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Palaeocurrent Pattern, Textures and Depositional Environment of Miliolitic Limestone of Diu, Western India

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Abstract: The present work deals with the palaeocurrent pattern and the textural attributes of the miliolitic limestone of Diu and their application for the interpretation of its origin and depositional mechanisms. The palaeocurrent pattern indicate a north to northeasterly direction of sediment transport which is similar to the present day wind pattern along Saurashtra coast. The limestone is fine to medium grained, moderate to better sorted, fine-skewed and leptokurtic to mesokurtic in nature. The study suggests a variable coastal marine beach to dune (eolian) environment of the limestone, representing the fluctuating sea levels of the Pleistocene Period. The constituent particles of the limestone, derived from the exposed beach and shallow-marine environments during lower sea levels, have been reworked by the prevailing wind and rain waters leading to limestone deposition.

Keywords: Sedimentology, Miliolitic Limestone, Diu.

INTRODUCTION

The bioclastic carbonate deposits, extensively exposed along the Saurashtra Coast and belonging to Middle Pleistocene Miliolitic Limestone Formation, have remained debatable for their origin. Their variable field characters and diverse modes of occurrence attracted the attention of several earth scientists (Evans, 1900; Shrivastava, 1968; Biswas, 1971; Lele, 1973; Sperling and Goudie, 1975; Rajaguru and Marathe, 1977; Verma and Mathur, 1978; Baskaran, 1986; Patel, 1991; Somayajulu, 1993; Patel and Bhatt, 1995). General textural account of these rocks is given in Patel and Allahabadi (1988) and their detailed Palaeowind analysis is included in Mathur (1987) and Patel and Bhatt (1992). Present study provides additional information on the texture and depositional environment of the Miliolitic limestone of Diu.

Diu, a small island off the southern Saurashtra coast (Fig.1), marks a partially submerged miliolite dune providing a striking example of the Mid-Late Pleistocene regression and Early Holocene transgression (Merh, 1977). The eastern part of the island exposes the limestone in the form of long parallel (dune) ridges trending parallel to the strand line, with parabolic or semicircular termination of each ridge. The central part of the island is covered with the Recent and Sub-Recent calcareous dunal sands, which are consolidated at places. The cliff sections of about 10 m height provide suitable sampling sites. The limestone is porous, friable and highly cavernous and on surface exhibits the mini-karst topography. The depositional features and the nature of the sediment are preserved to some extent below. A thin layer of hard dense caliche crust caps the limestone ridges.

SEDIMENTARY STRUCTURES AND PALAEOCURRENTS

Cross-bedding is the prominent sedimentary structure exhibited by the miliolitic limestone of Diu (Fig.2). The dips of the cross-bedded strata vary between 5° and 10°. The cross-bedding is mostly of high angle wedge type followed by large scale planar and herringbone types. The dips of the foreset varies from gentle (<10°) to quite steep (>25°). Abrupt reversals of the direction of dips observed at some places are due to the local changes in the direction of

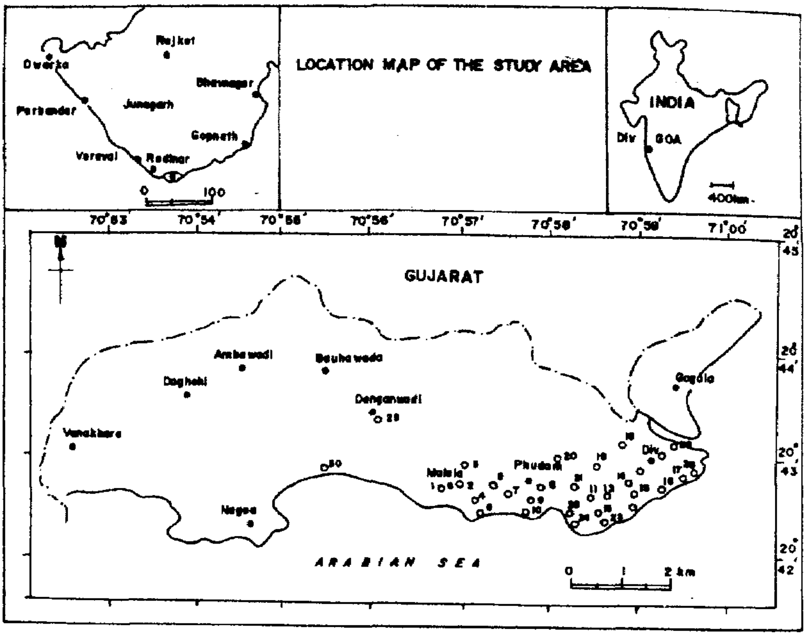

Fig.1. Map showing sample locations.

the transportational medium. The thickness of the individual cross-laminae vary from <5mm to several centimeters. Skeletal composition, grain-size changes and the weathered surfaces define the cross-strata. The individual cross-bedded units are 4-15m wide with a variable thickness of 1-5m. Other structures observed in these rocks include cavernous and minikarstic features, laminated bedding etc.

More than 200 readings of dip azimuths

Fig.2. Large scale cross-bedding structure in a cliff section (approx. 10m. height) of the miliolitic limestone (Location near Circuit House, Diu).

of the cross-bedded strata are recorded from the limestone exposures of Diu area. The vector means of the cross-bedding dip azimuths were calculated trigonometrically following Curray (1956), and Potter and Pettijohn (1963). Majority of the vector means of the Cross-bedding dip azimuths are directed onshore. The earlier estimated mean-palaeowind direction based on the cross-bedding data of miliolitic limestone of Saurashtra is 80°N. The present study indicated a composite vector mean direction of 31°N with vector magnitude of 44.51 suggesting a northeasterly direction of sediment transport (Fig.3), which is in agreement with the observations made by Mathur (1987). The low value (716) of variance is suggestive of aeolian origin. The present day wind pattern around Saurashtra Coast suggests that the wind blows from all directions, however the prominent being southwesterly. The directional features in the miliolitic limestone also suggest that a similar pattern existed during Pleistocene (Opdyke, 1961).

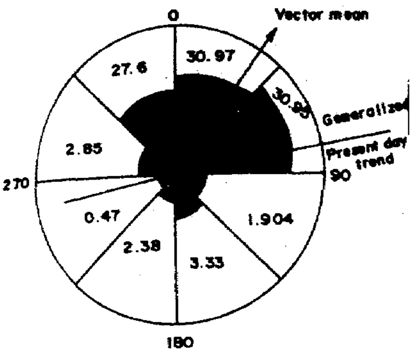

Fig.3. Composite rose diagram showing the distribution of cross-bedding dip *azimuths* in *the miliolitic* limestone.

TEXTURAL ATTRIBUTES

The interpretation of limestone deposition, to a large extent, is based on the types of grains present. Since, these provide useful information on the depth, salinity of water, degree of agitation etc. which give valuable information regarding the energy level and energy gradient of the depositional environment (Tucker, 1988). The textural parameters described for clastic sediments can also be applied for the carbonates though the carbonate particles are hydrodynamically different and vary greatly in size and shape.

Grain-Size Parameters

Grain size studies have been widely used for interpreting depositional environments of ancient and modern sediments (eg. Folk, 1966; Klovan, 1966; Friedman, 1961, 1967; Moiola and Weiser, 1968) and in the recent years these have been employed for carbonate sediments and rocks (Ginsburg, 1956; Folk, 1962, 1966; Pilkey *et al.* 1967; Lewis, 1969; Hoskin and Nelson, 1971; Davis and Conley, 1977; Nelson, 1977).

In all, 30 thin sections of representative limestone samples were made for textural study to determine the grain-size parameters, shape and roundness by grain projection method. The various size parameters viz. mean size, standard deviation, skewness and kurtosis were calculated after Folk and ward (1957) by graphical method. The one percentile(C) and fifty percentile (M) values have been recorded from the cumulative curves for plotting on the C-M diagram. Since most interpretations of grain size distribution are based on the evaluation of unconsolidated sediments (Sieve data) the necessary statistical corrections were made using the procedure laid in Krumbein (1938) and the data is presented in Table I and have been interpreted to understand the mechanism of sediment transport and depositional environment.

A marked unimodality in grain-size exists within all the limestone samples. The mean grain-size varies from 1.6197 to 3.2954ϕ with a mean of 2.2722ϕ, and standard deviation of 0.3779 suggesting their fine to medium grained nature. The standard deviation values range from 0.3529 to 0.6348, suggesting moderate to well sorted nature of the rocks (Friedman, 1967). Standard Deviation measures the sorting of the sediments and indicates the fluctuations in kinetic energy (velocity) conditions of the depositing agent in terms of its average velocity. Skewness values fluctuate from -0.2060 to 0.2736 indicating the presence of both finer and coarser fractions. The skewness close to zero reflects a broad spectrum of populations present in the samples. The skewness variation (-ve to +ve values) can readily be explained by the presence of sand sized materials in coarse and fine tails of the distibution. Kurtosis values fluctuate erratically around a central value of 1 (0.8361 to 1.1141) with dominant leptokurtic sands. Friedman (1967) points out that most sands are leptokurtic, a fact interpreted by Mason and Folk (1958) as resulting from mixing of predominant populations with very minor amount of fine gravel.

Grain Shape, Roundness and *Surface Textures*

The grain shape and roundness of the carbonate rocks require a critical evaluation because only some particles provide meaningful results (Folk, 1962). Some grains such as ooids, faecal pellets are rounded by themselves and some bioclasts like foraminifera are already rounded and/or spherical in comparison to the associated non-carbonate materials. Carbonate sand grains get abraded by wind action two to four times faster than the quartz grains (Glennie, 1970). Furthermore, degree of rounding shown by a biogenic grain will depend on its composition and the original microstructure etc. The sphericity and roundness parameters for these limestones were calculated after Riley (1942) and Wadell (1933). These values range from 0.6312 to 0.8710 and 0.3606 to 0.6920 (Table I) respectively, suggesting a near spherical, moderate to well rounded nature of the particles owing to considerable abrasion/rounding during their transportation.

SEM observation of selected limestone particles reveal the presence of surface features viz., (i) worn-out features of the tests, (ii) rounded outlines, smooth/polished surfaces and oriented etch pits displayed by the quartz grains, pellets and rock fragments. These features can be attributed to rolling and abrasion processes during aeolian sediment transport and under subsequent depositional environment.

Textural Plots

Various combinations of textural parameters have been utilized to differentiate sediments from various depositional environments. The present study utilizes the standard bivariate plots of Friedman (1961, 1967), Moiola and Weiser (1968), Passega (1957) and multivariate discriminant plot of Sahu (1983) for plotting and environmental interpretations. The two vectors $\bar{v}1$ and $\bar{v}2$ for plotting on the discriminant plot, are calculated after Sahu (1983) and the data is presented in Table I.

The Sinusoidal relationship between Mz and sorting described by Folk (1968) is partly evident from Fig.4a, although for any given grain-size the sorting is somewhat poorer. The sample data points fall mostly in dune and beach fields of the bivariate plots (4a, b, c and d). The relationship of grain-size with sphericity and roundness is shown in Fig.4e and f. The sample data plots on the C-M diagram (Fig.5) is suggestive of the transportation of sediment materials by saltation and traction processes and the overall C-M pattern (dashed area of Fig.5) is broadly consistent with beach deposition resembling that of Passega (1957). The sample data points on the multigroup discriminant plot (Fig.6) fall in both beach and aeolian fields.

DEPOSITIONAL ENVIRONMENT

The controversy regarding the origin of the miliolitic rocks of western India, whether marine or aeolian, has been brought out by Shrivastava (1968), Biswas (1971), Lele (1973), Sperling and Goudie (1975), Marathe *et al.* (1977), Verma and Mathur (1978), Patel (1991) and Patel and Bhatt (1992). It has been well established that the inland limestone deposits are attributed to aeolian activity (Patel, 1991; Biswas, 1971), while the coastal ones have been ascribed to mixed marine to beach environments (Biswas, 1971; Marathe *et al.* 1977).

The average grain-size of these rocks, as observed in the present study, resembles that of nearshore beach sands. This similarity, of course, does not rule out the possibility of other depositional environments resulting in similar textural characters. In general, the moderate to well sorted miliolitic limestone is negative to positively skewed. The variation in the skewness values can be explained by a general decrease in competency of the sediment carrying currents from a cross-bedded to horizontal bedded stratigraphic units. Such textural variations characterizing fluctuating depositional conditions are quite common in the coastal environments.

The bivariate and multivariate discriminatory plots of grain-size data suggest a mixed

Table I. Grain-size, sphericity and roundness data of Miliolitic Limestone of Diu.

	Mz (ϕ)	Var	SD	Sk	KG	C (ϕ)	M (ϕ)	v̄1	v̄2	Si	Rho
1	1.6197	.1964	.4432	.1299	.9784	0.7794	1.5833	1.3879	1.1486	.6701	.3840
2	1.8565	.3355	.5792	.1679	.8656	0.6650	1.7823	1.5536	1.0542	.7978	.5721
3	2.5228	.3528	.5940	.1085	.9453	1.3330	2.4891	1.8958	1.2672	.8501	.6490
4	2.5630	.3650	.6042	.0659	.8391	1.2896	2.5179	1.8583	1.1756	.8332	.5997
5	1.9766	.2937	.5420	.1996	1.0182	1.0250	1.9271	1.6659	1.2359	.6587	.6242
6	2.1758	.1580	.3975	.0525	1.0424	1.1150	2.1721	1.6281	1.3442	.7589	.5148
7	1.8646	.3243	.5695	.1454	.9551	0.7500	1.8077	1.5812	1.1329	.6668	.5021
8	1.8313	.3573	.5978	.2223	1.0026	0.7750	1.7609	1.6380	1.1615	.8696	.3790
9	2.9438	.1692	.4114	.0991	.9218	2.0006	2.9173	1.9695	1.4335	.7182	.5295
10	2.5088	.1877	.4333	.0176	1.0462	1.5313	2.5101	1.7942	1.4099	.8710	.6531
11	2.0436	.3185	.5644	-.0127	.9904	0.8850	2.0729	1.6150	1.1842	.8658	.5286
12	2.1002	.2537	.5037	.1355	1.0091	1.1650	2.0656	1.6703	1.2668	.7697	.6853
13	2.3117	.3639	.6033	.1209	.9796	1.2667	2.2824	1.8216	1.2410	.8101	.4548
14	2.2830	.1528	.3910	-.0948	.9625	1.2500	2.3059	1.5811	1.2827	.8231	.5306
15	2.4480	.1245	.3529	-.0427	.9806	1.6000	2.4674	1.6720	1.3595	.7213	.5411
16	2.1623	.3752	.6126	.1610	1.0474	1.0619	2.1140	1.8032	1.2624	.7502	.6036
17	2.9971	.3645	.6038	-.1902	1.0174	1.0619	2.1140	1.8032	1.2624	.7502	.6036
18	2.2464	.2926	.5410	.0565	1.0080	1.2350	2.2426	1.7323	1.3595	.7213	.5411
19	2.3502	.2881	.5368	.0568	.8863	1.2250	2.3312	1.7254	1.1969	.8258	.6020
20	1.7547	.2127	.4613	.1141	1.0635	0.7650	1.7329	1.4943	1.2432	.8193	.5335
21	2.6527	.3618	.6015	.2030	.9720	1.4167	2.5966	2.0141	1.3321	.7645	.4921
22	3.2954	.1598	.3998	-.1838	.9405	1.3250	2.3406	2.0260	1.4953	.7767	.6134
23	2.4191	.3113	.5580	.1846	1.0372	1.2917	2.3365	1.8919	1.3499	.6966	.5230
24	2.3122	.2117	.4601	-.1601	.9557	1.0833	2.3553	1.6023	1.2468	.7576	.5756
25	2.2266	.4029	.6348	.1161	1.0377	1.0313	2.1887	1.8289	1.2503	.6719	.4230
26	1.8641	.2427	.4927	.1517	1.1141	0.9150	1.8258	1.6033	1.3046	.6811	.3865
27	2.0944	.3614	.6012	.2736	.8986	0.9650	1.9730	1.7417	1.1449	.7021	.5129
28	2.2348	.2196	.4687	-.2060	.8458	1.2644	2.3093	1.5026	1.1247	.6312	.3606
29	2.0430	.1296	.3640	-.1183	1.0015	1.1815	2.0661	1.4591	1.2635	.7324	.6920
30	2.4638	.1620	.4025	-.0011	1.0189	1.5500	2.4683	1.7368	1.3848	.8552	.4757
Mean	2.2722	.2683	.5108	.0591	.9794	1.1705	2.2201	1.7178	1.2653	.7582	.5280
SD	0.3779	.0877	.0878	.1328	.0658	0.2947	0.3414	0.1727	0.1023	.0730	.0928
Min.	1.6197	.1245	.3529	-.2060	.8361	0.6650	1.5833	1.3879	1.0542	.6312	.3606
Max.	3.2954	.4029	.6348	.2736	1.1141	2.0006	3.0591	2.0418	1.4953	.8710	.6920

Mz - Mean Grain-Size; SD- Standard Deviation; Sk-Skewness; KG- Kurtosis; M-Median; C - One Percentile; v̄1 and v̄2 - Vectors 1 and 2; Si - Sphericity; Rho - Roundness;

coastal beach to aeolian environment of these rocks. The aeolian nature of sediment materials is evident from the grain-size parameters and textural plots (Figs.4a and b). All the sample data points fall adjacent to boundary between beach and aeolian fields on the multigroup discriminant plot (Fig.6) thus, indicating the intimate association of beach and coastal dune sediments. Further the plot of standard deviation *versus* skewness data (Fig.4c) also supports this. The well sorted nature of the samples together with the truncation of the field at 3ϕ boundary (Fig.5) is consistent with the beach deposition (Passega, 1957). The sedimentary structures such as cross-bedding of variable size and shape, minikarstic features and onshore palaeocurrent pattern with a relatively low variance further supports this view. There-fore, it is quite likely that the materials carry features characteristic of both the environments.

The sphericity, roundness and surface textures of limestone particles are controlled by their original forms and the abrasion history

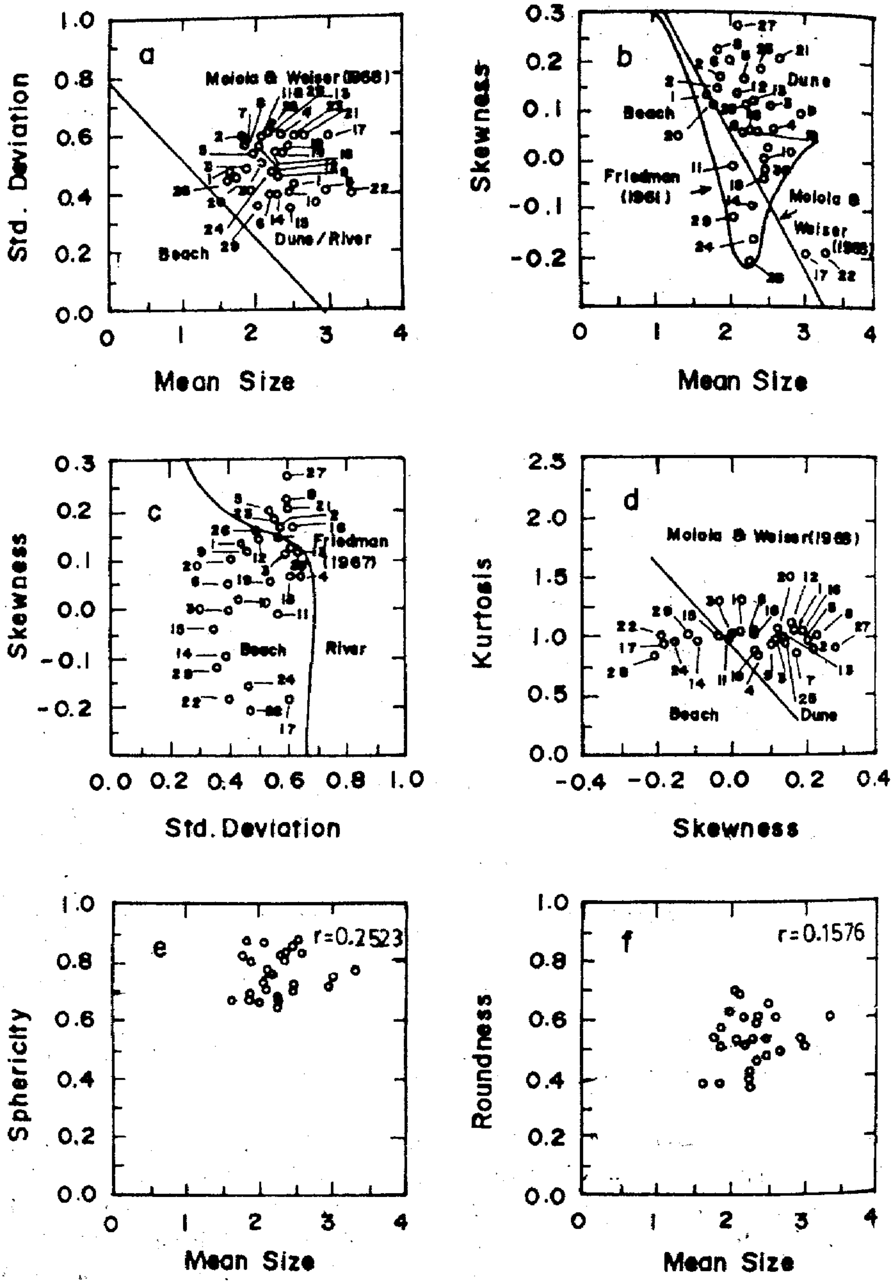

Fig.4. Relationships between grain-size parameters, sphericity and roundness.

during transportation. It is evident, from the scatter of data points on Figs.4e and f and correlation coefficient values, that with variation in grain- size the roundness varies greatly, as compared to sphericity. This indicates considerable reworking of the materials after their initial deposition. The constituent particles of the limestone are near spherical and

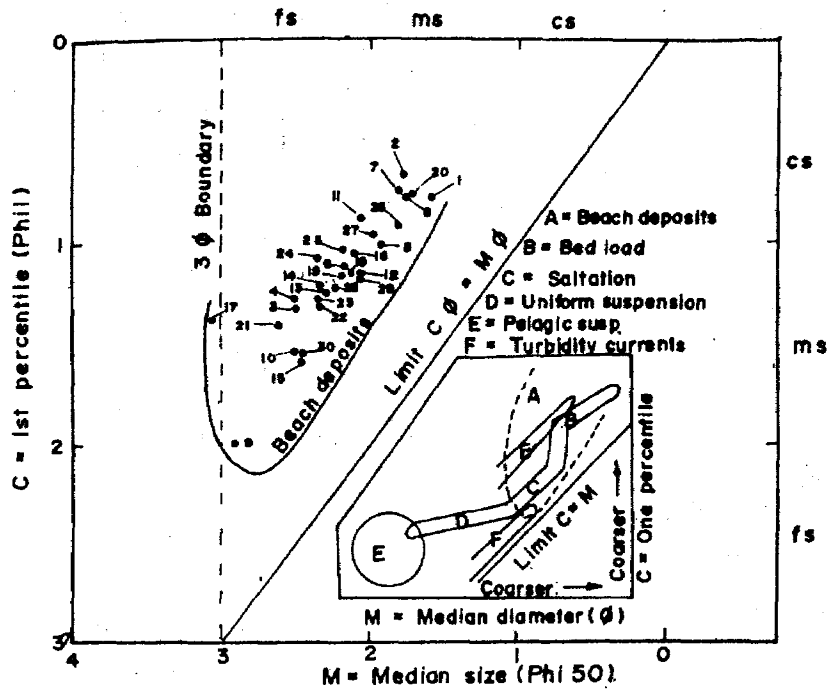

Fig.5. CM diagram of Diu miliolitic limestone samples.

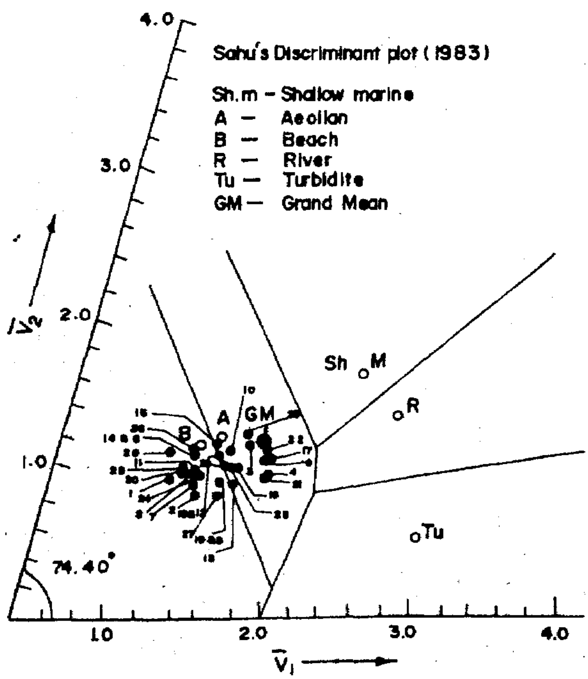

Fig.6. Multigroup discriminant Plot.

well rounded and indicate a short distance of transportation from a nearby source. Considerable reworking of these sediments by aeolian processes is further supported by the various surface textures viz., worn-out features, rounded outlines, smooth/polished surfaces and oriented etch pits shown by various rock particles.

The textural interpretations are compatible with those made independently on the basis of palaeontology and petrography. The petrographic study reveals a framework composition of the limestone (Fig. 7) consisting of carbonate

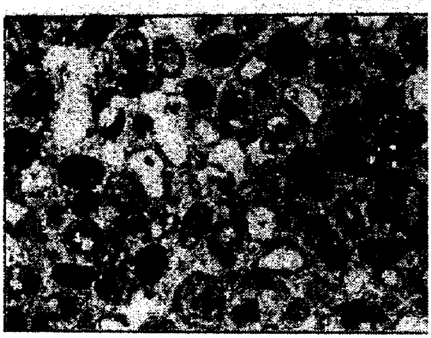

Fig.7. Photomicrograph of the biopelmicrite petrographic subtype of the miliolitic limestone of Diu showing moderate to well sorted nature of the limestone (40X, crossed nicols).

skeletal fragments of foraminifera, mollusk, echinoidea, brachiopoda, coral and algae and non-skeletal particles viz. pellets, coated grains, oolites, intraclasts, and early vadose cements. The skeletal composition, excellent preservation of pellets and some of the fossils, and the presence of broken as well intact tests of the foraminifera with varying degree of abrasion leading to micritization and peloid formation suggest that the immediate source of the limestones was beach to shallow marine environments. According to Patel (1991) and Patel and Bhatt (1995) these rocks represent reworked ancient biogenic beach sands generated during regressive phases of Middle Pleistocene high sea that lasted till Late Upper Pleistocene. The progressive regression of Middle Pleistocene high sea synchronized with glacial stage marked by dry climate exposed enormous amount of beach and littoral sands to reworking by strong southwesterly onshore winds resulting in the deposition of miliolitic limestone. Present textural study also supports an eolian origin of the miliolitic limestone. The constituent particles, originally formed in shallow-marine to beach environments, are reworked by the prevailing wind and rain waters during the Middle Pleistocene lowered sea levels and have been deposited as miliolitic limestone. The mixed marine/nearshore beach to eolian nature of the limestone reflected in variation of the textural attributes is mainly due to the fluctuating Pleistocene sea-levels.

CONCLUSIONS

Palaeocurrent pattern and textural study of the miliolitic limestone is found to be useful for interpretation of its origin and depositional environment. The limestone is fine to medium grained, well sorted, fine-skewed and leptokurtic. The variations in size parameters suggest corresponding changes in the depositing velocity of the depositional site. The various textural plots suggest a mixed beach to coastal eolian depositional environment of the miliolitic limestone. The evidences indicating the similar inferred depositional environment of these rocks include the cross-bedding features, palaeowind pattern, uniform grain-size, high degree of sorting and roundness, faunal assemblage and their highly abraded nature, polished surface of quartz grains and the presence of early vadose cements. The intimate association between beach and eolian deposits, and excellent preservation of pellets and some of the fossil constituents suggest that the immediate source of the limestones was the beach to shallow marine setup.

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