressive phase incorporates climatically induced small-scale repetitions (3rd order sea-level changes) during the early Eocene.

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