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Research Paper

LATE QUATERNARY CARBONATE DEPOSITS OF SAURASHTRA, WESTERN INDIA: INSIGHTS FROM PETROGRAPHIC ANALYSIS OF OSL DATED SEQUENCES

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Popularly known as 'Miliolite' or 'Miliolitic limestone', the late Quaternary carbonate deposits of Saurashtra, western India is a unique sequence that has been geochronologically constrained recently using Optically Simulated Luminescence (OSL) technique. The sequence contains three distinct type of depositional units, viz., (i) coastal shell limestone, (ii) coastal and inland aeolianites, and (iii) fluvial reworked sheets. Petrographic study has shown that the shell limestone units are mainly biomicrite, biopelmicrite and biopelsparite whereas, the coastal and inland aeolianites are biopelsparite and pelsparite. The allochems are mainly molluscan shell fragments, echinoid grains, bryozoan fragments, coralline algae, peloids, vadoids and intraclasts. The detrital grains in some case reach up to 45% having its minimum value around 2%. The cement is calcareous being mainly law magnesian sparite and microsparite with occasional presence of micrite. Overall the diagenesis of these units must have occurred in fresh water meteoric condition.

Keywords: Late Quaternary, Miliolite, Carbonate petrography, Saurashtra, India

INTRODUCTION

Late Quaternary carbonate deposits of Saurashtra, western India are popularly known as 'Miliolite' or 'Miliolitic limestones' in the literature. A formal lithostratigraphy classified it as the "Porbander Group" containing older 'Miliolite Formation' and younger 'Chaya Formation' (Mathur *et al.*, 1988). Accordingly, the Chaya Formation is constituted by coarse grained, poorly sorted, coast fringing rocks that could be designated as calcirudites, whereas the Miliolite Formation is comprised of fine to very fine grained, moderate to well sorted aeolianites forming rocks known as calcarenites; the terms being adopted from the classification after Grabau (1904). However, in Saurashtra the calcirudites are not restricted to one stratigraphic position but, occur at the base of three different calcarenite sequences forming shore parallel ridges at various elevations in the coastal areas, and hence

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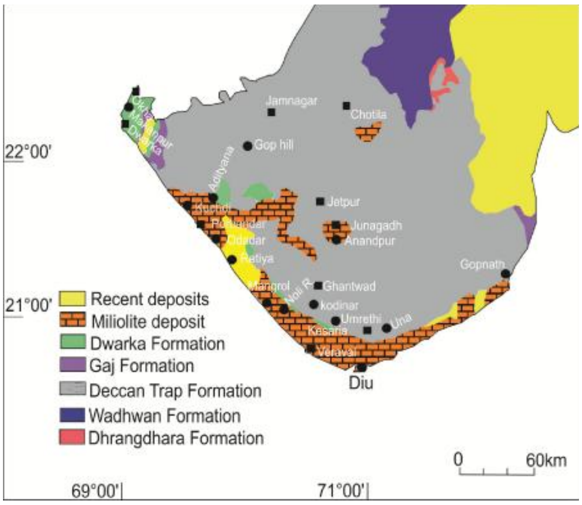
these have been described as the Shell limestones and/or bioclastic shore deposits by Bhatt and Patel (1998) and Bhatt (2000). Recently, Sharma *et al.* (2017) measured Optically Simulated Luminescence (OSL) ages of stratigraphically constrained samples from these units and identified three types of carbonate deposits in Saurashtra, viz., coastal shell limestone, aeolianites and fluvial reworked sheets of miliolite. We present here a comprehensive analysis of petrographic characteristics of these three types of carbonate deposits and their depositional events in light of the OSL ages.

STUDY AREA

Geologically, the Saurashtra landmass (20°40'N and 22°57'N latitudes and 68°57'E and 72°18'E longitudes) comprises magmatic rocks belonging to the Deccan Trap Formation of Late Cretaceous age (Figure 1). Jurassic-Cretaceous sedimentary formations (the Dhrangadhra and Wadhwan Formations) occur in the northeastern part, and sedimentary sequences of Miocene to Pliocene age (the Gaj and Dwarka Formations) occupy the northwestern and southeastern coasts and also as inliers along the southwestern coast. Quaternary deposits rest unconformably either on Miocene sediments or on Late Cretaceous magmatic rocks. It has been suggested that bioclastic carbonate deposits represent the time from Middle to Late Pleistocene and younger unconsolidated coastal dunes and tidal flats are of Middle to Late Holocene age (Merh, 1995). Geomorphologically distinct, Saurashtra peninsula in western India is bounded by the Gulf of Kachchh (north), the Arabian Sea (west) and the Gulf of Khambhat (east).

Figure 1: Geological Map of the Study Area Showing Locations of Sites Studied and Samples Collected, Geology is After Merh (1995)



METHODOLOGY

The carbonate sequences investigated are located between the coast and as far as ~200 km inland. Geographical locations of the sample collection sites were measured using Garmin make GPS. Brief details regarding its field set up are given in the following section. More details are available in Sharma *et al.* (2017). Samples for petrographic studies were collected from coastal environment (beach ridges, beach rocks, coastal sheets), aeolian environment (aeolianites and inland obstacle dunes) and fluvial environment (reworked miliolite sheets) from the study area. For bulk mineralogy these were subjected to the X-Ray Diffraction (XRD) studies at the Department of Earth Sciences, Pondicherry University. A detailed thin section study of 25 samples representing various depositional environments was done using petrological microscope at the Department of Geology, M. S. University of Baroda. The petrographic study included identification of allochemical grains, measurements of grain size and frequencies of constituent carbonate grains along with observation of diagenesis based on grain fabrics, cement morphology and mineralogy.

FIELD SET UP

Sharma *et al.* (2017) presented a detailed description of coastal, aeolian and fluvial settings of the carbonate deposits. The following sections provide a brief description of individual sites (Figure 1) from where the samples were studied for petrographic characteristics.

Coastal Environment

Samples representing coastal miliolite deposition are collected from seven locations; these are: (i) Kuchdi, (ii) Odadar, (iii) Ratiya, (iv) Makanpur, (v) Mangrol coastal quarry, (vi) Mangrol Kamnath temple and (vii) Umrethi.

Kuchdi (21°40.56' N; 69°32.13' E): At this location 5 m thick consolidated carbonate sequence is exposed in the form of a beach ridge which is half a kilometre inland from the present day coastline. Texturally the sequence does not show variability, dominated by medium to coarse grained sand, composed of scattered coral and molluscan fragments. For thin section study sample KCD-2 was collected from upper part of quarry ~3 m above the present sea level.

Odadar (21°33.27'N; 69°41.23'E): This site is located 5 km south of Porbandar from an active miliolite quarry. This is about 10 m thick miliolite section. The miliolite ridge runs parallel to coast at a distance of 700 m from coastline and has an elevation of ~17 m above mean sea level. Stratigraphically, two units can be identified. From bottom upwards 6 m thick medium grained, porous limestone shows cross bedding overlain by a 50 cm thick cavernous layer with epikarstic features like solution vugs and channels lined with thin layers of brownish silty sand. This is overlain by relatively porous 3.5 m thick coarse grained unit which is moderately sorted, and contains shell fragments. For thin section, samples OD-1 from lower unit and OD-2 from upper unit were collected.

Ratiya (22°20.58'N; 68°57.31'E): This is a beach ridge located 30 km south of Odadar near the locality Ratiya. This beach ridge is a southern continuation of Odadar beach ridge and hosts numerous abandoned quarries. One sample, viz., RT-1 was collected from the bottom part of a quarry which is approximately 2 m above sea level.

Makanpur (22°20'23"N, 68°57'44"): At this site the rocks are typical beach rocks which are termed as Okha Shell limestone of Chaya Formation (Bhatt, 2000). The beach ridge is about 8 m thick having seaward dipping planar cross beds. Texturally sediments are coarse grained, moderately sorted limestone with scattered lenses of beach shingles. Sample MKN-1 and MKN-2 were collected from the bottom and upper part of the unit for thin section study.

Mangrol Coastal Quarry (21°06.59' N; 70°05.32' E): This is an abandoned 2 m deep quarry at a distance of 200 m from the coast at an elevation of 1 m above the sea level. The coastal quarry is a part of a beach ridge which runs ~100 m parallel to the coast. The limestone unit is overlain by ~50 m high stabilized and partially or seasonally active coastal dunes that merges with the present day beach. The sequence is rather uniform, but the upper part of the sequence shows cavernous features where solution channels are seen up to 1 m depth. Sample MG-1 was collected for thin section studies from the middle part of the unit where limestone is relatively less porous and less weathered.

Mangrol Kamnath Temple (21°08.12’N; 70°10.46’E): At this location, ~2 m thick sequence comprising fluvial gravels and a miliolite sheet is preserved. The textural attributes allowed us to identify three sedimentary units. These are from bottom upwards, a 130 cm thick clast-supported conglomerate grading into matrix dominated (fining upward) in the upper part (unit-I). Above this unit a 30 cm thick fluvial gravel unit with tertiary limestone boulders is present (unit-II) which is separated from unit-I by erosion surface. This sequence ends with a 20 cm thick miliolite sheet deposit which is moderately compact and weathered (unit-III). For thin section a sample MG-3 was collected from unit – III.

Umrethi (21°01.17’N, 70°28.13’E): This site is in the Hiran river just downstream of the Umrethi dam where ~6 m thick miliolite deposit is exposed. In this section two distinct units can be identified. The lower 2 m thick unit is composed of very fine grained, white coloured limestone showing dune morphology. This is overlain by second unit which is 4 m thick and is separated from lower unit by an erosion surface. The upper unit has wedge shape planar cross stratifications. Sample for thin section study viz. UMT-1 and UMT-2 were collected from the lower and the upper units respectively.

Aeolian Environment

From aeolian environment total 6 sites have been investigated, viz., (i) Adityana, (ii) Gopnath, (iii) Diu, (iv) Mangrol, (v) Una and (vi) Gop Hill.

Adityana (21°43.51’ N; 69°41.51’ E): At Adityana, a typical obstacle dune is currently being mined for limestone. The section sampled is located 16 km inland and around 60 m above the present day sea level. The miliolite exposure is ~30 m thick sequence in which five stratigraphic units are identified. The dunes are mixed with thin intervening layers of granophyre sand and gravel indicating gravity fall and fluvial reworking. The lowermost unit is pink coloured and compact limestone. This is overlain by another unit about a meter thick comprise of reworked miliolite mixed with locally derived granophyres clasts. Above this unit 3 m thick aeolian unit is present. In appearance this unit is of buff white coloured and medium to fine grained nature. The topmost unit is about 5 m thick, white coloured fine grained limestone that shows planar wedge shape cross stratification. For thin section studies 3 samples viz., ADT-1, 2 and 5 were collected from lower most, middle and uppermost units respectively.

Gopnath (21°12.22N; 72°06.35’E): This site is located in the southeastern corner of Saurashtra coast. The section is exposed as a laterally persistent cliff of 12 m height and contains 3 distinct miliolite units which are separated by 0.5-1 m thick red soil layers. For thin section study two samples were collected, i.e., GPN-1 (lowermost) and GPN-3 (middle).

Diu: On the coast of Diu island near village Fudam (20°42.29’N; 70°59’E) an abandoned limestone quarry has exposed ~12m thick miliolite section. The entire section is of buff white colour, relatively friable and porous, medium to fine grained, moderately sorted and comprises several sets of cross-stratification with varying dip azimuth indicating dune morphology. For thin section studies sample DD-1 was collected from the upper part of the section.

Near to the Diu fort abandoned quarries in miliolite are famous as the Nayada caves (20°42.41’N; 70°58.53’E). Here a miliolite quarry face shows moderate to high angle planar cross stratifications in yellowish coloured, medium grained, well sorted miliolite indicating dune facies. For thin section studies sample DD-2 was collected from the upper part of the unit.

Mangrol (21°05.50'N; 70°09.23'E): Near the Noli river bridge at Mangrol, a 6 m high miliolite cliff section comprising five units is exposed. From the base upwards, 1 m thick pebbly stratified horizon is overlain by a partially eroded horizontal to sub-horizontal 40 cm thick miliolite layer. This is succeeded by 1.5 m thick reddish-brown sandy gravel unit. Overlying this is a 1 m thick mottled, well sorted sandy horizon with faint cross-stratification containing calcrete. The uppermost unit is a 30 cm thick miliolite with gentle inclination towards the northwest. Overall these units suggest marine intertidal deposition at the base grading upwards to fluvial deposits overlain by aeolian deposit. For thin section studies two samples from the older limestone unit (lowermost) MG-9, MG-10 and one sample MG-8 from the uppermost miliolite unit were collected.

Una (20°48.22'N; 70°57.19E): On the road to Una, north of the Diu island, where several mounds of aeolianits exist over a coastal plain, a quarry exposes about 15 m of section comprising dirty white coloured, well sorted miliolite with moderate to large scale cross stratifications and overall a parabolic dune geometry. For thin section studies sample UNA-1 was collected from the base of the section and sample UNA-2 was collected from the upper unit.

Gop Hill (22°02'40.73"N; 69°55'3.57"E): This site is in the north of Barda Hills that act as an obstacle to the aeolian transport of miliolitic sand. In the southern slope of the hill ~3 m thick aeolian sediments rest with wedge shape geometry. The sediments are white coloured, well sorted fine grained with planar cross beddings. At the base of the hill about 300 m downstream, miliolite sand mixed with significant basalt and granophyre sand and gravels provided a fluvially reworked sheet deposits. For thin section study sample GP-1 from the obstacle dune was collected.

Fluvial Environment

Two site viz., (i) Anandpur and (ii) Ghantwad were investigated for fluvially reworked miliolite sheets.

Anandpur (21°03.54'N; 71°48.22E): At Anandpur a cliff section of about 9 m height along the river bank contains fluvial gravels and sand overlain by miliolite, and was described earlier by Bhatt and Bhonde (2003). The sequence rests unconformably over weathered basalt. The lower most 2 m thick unit is compact, trough cross-bedded gravel, whereas in the upper part assorted pebbles and gravels with crude horizontal layering is observed. This unit is overlain by a 4.5 m thick silty sand unit with horizontal stratification in its lower part, whereas in the upper part low angle planar cross-stratifications are present. About 50 cm thick lens of gravelly sand occurs over the silty sand unit in a laterally discontinuous form. This is unconformably overlain by a sheet of miliolitic limestone having a variable thickness ranging between 0.5 and 2 m. From this section sample ANP-4 was collected from the topmost unit for thin section studies.

Ghantwad (20°55.33'N; 70°45.31'E): This site is located about 16 km north of the Kodinar and near Ghantwad village in the Singvado river where the river bank section of 5 m height was available for the study. Here miliolite sequence rest on a 0.5 m thick soil layer that is developed on basalt. The sequence contains 6-8 m thick, near homogeneous deposits of miliolite extending on both the banks. The rock was pinkish in colour, very fine grained and compact. Low angle planar and trough cross stratification, thin lenses of basalt sand and gravels, and crescent ripple marks were seen on exposed bedding surface. Sample KDR-1 was collected for thin section studies from the upper part of the miliolite sequence.

Some additional samples were collect from this variant of miliolite unit from the base of the Gop hill (GP-2) and Adityana (ADT-2) where such fluvially reworked unit occurs at local scale.

RESULTS

Petrography

The petrographic analysis has suggested that in coastal miliolites, peloids concentration ranges from 0.80-90%, intraclasts 0-5%, bioclasts 3-72%, detrital 3-32% and coated grains 0-5%. The detrital component in miliolite consists of quartz, pyroxene, feldspar, iron oxide and lithoclasts of basalt. For coastal deposits average grain size of peloids varies between 0.01-0.04 mm, whereas minimum grain size ranges from 0.002-0.01 mm and maximum grain size ranges between 0.02-0.1 mm. In aeolianites (coastal and inland) the concentration of peloid ranges between 6-95%, intraclasts 0-11%, bioclasts 2-18%, detrital 2-42% and coated grains 0-9.5%. For coastal and inland aeolianites, average grain size is 0.01 mm, whereas maximum grain size ranges between 0.02-0.03 mm and minimum grain size ranges between 0.002-0.004 mm. In fluvial environment peloid ranges between 69-85%, intraclasts 0.2-1%, bioclasts 0.3-7%, detrital 9-20% and coated grains 0-14%. For fluvial deposits average grain size of peloids is identical for all samples to be 0.01 mm whereas, maximum grain size of peloid ranges between 0.02-0.04 mm and minimum grain size is 0.002 mm. Average grain size of foraminifera tests in fluvial deposits is 0.01 mm whereas, maximum grain size ranges between 0.01-0.2 mm and minimum grain size ranges between 0.004-0.1 mm. Details of the allochemical composition (%), mineral assemblage and grain size are presented in Tables 1 and 2 respectively. Table 1 also presents OSL age of the carbonate units along with their depositional environment.

XRD Studies

In coastal miliolite the minerals observed are calcite, quartz, magnesian calcite, aragonite and ferro-dolomite. In aeolian miliolites calcite, quartz, lepidocrocite, microcline, ankerite, law magnesian calcite and aragonite are observed. In fluvially reworked miliolite the minerals observed are calcite, law magnesian calcite, quartz, aragonite and polyhalite (Table 1). It has been observed that majority of the samples contain carbonate along with quartz and sometimes with plagioclase feldspar. In many samples the principal carbonate mineral is law magnesian calcite and calcite. The difference essentially lies in the extent of substitution of Ca by Mg in calcite, which is related to the interaction between aqueous fluid and the calcite precipitated from it. Presence of calcite (or magnesian calcite) as well as aragonite in some samples indicates conversion of one to another. Calcite is generally stable at low P (also at higher T), and aragonite at higher P. In many samples, along with the principal carbonate mineral (mentioned above), aragonite is also present (it is a dimorph of calcite). In some samples ankerite (Ca, Fe, Mg carbonate) or ferroan dolomite is present. Few samples (like ANP-1) contain essentially silicates including plagioclase feldspar, pyroxene (augite) and potash feldspar (orthoclase) that could be derived from the dertital grains. A low temperature variety of zeolite called “laumontite” is present is few

Table 1: Allochemical and Mineralogical Composition of Carbonate Sequences with Details of their OSL Age, Depositional Environment and Classification Following Folk (1962)

S. No.	Sample Location	Sample No	Peloid	Intraclasts	Bioclasts	Detrital	Coated Grain	Mineral Assemblage	OSL Age (ka)	Environment	Classification
1	Odadar	OD-1	31.78	1.94	42.1	21.85	2.33	Calcite, quartz	80±8	Beach Ridge	Pelbiosparite
2	Odadar	OD-2	48.81	3.79	28.74	18.25	0.4	Magnesian calcite, quartz, calcite	99±8	Beach Ridge	Biopelsparite
3	Kuchdi	KCD-2	40.42	0.42	32.66	26.5	0	Magnesian calcite, quartz	67±5	Beach Ridge	Biopelmicrite
4	Makanpur	MKN-1	6.08	0.45	58.9	34.27	0.3	Magnesian calcite, quartz , aragonite, ferroan dolomite	84±10	Beach Ridge	Pelbiomicrite
5	Makanpur	MKN-2	15.95	0.52	52.52	30.11	0.91	Quartz, magnasian calcite	75±7	Beach Ridge	Pelsbioparite
6	Mangrol	MG-1	25.43	1.3	40.78	31.78	0.72	Calcite, quartz	44±4	Beach Ridge	Pelsbioparite
7	Mangrol	MG-3	12.5	5.36	58.21	18.57	5.36	Magnesian calcite, quartz	18±1	Coastal Swamp	Pelbiomicrite
8	Mangrol	MG-8	89.32	0.04	2.01	5.5	3.13	Magnesian calcite, quartz	43±2	Aeolianite	Biopelsparite
9	Mangrol	MG-9	3.88	0	51.72	44.4	0	Magnesian calcite, quartz	165±15	Beach Rock	Biopelsparite
10	Mangrol	MG-10	0.83	0.12	72.02	27.02	0	Calcite, quartz	163±13	Beach Rock	Biomicrite
11	Umrethi	UMT-1	93.72	0.12	2.85	2.47	0.85	Magnesian calcite, calcite	150±12	Coastal sheet	Pelsparite
12	Ratiya	RT-1	16.08	3.5	36.69	43.17	0.7	Magnesian calcite, quartz, aragonite, polyhalite	81±5	Beach Ridge	Pelbiomicrite
13	Gopnath	GPN-3	38.33	0.13	19.84	41.3	0.4	Calcite, quartz	>156	Aeolianite	Biopelmicrite
14	Gopnath	GPN-1	38.62	0	31.27	30.11	0	Calcite, quartz, ankerite	>156	Aeolianite	Biopelsparite
15	Adityana	ADT-1	85.27	0.13	7.24	3.88	3.49	Magnesian calcite, quartz	140±16	Aeolianite	Biopelsparite
16	Adityana	ADT-5	80.54	0.48	2.68	6.81	9.49	Magnesian calcite, calcite	77±5	Aeolianite	Biopelsparite
17	Umrethi	UMT-2	95.49	0.43	2.08	2	0	Calcite, quartz	48±2	Aeolianite	Pelsparite
18	DIU	DD-1	37.58	11.43	35.82	14.51	0.66	Magnesian calcite, quartz, ankerite	45±3	Aeolianite	Biopelsparite
19	DIU	DD-2	76.92	0	5.13	13.75	4.2	Calcite, quartz	126±12	Aeolianite	Biopelmicrosparite
20	UNA	UNA-1	84.23	0.42	11.58	2.65	1.12	Magnesian calcite, aragonite	20±1	Inland Aeolianite	Biopelspatite
21	UNA	UNA-2	77.19	0.4	17.61	3.31	1.48	Calcite, aragonite	11±1	Inland Aeolianite	Biopelmicrosparite
22	Anandpur	ANP-4	78.11	0.2	0.33	20.31	1.05	Magnesian calcite, quartz	18±2	Fluvial reworked	Biopelsparite
23	Gop Hill	GP-1	84.62	0.3	5.86	9.25	0	Calcite, albite, diopside	80±5	Fluvial Reworked	Biopelsparite
24	Kodinar	KDR-1	74.43	1.15	6.9	16.67	0.86	Magnasian calcite, quartz	174±12	Fluvially reworked	Biopelsparite
25	Adityana	ADT-2	68.93	1.05	5.04	11.48	13.5	Quartz, magnesian calcite, polyhalite	28±3	Fluvially reworked	Biopelsparite

Table 2: Grain Size Variations in Rounded Allochems from Carbonate Sequences

S. No.	Location	Sample No.	Distance (km)	Peloid Max. Grain Size (mm)	Peloid Min. Grain Size (mm)	Peloid Average Grain Size (mm)	Foram Max. Grain Size (mm)	Foram Min. Grain Size (mm)	Foram Average Grain Size (mm)	Environment
1	Odadar	OD-1	0.67	0.04	0.002	0.01	0.02	0.01	0.02	Beach Ridge
2	Odadar	OD-2	0.67	0.04	0.01	0.02	0.03	0.01	0.02	Beach Ridge
3	Kuchadi	KCD-2	0.46	0.1	0.01	0.02	0.03	0.01	0.02	Beach Ridge
4	Makanpur	MKN-1	On the coast	0.06	0.01	0.02	0.03	0.01	0.01	Beach Ridge
5	Makanpur	MKN-2	On the coast	0.02	0.004	0.01	0.03	0.01	0.01	Beach Ridge
6	Mangrol	MG-1	0.3	0.1	0.01	0.03	0.03	0.03	0.03	Beach Ridge
7	Mangrol	MG-3	8.14	0.04	0.01	0.02	0.02	0.02	0.02	Coastal Swamp
8	Mangrol	MG-9	3.14	0.1	0.01	0.03	0.03	0.02	0.02	Beach Rock
9	Mangrol	MG-10	3.14	0.05	0.004	0.02	0.02	0.01	0.01	Beach Rock
10	Umrethi	UMT-1	17.43	0.03	0.002	0.01	0.01	0.01	0.01	Coastal sheet
11	Ratiya	RT-1	0.67	0.08	0.01	0.04	0.07	0.01	0.03	Beach Ridge
12	Gopnath	GPN-3	On the coast	0.04	0.004	0.01	0.02	0.01	0.01	Aeolianite
13	Gopnath	GPN-1	On the coast	0.02	0.004	0.01	0.02	0.01	0.02	Aeolianite
14	Adityana	ADT-1	1.92	0.03	0.003	0.01	0.02	0.01	0.02	Aeolianite
15	Adityana	ADT-5	1.92	0.02	0.002	0.01	0.02	0.01	0.01	Aeolianite
16	Mangrol	MG-8	3.14	0.02	0.002	0.01	0.02	0.01	0.01	Aeolianite
17	Umrethi	UMT-2	17.43	0.02	0.002	0.01	0.02	0.01	0.01	Aeolianite
18	Diu	DD-1	0.11	0.03	0.003	0.01	0.03	0.005	0.01	Aeolianite
19	Diu	DD-2	0.5	0.02	0.002	0.01	0.02	0.01	0.01	Aeolianite
20	Una	UNA-1	9.81	0.03	0.002	0.01	0.02	0.01	0.01	Inland Aeolianite
21	Una	UNA-2	9.81	0.03	0.002	0.01	0.03	0.01	0.02	Inland Aeolianite
22	Anandpur	ANP-4	45.77	0.02	0.002	0.01	0.01	0.01	0.01	Fluvial reworked
23	Gop	GP-2	56.86	0.02	0.002	0.01	0.03	0.004	0.01	Fluvial reworked
24	Kodinar	KDR-1	22.96	0.04	0.002	0.01	0.2	0.1	0.01	Fluvial reworked
25	Adityana	ADT-2	1.92	0.02	0.002	0.01	0.02	0.01	0.01	Fluvial reworked

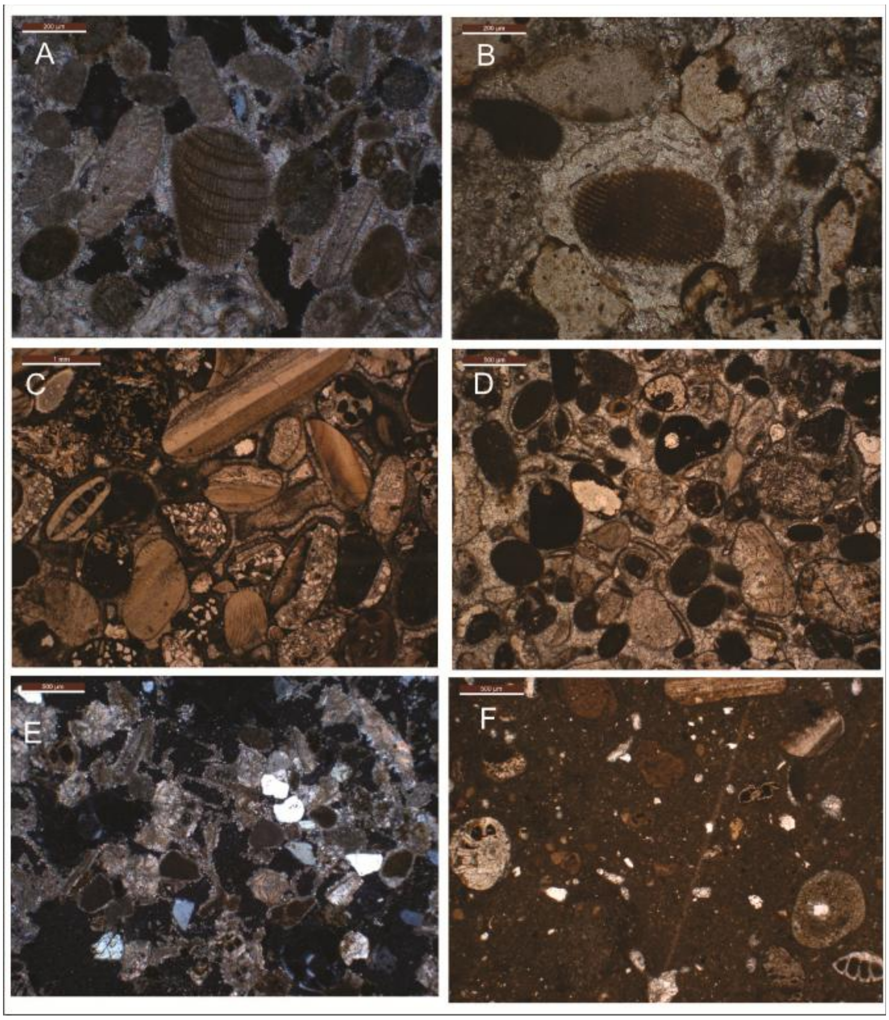
samples which must have been derived from the amygdaloidal basalt, the substrate rock. Few samples showed the possibility of halide salts, including RT-1. These could be secondary minerals either crystallized from the pore water or derived from the amygdaloidal basalt which is the substrate rock in the region.

DISCUSSION

The miliolites that are deposited by aeolian process viz., coastal and inland aeolianites, and fluvially reworked miliolite sheets contain moderate to well sorted grains. These grains are cemented together with sparite and microsparite cement. Morphologically they show meniscus and rim cement. Such cements are known to precipitate in the vadose zone at the grains contacts due to the meniscus of liquid held by capillary forces during the draining of interstitial waters (Bhatt and Patel, 1996). In addition to this, microsparite rim on the grains and diagenetically formed coated grains are also observed. Thus, the nature of cementation suggests that the post deposition diagenesis occurred under fresh water conditions.

The carbonate units that are deposited under coastal environment, viz., beach rock, beach ridges and coastal sheet deposits comprise a variety of allochems, viz., mega and micro shells of gastropoda and pelecypoda, and tests of foraminifera together with fragments of bryozoans, echinoids, coralline algae and sponges, etc. The intraclasts, beach shingles and lithoclasts of older rocks are also found within them (Bhatt and Patel, 1998). In the coastal samples most are bounded together with microsparite and sparite cement except the sample MG-3 that shows micritic cementing material and suggests its deposition in littoral

Figure 2: Photomicrographs Showing Typical Texture, Composition and Diagenetic Imprints in Carbonate Units



Note: (A) Typical coastal aeolianite with higher amount of porosity and meniscus cement at grain boundaries. (B) Syntaxial overgrowth of echinoid grain in miliolite sheet. (C) Typical section of shell limestone with fibrous rim cement followed by sparite cement. Detrital grains of sandstone can also be seen. (D) Vadoid grains with thin coatings around peloids can be seen in the aeolianite thin section. (E) Highly porous nature of inland aeolianite showing microsparite cement along grain contacts and round the grains. Detrital quartz grains can also be seen. (F) Biomicrite from the coastal sheet showing floating grains of foraminifera. Bar scale represent for A and B 200 micron, for C 1000 micron and for D and E 500 micron.

environment. Figure 2 shows typical thin sections of the miliolite deposits in aeolian, coastal and fluvial environment exhibiting different cement types and typical bioclasts.

Interestingly the freshwater cementation in the coastal miliolite deposits indicates that the diagenesis of these deposits occurred in vadose zone by the meteoric water following the recession of the sea. We do not find any correlation i.e. decreasing grain size as a function of distance from the coast. Although the aeolianite grains show well sorted characteristics and are relatively smaller in size compared to their coastal counter parts.

In light of the OSL ages after Sharma *et al.* (2017), the coastal beach ridges and beach rock samples occurs within the range of 165±15 ka to 44±4 ka with major beach ridge formation between 99±8 ka and 67±5 ka. Within these samples clear effects of diagentic alteration could be seen in terms of recrystallisation and pore filling cement of older units in comparison to that of the younger ones. The coastal aeolianites that formed more or less coeval to the beach ridge formation also shows presence of more cement in its pores in comparison with the younger inland aeolianites. The carbonate minerals are seen having presence of magnesian calcite, calcite and aragonite in coastal settings, whereas the inland miliolite contains calcite. However, younger aeolian deposits also contain metastable carbonate minerals like aragonite and magnesian calcite due to its less diagenetic maturity. Fluvial reworked miliolite shows increased amount of detrital grains largely derived from the substrate rocks like basalt and granophyres.

CONCLUSION

The study permits to draw the following major conclusions.

1. The thin section study indicates that post depositional diagenetic alterations of miliolite seems to be independent of the nature of depositional environment in which miliolite were deposited.
2. Our study shows that diagenetic alterations (compaction and cementation) occurred under vadose zone by interaction of fresh water.
3. No definitive correlation in the grain size as a function of distance was observed.
4. The XRD study suggests dominantly the carbonate minerals that contains locally derived detrital grains such as feldspars and pyroxenes along with secondary minerals derived from the older rocks. Presence of magnesian calcite and aragonite represents its formation in shallow marine condition whereas the authigenic (cement) carbonate mineral being calcite suggests a role of freshwater.
5. Petrographic analysis suggests reworked nature of the carbonate (allochemical) grains which were derived from the coastal environments and were deposited as coastal as well as inland aeolianites and re-deposited under the influence of local fluvial agencies.

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