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Depositional environment of the Fort Member of the Jurassic Jaisalmer Formation (western Rajasthan, India), as revealed from lithofacies and grain-size analysis

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ABSTRACT

Lithofacies and granulometric analysis were carried out to decipher the depositional environment of the Fort Member of the Jurassic Jaisalmer Formation. Based on field data nine lithofacies have been identified including trough cross-bedded sandstones, planar cross-bedded sandstones, matrix supported conglomerates, thinly bedded siltstone and sandstones, herringbone cross-bedded sandstones, wave rippled sandstones, laminated sandstones, hummocky cross-bedded sandstones, limestones and shales. Granulometric analysis of sandstone samples has been carried out for their statistical and textural parameters. Bivariant plots of textural parameters such as graphic skewness versus graphic standard deviation and skewness versus standard deviation confirm the high energy (beach) origin of sandstones. These results suggest a wide spectrum of marine environments ranging from inner shelf to upper shoreface for the Fort Member sandstones.

KEYWORDS | **Lithofacies. Grain-size analysis. Depositional environment. Shallow marine. Fort Member. Jurassic.**

INTRODUCTION

Jaisalmer Basin representing the eastern flank of the Indus shelf is considered to be a potential hydrocarbon basin (Awasthi, 2002; Singh *et al*., 2005). The Triassic to Middle Eocene stratigraphic sequence deposited forming recurrent transgressive-regressive cycles, which are considered favorable for development of source, reservoir and cap rocks. The Jaisalmer Formation is believed to be deposited on a wide stable shelf having a very low angle depositional slope, thus, favoring development of carbonate build-up zones suitable for providing reservoir, cap and source rocks. In order to ascertain theses properties, a detailed lithofacies and granulometric study of the Fort Member sandstones of the Jaisalmer Formation was carried out. The present investigation aims to construct a depositional model for the Fort Member sandstones in the Jaisalmer Formation. The study is based on the measurement of stratigraphic sections, lithofacies and grain-size analysis. Grain-size analysis was performed to confirm the depositional environment setting concluded from the lithofacies analysis.

The genetic interpretation of grain-size characteristics of sediment has proved to be a challenging task over the years. The extended efforts to study this aspect by a large number of workers have produced voluminous literature, which includes excellent reviews of grain-size parameters and their relationship with depositional processes (Udden, 1898; Folk and Ward, 1957; Friedman, 1961, 1967; Krumbein and Graybill, 1965; Griffiths, 1967; Visher, 1969; Friedman, 1979; Bridge, 1981; McLaren and Bowles, 1985; Forrest and Clark, 1989 and others).

However, a detailed textural analysis is still lacking for the area in consideration. In the present study, various graphical and statistical measures, such as graphic mean, median, standard deviation, skewness, kurtosis etc., have been carried out in the sediments of the Fort Member of the Jurassic Jaisalmer Formation. The bivariant plots between various parameters have also been constructed to interpret the sediment characteristic and establish its relation with the depositional environment.

No detailed lithofacies and granulometric studies have been attempted so far in the Fort Member of the Jurassic Jaisalmer Formation. Lithofacies and granulometric studies are used to determine the environment of deposition, classify the siliciclastic sedimentary rocks and study the energy condition of the transporting medium and dominant mechanism of transportation. In order to interpret the sedimentary environments represented in this unit, lithofacies and granulometric studies of the sandstones, shales and limestones of the Fort Member of the Jaisalmer Formation were taken up in the present investigation.

GEOLOGICAL SETTING

The Jaisalmer Formation was first described by Oldham (1886) as "Jaisalmer Limestones" consisting of a thick sequence of cream, buff and brown colored, fossiliferous limestones along with oolitic limestones and grayish brown sandstones. Geologically, the Jaisalmer sedimentary basin is significant for its fossiliferous Jurassic sedimentary rocks (Blanford, 1877; Oldham, 1886; Das Gupta, 1975; Fursich *et al*., 1992; Kulkarni *et al*., 2008; Pandey *et al*., 2009b, 2010, 2012b), hydrocarbon reserves, other natural resources (Mukhtinath, 1967, 1969) and building stones. The thickness of the Jaisalmer Formation ranges from 170m in the southern part to 120m in the northern part. The Jaisalmer Basin occupies an area about 30,000sq km (Fig. 1). The depositional setting varies from fluvial/lagoonal, delta front, shore face to offshore environments with fluctuating water energy and salinity (Pandey *et al*., 2006a, b; Bhat and Ahmad, 2013). The Jaisalmer Basin is a pericratonic basin, now placed on the northwestern margin of the Indian peninsular shield and dipping to the northwest. During the Jurassic, the basin was situated about 23° South of the equator and constituted the southern Tethyan margin. The Jaisalmer Basin lies on the northwestern part of India, at the western border of the Rajasthan. The Jurassic depositional history of the Jaisalmer Basin begins with widespread fluvial, deltaic, and lacustrine sediments (lower part of the Lathi Formation) in the southeastern part of the basin (Srivastava, 1966; Lukose, 1972; Bonde, 2010), followed by marginal marine sediments (Lathi Formation), and a succession of several non-marine, marginal-marine, and fully marine sediments which are grouped into the Jaisalmer, Baisakhi and Bhadasar formations (Das Gupta, 1975; Pareek, 1984; Mahendra and Banerji, 1989; Fursich *et al*., 1992; Pandey *et al*., 2005, 2006a, b, 2009b, 2010). The outcrops of younger Jurassic formations are confined to the raised Mari-Jaisalmer arch (Oldham, 1886; Swaminathan *et al*., 1959).

The Jaisalmer Formation is represented by alternating siltstones/sandstones and limestones and bioturbated and cross-bedded sandstones. Local erosional surfaces, lateral changes in lithology and repetitions of sedimentary facies are common features limiting the potential of intra basinal stratigraphic correlations. The sandstones of the Lathi and Jaisalmer formations come from the hinterland in the North and northeast, from where the sediments were transported by the fluvial system draining the western Rajasthan shelf, and deposited in a shallow marine setting in the Jaisalmer Basin. According to Kachhara and Jodhawat (1981) and Pandey *et al*. (2012b), the Jaisalmer Formation comprises six members: Hamira, Joyan, Fort, Badabag, Kuldhar and Jajiya in ascending order of superposition (Table 1).

The Fort Member (Narayanan *et al*., 1961) consists of fine- to medium-grained sandstones, oolitic, sandy, bioturbated and fossiliferous limestones, and cross bedded sandy limestones (Mahendra and Banerji, 1990; Pandey and Dave, 1998; Pandey *et al*., 2006a). It is best exposed in the Jaisalmer Fort escarpment and comprises grayish white, medium to fine-grained sandstones at the base. These sandstones are calcareous and bear current bedding in the upper part. The sandstones are followed by several beds of yellowish brown, compact and fossiliferous limestones that possess thin interbeds of argillaceous limestone which contain brachiopods and mollusca shell fragments. The limestones at the top of the member are yellow, sandy and locally oolitic and fossiliferous. The limestones record a shallowing of the basin from below to above the fair-weather wave-base, with increasing water energy, occasionally affected by storms and also with a higher rate of influx of sediment. The sandstone samples were collected from the basal part of the exposed scarp, where lithosections were measured. Based on the inter-basinal correlation of marker-beds (Pandey *et al*., 2009a) and the stratigraphic position of the Fort Member, which is above the late Bajocian coral bearing horizon of the Joyan Member and below the late Bathonian ammonite-bearing Badabag Member, the age of the Fort Member can be safely stipulated as early Bathonian to middle Bathonian/ late Bathonian.

MATERIAL AND METHODS

During the field work two well exposed sections of the Fort Member were studied (Fig. 2). Based on field

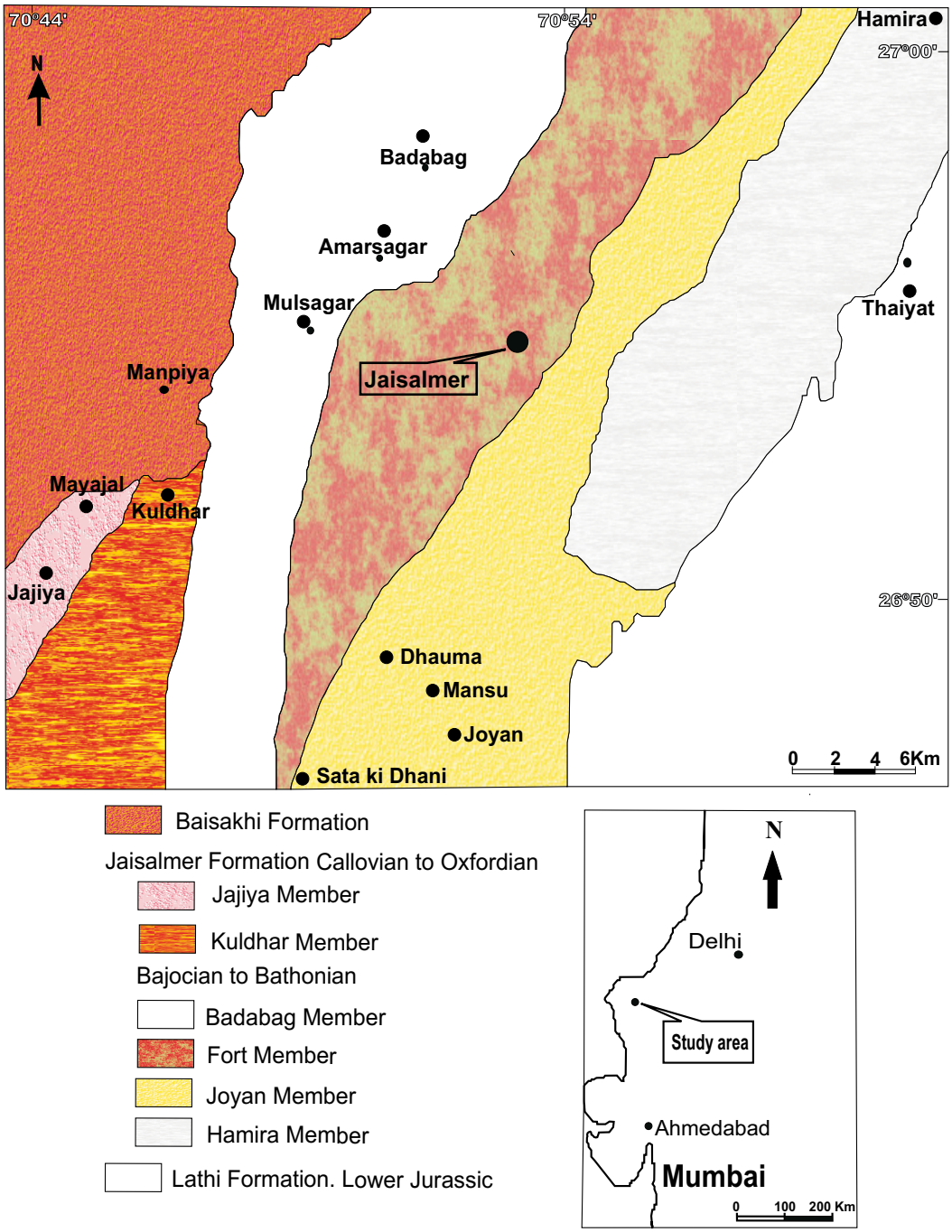

FIGURE 1. Geological map of western Rajasthan showing the study area (modified after Jodhawat and Kachhara, 2000).

parameters such as grain-size, sedimentary structures, geometry of litho-units and palaeocurrent pattern nine lithofacies were identified. For detailed grain-size analysis, the Fort Member sections are litho-logged and were systematically sampled from lower to upper stratigraphic levels, especially when sampling sandstone horizons. 25 representative samples were collected. The statistical parameters of grain-size distribution were derived from the cumulative frequency curve plots. Cumulative frequency curves of grain-size data were plotted on log probability paper. The grain diameter in phi units represented by Φ5, Φ16, Φ25, Φ50, Φ75, Φ84 and Φ95 percentiles were read from the size frequency curves. In this study, roundness scale by Powers (1953) has been employed, which has six class scales being class limits closely approximates a $\sqrt{2}$ geometrical scale. The most commonly used method for determining the sphericity is through visual comparison. In the present study, the comparison chart for sphericity

TABLE 1. Lithostratigraphy of Jurassic sediments, Jaisalmer Basin, western India (after Kachhara and Jodhawat, 1981)

Formation	Member	Age
Jaisalmer	Jajiya	Callovian to Oxfordian
	Kuldhar	
	Badabag	Bajocian to Bathonian
	Fort	
	Joyan	
	Hamira	
Lathi	Thaiat	Lower Jurassic

given by Krumbein and Sloss (1963) was used for the classification of the sandstones.

LITHOFACIES

A total of nine lithofacies have been recognized in the study area.

Lithofacies 1: Trough cross-bedded sandstones facies (St)

The facies is up to 1.5m thick, with an erosional base and medium to coarse-grained trough cross-bedded sandstones bearing a bipolar palaeocurrent direction. These cross-bedded sandstone facies occur at two stratigraphic levels in the measured section (Fig. 3A). Sediment dispersal pattern inferred from the study of trough cross bedding indicates southwestwards palaeocurrent direction along shore currents. The sequence is interpreted to represent a storm deposit on an open shelf. The large and rip up clasts and parallel lamination are characteristic of storm deposits. Dip angles of cross bedding foresets generally range from 5º to 23º. They rarely range up to 32º, and have an average of 14º. Large scale trough cross-bedding is abundant.

Lithofacies 2: Planar cross-bedded sandstones facies (Sp)

This facies occurs at four stratigraphic levels (Fig. 3B). The sandstones (subarkose) are medium to coarse-grained and moderately well sorted. The sandstones can be both thick and thin bedded. The planar cross-bedding locally transitions laterally into a parallel lamination. The foresets show a bimodal-bipolar palaeocurrent pattern. The thickness of the cross bedding range from 4cm to 20cm and average 7cm. Planar cross bedding is abundant. The sediment dispersal pattern obtained from planar cross bedding azimuths suggests mainly an ENE palaeocurrent. Large-scale planar cross-bedded sandstones can be interpreted as a deposit of inter-tidal flood ramps, the lateral accretion of tidal channel bars. The presence of small-scale cross-bedded sandstones in assemblage with laminated sandstones suggests a mixed tidal flat depositional environment.

Lithofacies 3: Matrix supported conglomerates facies (G)

This facies is confined to the upper and middle parts of Fort Member sandstones (two stratigraphic levels). It is composed of 1.5m thick beds with quartzite clasts and quartz veins of a maximum clast size of 1cm to 4cm, and it also consists of shale pebbles (Fig. 3C). The clasts are imbricated, rounded to sub-rounded and moderately spherical in shape. The matrix is mainly composed of coarse sand and granules of vein quartz at the base and fine to medium-grained sand at the upper part of the lithosection. Shale pebbles are olive, yellow, purple and buff colored. Their shape and size are variable. They are irregular to oval and rounded, and range in size from less than a millimeter to 4cm.

Lithofacies 4: Interbedded shales sandstones/siltstones facies (Fi-S)

This facies consists of fine- grained sandstones (quartzarenite to subarkose) interbedded with thinly bedded reddish white shales of variable thickness (1-2m thick).The sandstones unit of the facies exhibit plane to wavy lamination and small cross-bedding. Herringbone cross-lamina sets occur in the upper part of the facies (Fig. 3D). This facies shows gradational contact with the intervening shales beds. This facies occur at two stratigraphic levels.

Lithofacies 5: Herring-bone cross-bedded sandstones facies (S-hb)

This facies occurs at two stratigraphic levels. Herring-bone cross-beds have developed in a 2.5cm thick sandstones bed. The sandstone is medium to coarse-grained, thick-and-thin bedded, and occasionally laminated. These sandstones show sharp boundary contact with the overlying fine grained beds and have an erosional base. Herring-bone cross beds are associated with tabular cross-bedding and laminations.

Lithofacies 6: Wave rippled sandstones facies (Sr)

This facies is composed of fine to coarse-grained sandstones and is found within Fort Member. It occurs at four stratigraphic levels. Bed contacts are sharp and wavy. The increase in the size of the quartz grain indicates shallowing towards top of the unit. Occasional occurrence of interference ripples is observed. Asymmetrical ripples

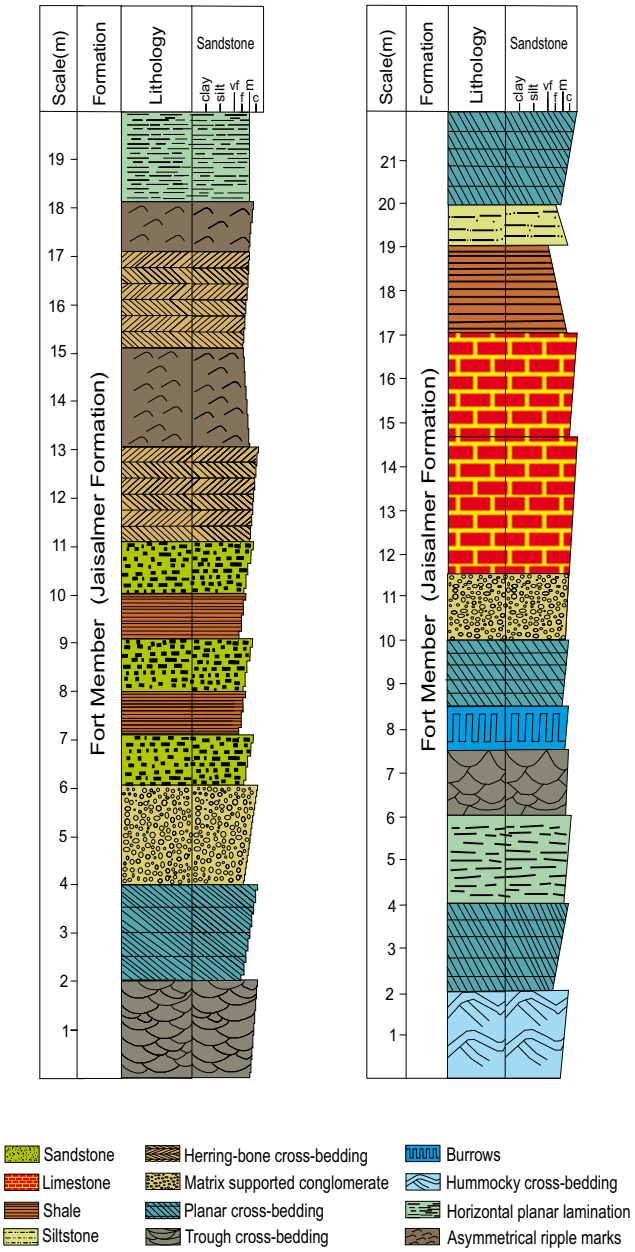

FIGURE 2. Lithostratigraphic columns showing lithofacies of the Fort Member succession of the Jaisalmer Basin.

marks have slightly undulating straight crests. Ripple wave length ranges from 6cm to 12cm (Fig. 3E-F). Asymmetrical ripple marks superimposed at 180° on foresets of cross bedding indicate reversal in current direction. The sandstone bed on the top shows numerous cavities which are mostly parallel to the bedding and up to 12cm in length. These cavities represent removed intraclasts. Ripple bedded sandstones facies represents shallow water sand deposits in tidal depositional settings. Flat and rounded tops of the ripple bed form reflect planning off during tidal reversal. Undulation in ripple-crests implies a transition from low energy to high energy conditions.

Lithofacies 7: Laminated sandstones Facies (Sl)

This facies is composed of very thinly laminated, whitish-brown, 2m-thick sandstone beds occurring at two stratigraphic levels. Mud cracks occur locally (Fig. 3G). Beds are tabular and some have rippled tops. They are mostly evenly laminated. Some beds have combination of horizontal lamination and low-angle cross-beds (Fig. 3H). Their contacts are sharp. Mud drapes occur within this unit.

Lithofacies 8: Hummocky cross-bedded sandstones facies (S-hcs)

This facies consists of 2m thick beds of sandstones, which are light brown and fine to medium-grained. The upper part of the sandstones unit shows hummocky cross-bedding. The hummocky cross-beds are, however, poorly developed and may be delineated only on close examination. They are either aggradational or originated from laminae drapping shallow and very low angle truncations. Laminae are parallel and conform to the underlying surfaces and show downlap and onlap relationship with underlying surface at very low angle. The hummocks are commonly built up sets of tabular laminae without erosion.

Lithofacies 9: Limestones facies

The overlying 8.5m comprise a limestones-shales sequence. This facies occurs at two stratigraphic levels. The limestones consist of nodular-bedded and bioturbated terrigenous pelletal, peloidal and bioclastic wackstone-packstones. The interbedded shales-siltstones are also bioturbated and show irregular bedding. The top of the sequence consists of cross bedded terrigenous peloidal and bioclastic packstone-grainstones with some ooids. Wackstone-packstones and interbedded shales were deposited in a deeper offshore part of an open shelf marine environment. Limestones facies is characterized by greenish grey and brown, coarse- to medium-grained, thick to thin bedded, soft and friable to compact fossiliferous beds with straight to irregular bounding surfaces. Sub-facies reported within this facies include a bioclastic facies and an ooid bearing calcareous sandstones facies. Burrowing is common and has resulted in irregular bedding and micritic or sparitic limestones facies. Texturally, the rocks are mature, containing rounded to subrounded silt to medium sand-size quartz grains. Limestones present echinoderms, brachiopods, thin-valved pelecypodes and gastropods. Yellow and gray colored calcareous siltstones and fine sandstones are soft, friable, and show irregular bedding.

FACIES INTERPRETATION

The basal part of Fort Member sandstones form a coarsening upward sequence consisting of laminated to

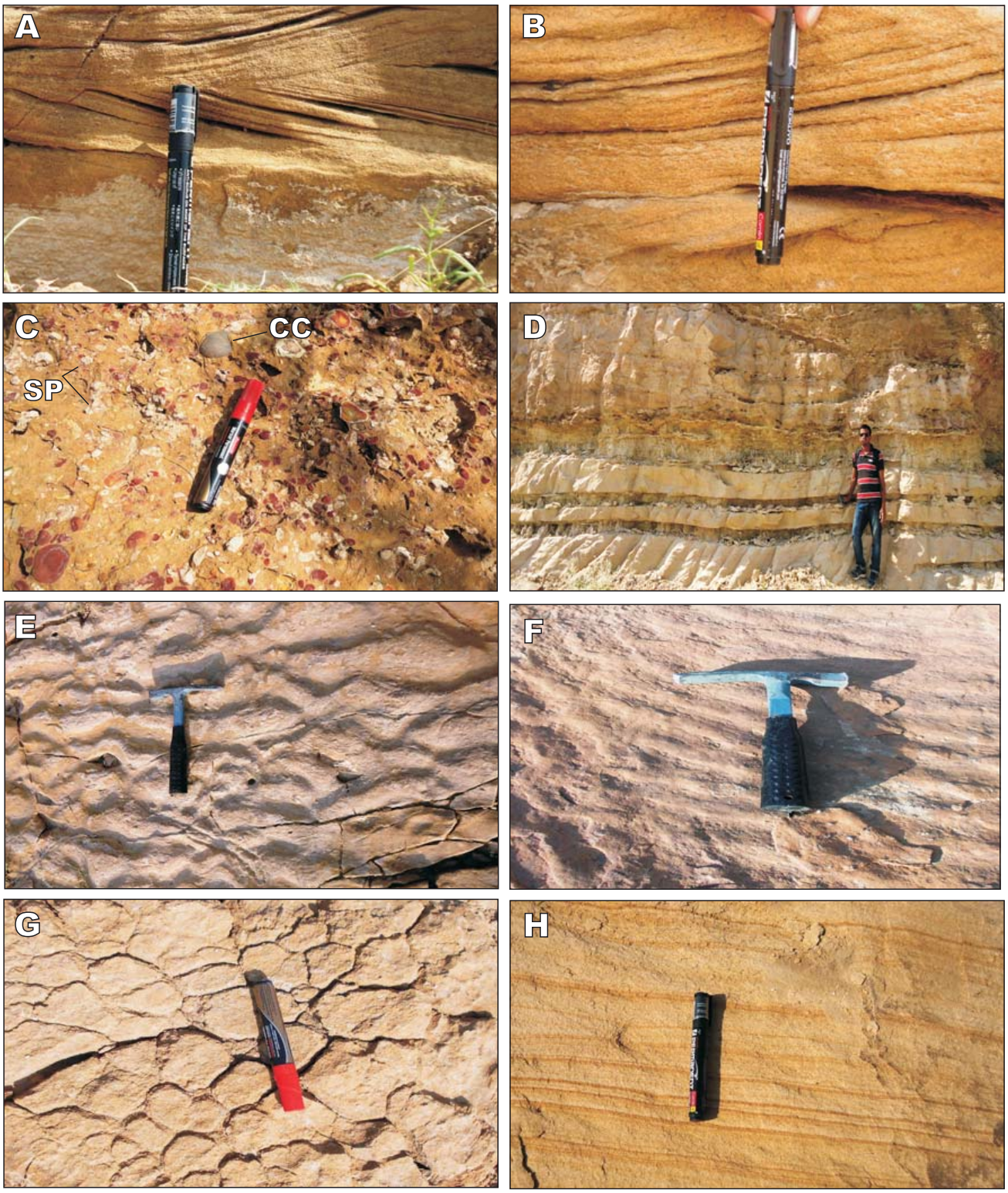

FIGURE 3. Field photographs showing A) cross-bedding in 1.5m thick medium to coarse-grained sandstones, B) moderately well sorted, medium to coarse-grained planar cross-bedded sandstones with an average bedding thickness of 7cm, C) matrix supported rounded to sub-rounded (moderately spherical) conglomerate clasts (CC) of 1-4cm, where the matrix is mainly composed of coarse sand and granules of quartz veins at the base, and fine to medium-grained sand at the upper part of the section, this matrix supported bed also has shale pebbles (SP) that are irregular to oval to rounded in shape, from 1mm-40mm in size, D) interbedded shales within the thinly bedded fine- grained sandstones, interbedded reddish white shales are of variable thickness, E) asymmetrical ripple marks with ripple wavelength range from 6cm to 12cm, F) symmetrical ripple mark, G) tabular and rippled top mud cracks, H) horizontal lamination in 2m thick whitish-brown sandstone beds.

thin-bedded, bioturbated fine sandstones characterized by wavy and undulating bedding which resembles hummocky cross-bedding (Harms *et al.*, 1975). Interbeds of shales-siltstones are common in the lower part. In the upper part, cross-bedding appears first as few meters thick single tabular sets and then as wedge-shaped cosets near the top. In the lower part, thinly laminated fine sandstones and interbedded siltstones-shales are interpreted to be lower shoreface sediments deposited mainly from suspension during storms resulting in horizontal laminations. The alternating irregular and disturbed beds represent biogenic reworking during fair weather periods (Howard, 1971; Howard and Reineck, 1972; Kumar and Sanders, 1976). Hummocky cross-bedding has been attributed to the action of strong-wave surges and is considered diagnostic of inner-shelf storm deposits (Harms *et al.*, 1975).

The overlying planar cross-bedded sandstones are characterized by the presence of single sets and highly variable set thicknesses. Single sets of cross-bedding alternating with thinly laminated and bioturbated sandstones suggest temporal variation in wave regime between fair weather and storm conditions. Cosets of cross-bedding towards the top suggest frequent water agitation and sand transport as a result of shoaling. Shoaling upward sequence suggest a change from shallow marine wave processes to beach processes involving swash and backwash. The sediment dispersal pattern of the sequence resembles the modern near shore pattern comprising offshore and longshore sediment transport. The overlying calcareous shales are interbedded with nodular and wavy bedded microbioclastic pelletal packstone and pelletal wackestone which have been interpreted elsewhere as to represent deposition below wave base on an open shelf with normal marine circulation. The associated shales represent an offshore environment dominated by mud deposition. The interbedded fine grained sandstones and shales facies indicate deposition in lower shoreface transition zone of the inter-tidal environment. Alternation of sandstones and shales with abundant small scale wave and current formed structures suggested their deposition in low energy intertidal environment (*e.g.* Van Stratten, 1954; Evans, 1965; Corcoran *et al.*, 1998). The intertidal environment is characterized by phase of high energy represented by cross-bedded sandstones and low energy condition represented by shales. The inter-bedding of shales reflects a transition from a wave- agitated shoreface setting to below wave base depositional setting. The presence of lamination and wave generated structures in the shale facies suggested deposition in a quite water environment below wave base (*e.g.* Mukhopadhyay and Choudhuri, 2003; Banerjee *et al.*, 2006). The calcareous shales with interbedded bioclastic and peloidal wackestones and packstones indicate the below wave-base zone of shallow marine shelf environment. Large-scale planar and trough cross-bedding are common. Other sedimentary structures include ripple marks of asymmetrical, interference and ladder type's intraclasts, animal tracks and trails. Asymmetrical ripple marks superimposed at 180º on foresets of cross-bedding indicate reversal in current direction.

The presence of herring-bone cross-beds reflects the bed load deposition by reversal of tidal currents of equal bed shear intensity and bottom current velocities. Flow direction reversals are associated with both rising flood and falling ebb stage of tidal cycle and these reversals are generally bi-polar (Reading, 1986). Reineck and Singh (1980) attributed these sedimentary structures to near shore barrier-associated tidal environments. Moore (1979) attributed these facies to inter-tidal and shallow sub-tidal environment. Reading (1986) attributed herring-bone type cross-bedding in sandstones as a diagnostic feature of tidal currents.

TEXTURAL ATTRIBUTES

The studied sandstones are medium to coarse-grained, moderately sorted to well sorted, near symmetrical and mesokurtic to platykurtic. The quartz grains are subangular to subrounded and show medium to high sphericity (Tables 2, 3, 4). Their mean size was plotted against their sorting. The 0.03 correlation coefficient indicates that the mean size of the grains decreases with the increase in sorting. Mean size versus skewness plot with a correlation coefficient of -0.3 show moderate inverse relationship between the two parameters. Mean size versus roundness plot show an inverse relationship with their correlation coefficient value

TABLE 2. Statistical parameters of grain-size distribution of the Fort Member sandstones of Jaisalmer Formation, western Rajasthan

	Mz	Verbal Limit	σ_1	Verbal Limit	K_G	Verbal Limit	SK_I	Verbal Limit	Median
Range	1-2.7		0.42-1.1		0.68-1.67		-0.51-0.86		0.45-0.92
Average	1.8	Medium	0.6	Moderately well sorted	1.1	Meso kurtosis	0.1	Coarse skewness	0.64

TABLE 3. Range and average of sphericity of detrital grains of Fort Member sandstones of Jaisalmer Formation, western Rajasthan

	Low sphericity (< 0.3)		Medium sphericity (0.6)		High sphericity (< 0.9)		Total grains	Mean sphericity
	N	%	N	%	N	%		
Range	56.0-125.0	14.9-33.0	163.0-337.0	62.0-81.1	6.0-35.0	1.4-9.0	258.0-445.0	0.7-0.8
Average	92.72	25.01	260.61	69.93	19.34	5.15	371.47	0.72

of -0.41 that suggest that decrease in size is accompanied by decrease in roundness of quartz grains. Roundness versus sorting has correlation coefficient value of 0.52 which suggest that sorting of grains decrease as their roundness decrease. Sphericity is plotted against sorting and the correlation coefficient value for the plot -0.160 shows a weak relationship between sorting and sphericity. Sorting of the grains decreases as their sphericity decreases (Fig. 4A-F).

STATISTICAL PARAMETERS AND BIVARIANT PLOTS

The representative twenty five samples of the Fort Member sandstones were plotted on bivariant diagrams based on five different combinations of grain-size statistical parameters. Mean size plotted against standard deviation (sorting) is generally considered to be an effective discriminator between recent river, dune and beach sands by Friedman (1961), Moiola and Weiser (1968). The plot in Figure 5 indicates that most sandstone samples come from a coastal environment (Friedman's diagram, Moiola and Weiser's plot).

Skewness versus mean size has been used to differentiate between river, wave and slack water processes (Stewart, 1958), between beach and dune sands (Friedman, 1961, 1967; Moiola and Weiser, 1968) and between inland and coastal dune sands (Moiola and Weiser, 1968). Since median and mean size of the all the sandstones are very similar, Stewart's discriminating boundaries based on median and skewness may be safely used. Accordingly, most samples cluster in the zone of river and wave processes (Fig. 6).

Mason and Folk (1958) and Moiola and Weiser (1968) have proposed a plot of kurtosis versus skewness to distinguish among beach, dune and aeolian flat sands and between inland dune and beach sands. In the present case, such plots yield inconclusive results because most samples lie within the beach and dune fields discriminated by Mason and Folk (1958). However, according to Moiola and Weiser's diagram sandstones plot mostly in coastal environments and a minor contribution from the inland dune environments (Fig. 7).

Friedman (1961) proposed that dune, beach and river sands could be differentiated by movement parameters which he interpreted to reflect differences in the mode and energy of sediment transport. He concluded that the movement parameters are more sensitive to differences in grain-size distributions than the ones corresponding to graphical parameters. However, plots of graphical parameters, median versus standard deviation (σ_1) (Fig. 8) and standard deviation (σ_1) versus skewness (SK_1) (Fig. 9) are confined to the field of beach and river sands. Beach sands are more prominent according to the plots of Friedman and Moiola and Weiser (Fig. 5). However, when the data are plotted in the diagram of Friedman and Sanders (1978) most of the samples cluster in the river sand zone (Fig. 9).

TABLE 4. Range and average of roundness of detrital grains of the Fort Member sandstones of Jaisalmer Formation, western Rajasthan

	Very Angular (0.12-0.17)		Angular (0.17-0.25)		Subangular (0.25-0.35)		Subrounded (0.35-0.49)		Rounded (0.49-0.70)		Well rounded (0.70-1.0)		Total grains	Mean roundness
	N	%	N	%	N	%	N	%	N	%	N	%		
Range	12.0-80.0	5.8-41.0	10.0-67.0	8.9-34.3	14.0-77.0	10.6-24.2	4.0-120.0	6.7-39.6	7.0-75.0	4.9-30.2	7.0-35.0	3.6-20.4	60.0-321.0	0.3-0.5
Average	39.2	17.1	39.2	17.3	44.5	18.3	50.2	19.8	46.3	19.6	21.6	9.4	234.7	0.5

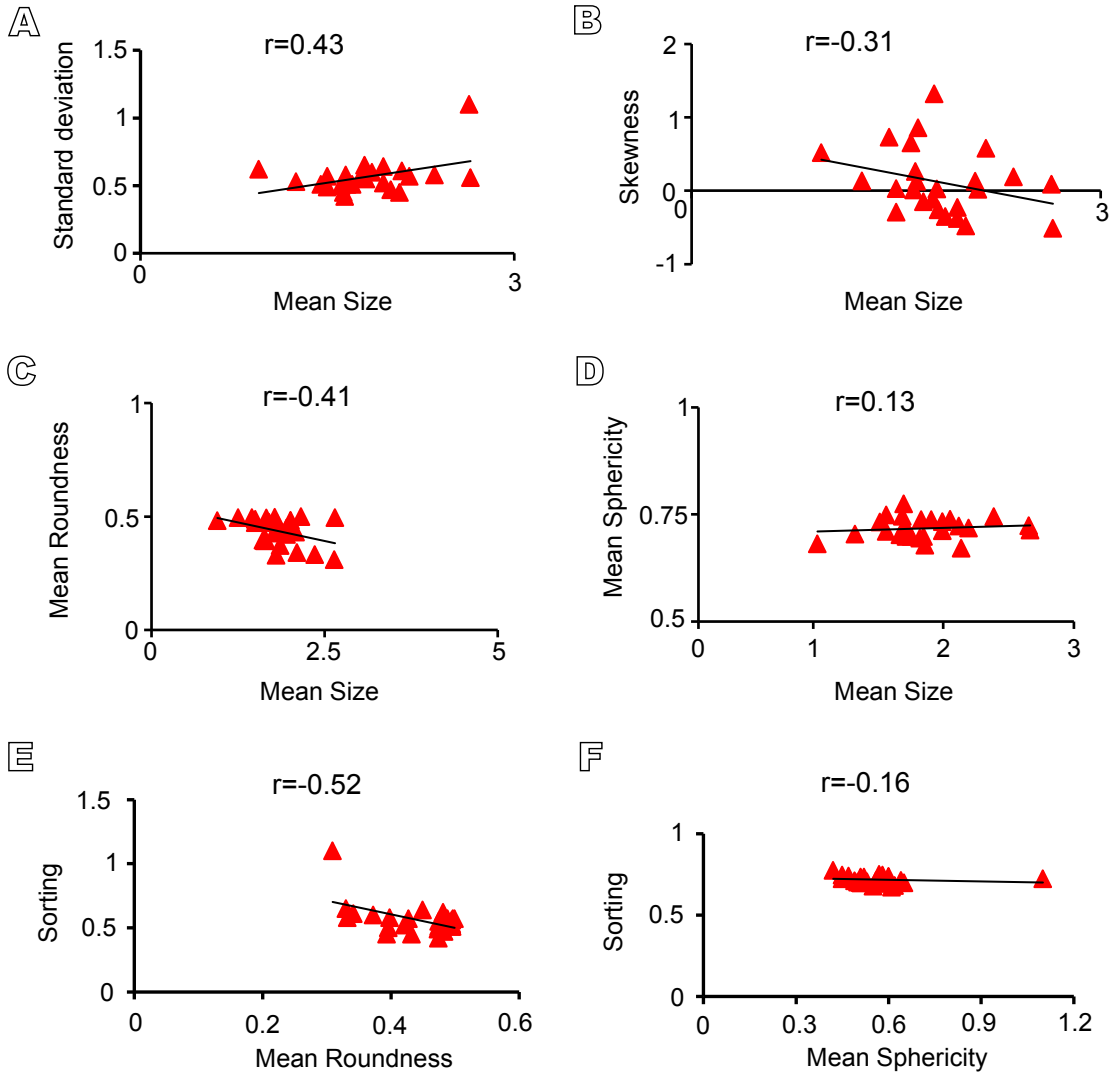

FIGURE 4. Bivariant plot of the Fort Member sandstones A) mean size versus standard deviation, B) mean size versus skewness, C) mean size versus mean roundness, D) mean size versus mean sphericity, E) mean roundness versus sorting and F) mean sphericity versus sorting.

DISCUSSION

The Fort Member of Jaisalmer Formation undergoes three cycles, each comprising three lithological units: sandstones, shales and limestones from bottom to top (Fig. 10). The base of each cycle comprises a sandstones unit deposited during an abundant supply of terrigenous sediment. Basal sandstones units are interpreted as deposits of shallow marine environments, mainly shoreface and their basin-ward transition to inner shelf. Sandstones units have been compared with depositional models of shallow marine sands, both modern and ancient, reviewed by Heckle (1972), Johnson (1978), Walker (1979) and Harms *et al.* (1982). Sandstones units generally consist of coarsening-upward sequences which can be divided in three facies: a lower parallel laminated and burrowed sandstones-siltstones/shales facies of inner shelf; a middle hummocky or wavy-bedded sandstones of lower shoreface and a cross-bedded sandstones of upper shoreface. The facies sequence reflects progradation into a sub-littoral environment, while emergence features are lacking. A storm-dominated shallow marine depositional model is interpreted for the basal sandstones units based on sedimentary structures, biogenic activity, sediment dispersal patterns and grain-size characteristics. All these features in the studied sandstones suggest alternation of low-energy and high-energy conditions, which reflect the fair weather and storm periods.

Shale pebbles are common features in the sandstones units. Mud drapes are generally attributed to tidal activity and believed to form by fall out of fine-grained suspended sediment during the slack water period of the tidal cycle (Reineck and Wunderlich, 1968; Klein, 1970). Others

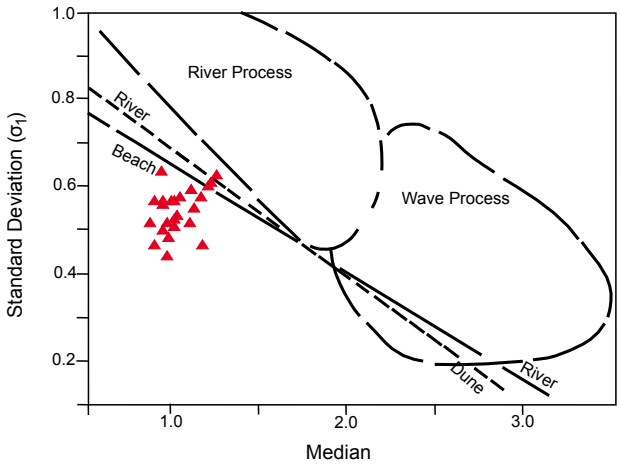

FIGURE 5. Bivariant plot of inclusive graphic standard deviation versus mean diameter, after Stewart (1958) and Moiola and Weiser (1968).

(McCave, 1970) claim that the duration of slack water period in each tidal cycle is too short to deposit even a 2mm thick lamina, and therefore mud drapes do not indicate tidal activity. Calculations based on suspended sediment concentrations and settling velocities led McCave (1970) to suggest that mud drapes are due to a combination of abnormally high suspended sediment concentration, low current velocities and low water intensity over a longer period. These conditions are fulfilled following a storm when suspended sediment concentrations are high combined with a decrease in wave and current activity.

The lower facies of the coarsening-upward sequences is characterized by alternating horizons of parallel laminated and bioturbated sandstones. This facies resembles modern shoreface sediments and shows a repeated alternation of physical and biogenic processes related to storm and fair weather periods (Howard, 1971; Howard and Reineck, 1972; Kumar and Sanders, 1976). The hummocky cross-bedding has received a great deal of attention in recent years and is considered to be diagnostic of shallow-marine sedimentation (Swift *et al.*, 1983). The hummocks and troughs were interpreted as forms produced by the oscillatory motion of storm waves affecting the bottom (Harms *et al.*, 1975; Hamblin and Walker, 1979). The hummocky beds are now considered good indicators of deposition below fair-weather wave base but above storm wave base. The sediment dispersal pattern of the studied sandstones indicates sediment transport mostly alongshore and offshore. The onshore sediment dispersal is negligible. This pattern fits very well with the wave-induced nearshore current system observed in modern seas (Shepard and Inman, 1950; Komar, 1976; Komar and Inman, 1970). In a typical set up, waves approaching the shoreline drive surface water landward. The shelf water column piled up against the coast responds by flowing alongshore. As set up increases and the flow intensifies the frictional drag of the bottom results in downwelling and seaward directed bottom currents. On the Atlantic shelf shoreface, storms generate a down welling situation in which unidirectional bottom currents flow slightly obliquely offshore or parallel to the shore (Johnson, 1978; Swift *et al.*, 1983).

The limestone unit is comparatively thin in the first and second cycles. In the first cycle, the limestones unit (3m thick) consists of dolomitized peloidal packstones interpreted as tidal flat deposits. The limestones unit of the second cycle (5m thick) is a shoaling upward sequence. The lower part of the sequence comprises bioturbated and nodular bedded wackestones-packstones interpreted as deposits of normal marine open shelf environment. The upper part of the sequence consists of dolomitized terrigenous pelmicrite and associated lenticular cross-bedded bioclastic grainstones interpreted as tidal flat and tidal channel deposits.

In the third cycle, the limestones unit has a very marked shoaling upward character. The lower part of sequence comprises bioturbated and nodular bedded wackestones-packstones and rare grainstones. The wackestones-packstones represent normal marine open-shelf deposits of deeper water and below the wave base. The interbedded grainstones represent storm deposits. They show SW longshore dispersal. The wackestones-packstones are overlain by cross-bedded, terrigenous, pelletoidal and coated bioclastic grainstones. They mainly present an onshore sediment dispersal pattern. The grainstones were deposited in shallow agitated water above wave base. Thin conglomerate horizons in grainstones indicate very shallow

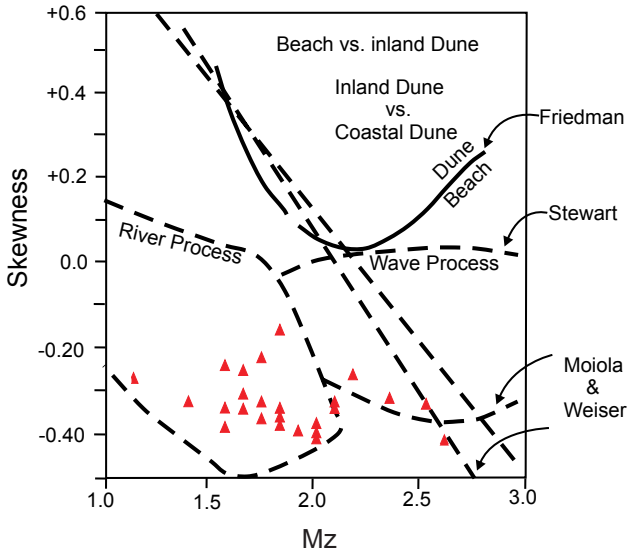

FIGURE 6. Bivariant plot of skewness versus mean size, after Stewart (1958), Friedman (1961) and Moiola and Weiser (1968). Triangles correspond to Fort Member sandstone.

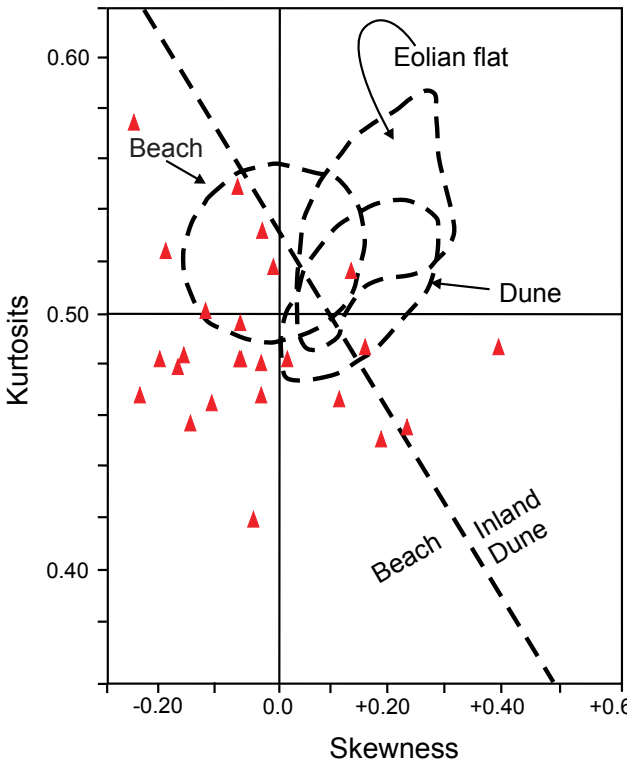

FIGURE 7. Bivariant plot of kurtosis vs. skewness, after Mason and Folk (1958) and Moiola and Weiser (1968). Triangles correspond to Fort Member sandstone.

water conditions with a periodic emergence. Gradual transgression and an increase in the depth, followed by the deposition of the Fort Member along with deep open marine conditions were established.

The mean size distribution pattern indicates fluctuations in the depositional environment with medium-grained sands deposited in high energy environment. The poor to moderately well sorted grain is indicative of deposition of sand during the little sorting in the fluvial regime. The positive skewness character of the sands indicates deposition in low to moderate energy condition. Most of the kurtosis values are mesokurtic indicating that central portion of the distribution was better sorted than extreme values represented in the curves. Large populations of subangular, angular and subrounded grains indicate short transportation of sediments. However, these features may remain even after long distance of transport (Pettijohn, 1975). The overall texture of the sandstones can be considered as sub-mature. Bivarient plots of various parameters indicate that mean size versus sorting has positive relationship between size and sorting which indicate decrease in grain-size with increased sorting which reflects fluctuating hydrodynamic condition during deposition. Mean size versus skewness has poor inverse relationship and the samples are strongly fine skewed to strong coarse skewed in narrow range of mean size indicating fluctuation in energy condition of depositional medium. Mean size versus roundness has moderate inverse relationship indicating increase in roundness with decreasing grain-size. Mean size versus sphericity has poor relationship, hinting a decrease in sphericity with a increase in grain-size. Roundness versus sorting has moderate inverse relationship giving indication of an increase in roundness with a decrease in sorting. Sphericity versus sorting has poor negative relationship giving a hint of an increase in sphericity.

The scatter plot of Moiola and Weiser (Fig. 5) reveals that the sediment samples fall within the beach field. It may be concluded that these sediments probably must have deposited in a mixed environment where marine processes have dominance over fluvial processes. However, the scatter plot of Friedman (Fig. 6) indicates a fluvial environment of deposition as all the scatter plots were concentrated in the river field. Bivariant scatter plot proposed by Moiola and Weiser (Fig. 6) between the two size parameters, graphic mean size and inclusive graphic skewness show that all the samples fall within the river field. The scatter plot of Friedman (Fig. 9) also suggests

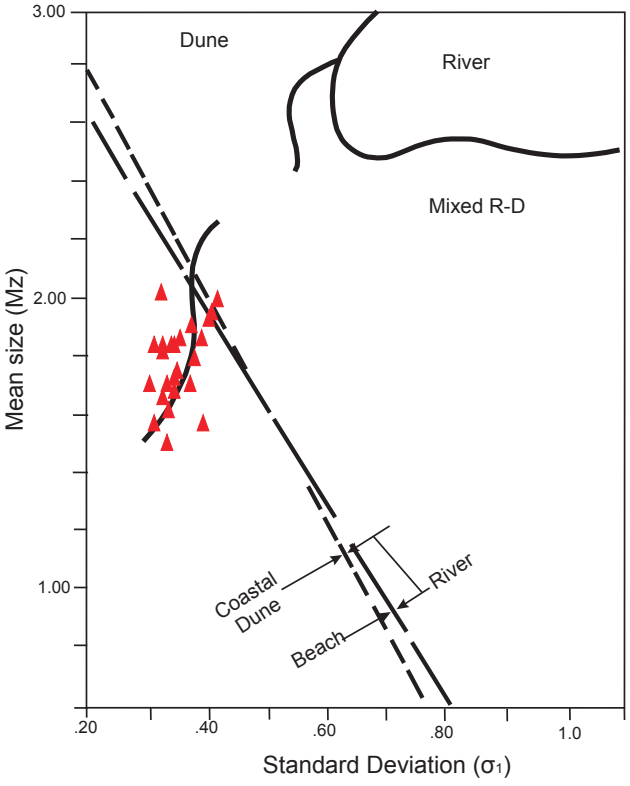

FIGURE 8. Bivariant plot of mean size versus inclusive graphic standard deviation, after Friedman (1961) and Moiola and Weiser (1968). Triangles correspond to Fort Member sandstone.

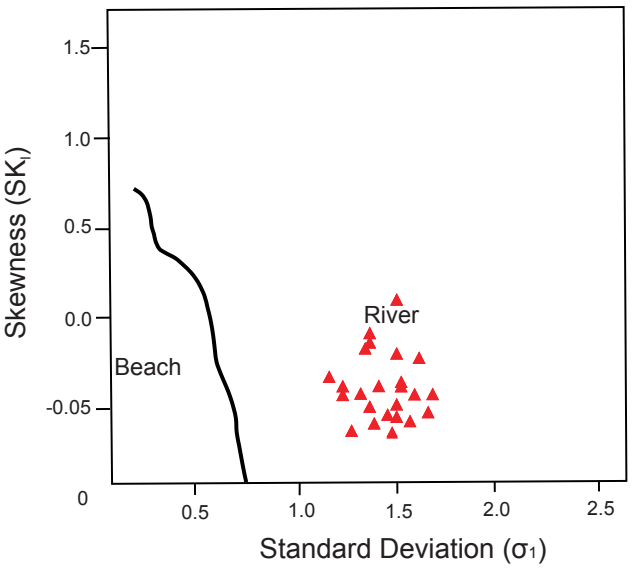

FIGURE 9. Bivariant plot of skewness versus inclusive graphic standard deviation, after Friedman (1967). Triangles correspond to Fort Member sandstone.

a fluvial environment since the entire sample falls within the river field.

From the scatter plot proposed by Friedman (Fig. 7) between the size parameters of inclusive graphic skewness and graphic kurtosis, a fluvial environment with a minor beach influence is suggested. The scatter plot of Moiola and Weiser (Fig. 5) also suggest a fluviatile environment of deposition as almost all the samples fall in the river field except for four samples.

CONCLUSIONS

Three sedimentation cycles were recognized in the Fort Member Sandstone of the Jaisalmer Formation. Each cycle begins with deposition of terrigenous facies in a storm-dominated shallow marine environment.

The Fort Member sandstone is medium to coarse-grained, moderately well sorted, strongly fine skewed followed by a fine skewed with a platy- to leptokurtic grain-size distribution. The mean sphericity values of the individual samples range from 0.7 to 0.8. The roundness values vary from 0.3 to 0.5, suggesting sub-angular to sub-rounded nature of the grains.

In the light of the information obtained from the graphical, statistical parameters and bivariant plots, in combination with sedimentary structures and sediment dispersal patterns, it can be concluded that the Fort Member sandstones were deposited in a range of nearshore environments, from inner shelf to upper shoreface, where marine processes dominated over the fluvial processes.

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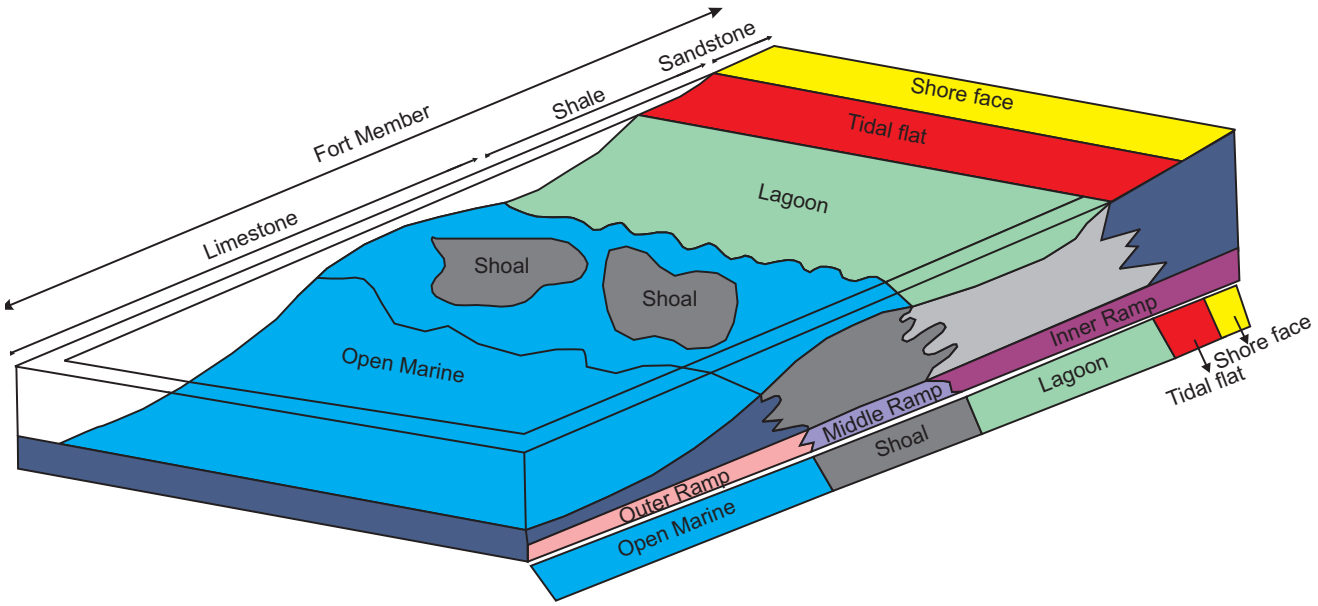

FIGURE 10. Depositional model of Fort Member, Jaisalmer Formation, western Rajasthan.

REFERENCES

Awasthi, A.M., 2002. Geophysical exploration in Jaisalmer Basin - a case history. Geohorizons, 1-6.

Banerjee, S., Bhattacharya, S.K., Sarkar, S., 2006. Carbon and Oxygen isotope compositions of the carbonate facies in the Vindhyan Supergroup, Central India. Journal of Earth System Science, 115, 113-134.

Bhat, G.M., Ahmad, A.H.M., 2013. Temporal facies and diagenetic evolution of the mixed siliciclastic-carbonate Jajiya Member (Callovian-Oxfordian), Jaisalmer Formation, West India. Volumina Jurassica, 11, 147-162.

Blanford, W.T., 1877. Geological notes on the Great Indian Desert between Sind and Rajputana. Record Geological Survey of India, 10, 10-21.

Bonde, S.D., 2010. A new genus of podocarpaceous wood from the Lathi Formation (Early Jurassic) of Rajasthan, India. Geophytology, 38(1-2), 19-24.

Bridge, J.S., 1981. Hydraulic interpretation of the grain size distribution using a physical model for bed load transport. Journal of Sedimentary Petrology, 51, 1109-1124.

Corcoran, P.L., Muller, W.U., Chown, E.H., 1998. Climatic and tectonic influences on fan deltas and wave to tide controlled shoreface deposits, evidence from the Archean Keskarrah Formation, slave province, Canada. Sedimentary Geology, 120,125-152.

Das Gupta, S.K., 1975. A revision of the Mesozoic-Tertiary stratigraphy of the Jaisalmer basin, Rajasthan. Indian Journal of Earth Sciences, 2, 77-94.

Evans, G., 1965. Intertidal flat sediment and their environments of deposition in The Wash. Quarterly Journal of the Geological Society of London, 121, 209-245.

Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. Journal of Sedimentary Petrology, 27, 3-26.

Forrest, J., Clark, N.R., 1989. Characterizing grain size distribution: evaluation of a new approach using multivariate extension of entropy analysis. Sedimentology, 36, 711-722.

Friedman, G.M., 1961. Distinction between dune, beach and river sands from the textural characteristics. Journal of Sedimentary Petrology, 31, 514-529.

Friedman, G.M., 1967. Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands. Journal of Sedimentary Petrology, 37(2), 327-354.

Friedman, G.M., 1979. Address of the retiring President of the International Association of Sedimentologists, Differences in size distributions of particles among sands of various origins. Sedimentology, 26, 3-32.

Friedman, G.M., Sanders, J.R., 1978. Principles of sedimentology. New York,Wiley, 792pp.

Fursich, F.T., Oschmann, W., Singh, I.B., Jaitly, A.K., 1992. Hardgrounds, reworked concretion levels and condensed horizons in the Jurassic of western India: their significance for basin analysis. Journal of the Geological Society of London, 149, 313-331.

Griffiths, J.C., 1967. Scientific Method in Analysis of Sediments. New York, McGraw-Hill, 508pp.

Hamblin, D.P., Walker, R.G., 1979. Storm-dominated shallow-marine deposits: the Fernie-Kootenay (Jurassic) transition, Southern Rocky Mountains Canada. Journal of Earth Science, 26, 1673-1689.

Harms, J.C., Southard, J.B., Spearing, D.R., Walker, R.G., 1975. Depositional environments as interpreted from primary sedimentary structures and stratification sequences. Society of Economic Paleontologists and Mineralogists Short Course, 2, 161pp.

Harms, J.C., Southard, J.B., Walker, R.G., 1982. Structures and sequences in clastic rocks. Society of Economic Paleontologists and Mineralogists Short Course, 9, 8-51.

Heckle, P.H., 1972. Recognition of ancient shallow marine environments. In: Rigby, J.K., Hamblin, W.K. (eds.). Recognition of Ancient Sedimentary Environments. Society for Economic Paleontologists and Mineralogists, Special Publication, 16, 226-286.

Howard, J.D., 1971. Comparison of the beach to offshore sequence in modern and ancient sediments. In: Howard, J.D., Valentine, J.W., Warme, J.E., (Eds.), Recent Advances in Palaeoecology and ichnology. American Geological Institute, Short course, Lecture notes. 148-183.

Howard, J.D., Reineck, H.K., 1972. Physical and biogenic sedimentary structures of the nearshore shelf. Senckenberg Mar, 4, 81-123.

Jodhawat, R.L., Kachhara, R.P., 2000. Modiolus zonation of the Jaisalmer Formation, Rajasthan. Proceedings 16th Indian Colloquium on Micropalaeontology and Stratigraphy, Oil and Natural Gas Corporation Bulletin, 37(1), 207-211.

Johnson, H.D., 1978. Shallow siliciclastic seas. In: Reading, H.G. (ed.). Sedimentary Environments and Facies. Blackwell Oxford, 207-258pp.

Kachhara, R.P., Jodhawat, R.L., 1981. On the age of Jaisalmer Formation, Rajasthan, India. Proceedings of IX Indian Colloquium on Micropaleontology and Stratigraphy, 235-247.

Klein, G.deV., 1970. Tidal origin of a Precambrian quartzite-the Lower Fine Grain Quartzite (Middle Dalradian) of Islay, Scotland. Journal of Sedimentary Petrology, 40, 973-985.

Komar, P.D., 1976. Beach processes and sedimentation. New Jersey, Prentice-Hall, 429pp.

Komar, P.D., Inman, D.L., 1970. Longshore sand transport on beaches. Journal of Geophysical Research, 75, 5914-5927.

Krumbein, W.C., Graybill, F.A., 1965. An Introduction to Statistical Models in Geology. New York, McGraw-Hill, 475pp.

Krumbein, W.C., Sloss, F.J., 1963. Stratigraphy and Sedimentation. San Francisco-London, Freeman, 660pp.

Kulkarni, K.G., Borkar, V.D., Petare, T.J., 2008. Ichnofossils from the Fort Member (Middle Jurassic), Jaisalmer Formation,

Rajasthan. Journal of the Geological Society of India, 71, 731-738.

Kumar, N., Sanders, J.E., 1976. Characteristics of shoreface deposits: modern and ancient. Journal of Sedimentary Petrology, 46, 145-162.

Lukose, N.G., 1972. Palynological evidence on the age of Lathi Formation, Western Rajasthan.Proceedings Seminar on Paleopalynology and Indian Stratigraphy, Calcutta University, 155-159.

Mahendra, K., Banerji, R.K., 1989. Textural study and depositional environment of sand grains from rocks of Jaisalmer Formation, Jaisalmer District, Rajasthan, India. Journal of Geological Society of India, 33(3), 228-242.

Mahendra, K., Banerji, R.K., 1990. Petrography, diagenesis and depositional environment of Middle Jurassic Jaisalmer Carbonates, Rajasthan, India. Indian Journal of Earth Sciences, 17(3/4), 19-207.

Mason, C.C., Folk, R.L., 1958. Differentiation of beach, dune and aeolian flat environments by size analysis. Mustang Island, Texas. Journal of Sedimentary Petrology, 28, 211-226.

McCave, I.N., 1970. Deposition of fine grained suspended sediment from tidal currents. Journal of Geophysical Research, 75, 4151-4159.

McLaren, P., Bowles, D., 1985. The effect of sediments transport on grain size distribution. Journal of Sedimentary Petrology, 55, 457-470.

Moiola, R.J., Weiser, D., 1968. Textural parameters: An evaluation. Journal of Sedimentary Petrology, 38(1), 45-53.

Moore, C.H., 1979. Porosity in carbonate rock sequences. In: Geology of carbonate porosity. American Association of Petroleum Geologists continuing education course notes, 11, Al-A124 Tulsa.

Mukhopadhyay, J., Choudhuri, A.K., 2003. Shallow to deep water deposition in a cratonic basin; an example from the Proterozoic Penganga Group, Pranhita-Godavari Valley, India. Journal of Asian Earth Sciences, 21, 613-622.

Mukhtinath, M., 1967. Phosphate deposits in Rajasthan. Indian Mineral, 21, 83-101.

Mukhtinath, M., 1969. Phosphate deposits in Rajasthan. Indian Mineral, 23(7), 29-42.

Narayanan, K., Subrahmanyan, M., Srinivasan, S., 1961. Geology of Jaisalmer. Unpublished report, Oil and Natural Gas Corporation Dehradun, India.

Oldham, R.D., 1886. Preliminary note on the geology of northern Jaisalmer. Record Geological Survey of India, 19,157-160.

Pandey, D.K., Choudhary, S., Bahadur, T., Swami, N., Sha, J., 2012b. A review of the Lower–lowermost Upper Jurassic lithostratigraphy of the Jaisalmer Basin, western Rajasthan, India an implication on biostratigraphy. Volumina Jurassica, 10, 61-82.

Pandey, D.K., Fursich, F.T., Bron-Szabo, R., 2009a. Jurassic corals from the Jaisalmer Basin, Rajasthan, western India. Zittelina, A48/49, 13-37.

Pandey, D.K., Fursich, F.T., Sha, J., 2009b. Interbasinal marker intervals- A case study from the Jurassic basins of Kachchh and Jaisalmer, Western India. Science in China Series D-Earth Sciences, 52(12), 1924-1931.

Pandey, D.K., Kashyap, D., Choudhary, S., 2005. Microfacies and depositional environment of the Gharoi River section (upper Jaisalmer Formation), west of Baisakhi Village, Jaisalmer Basin, Rajasthan. Jaipur, Proceedings of the National Seminar on Oil, Gas & Lignite Scenario with special Reference to Rajasthan, 117-130.

Pandey, D.K., Sha, J., Choudhary, S., 2006a. Depositional environment of Bathonian sediments of the Jaisalmer Basin, Rajasthan, western India. Beijing, Progress in Natural Science (Special issue of IGCP 506 on the Jurassic Boundary Events), 16, 163-175.

Pandey, D.K., Sha, J., Choudhary, S., 2006b. Depositional history of the early part of the Jurassic succession on the Rajasthan Shelf, western India. Beijing, Progress in Natural Science (Special issue of IGCP 506 on the Jurassic Boundary Events), 16, 176-185.

Pandey, D.K., Sha, J., Choudhary, S., 2010. Sedimentary cycles in the Callovian-Oxfordian of the Jaisalmer Basin, Rajasthan, western India. Volumina Jurassica, 8, 131-162.

Pandey, J., Dave, A., 1998. Stratigraphy of Indian petroliferous basins. In: Proceedings of XVI Indian Colloquium on Micropalaeontology and Stratigraphy, 1-248.

Pareek, H.S., 1984. Pre-Quaternary Geology and Mineral Resources of northwestern Rajasthan. Memoirs of the Geological Survey of India, 115, 1-99.

Pettijohn, F.G., 1975. Sedimentary rocks.New York, Harper and Row Publishers, 628pp.

Powers, M.C., 1953. A new roundness scale for sedimentary particles. Journal of Sedimentary Petrology, 23, 117-119.

Reading, H.G., 1986. Sedimentary Environment and Facies. Blackwell Scientific publication, London, 615pp.

Reineck, H.E., Singh, I.B., 1980. Depositional Sedimentary Environment. New York, Springer-Verlag, 549pp.

Reineck, H.E., Wunderlich, F., 1968. Classification and origin of flaser and lenticular bedding. Sedimentology, 11, 99-104.

Shepard, F.P., Inman, D.L., 1950. Near shore circulation related to bottom topography and wave refraction. Transactions - American Geophysical Union, 31, 555-565.

Singh, A.K., Sethi, J.R., Rai, A.K., Kumar, S., Kundu, J., Goel, S.M., 2005. An overview of exploration and exploitation strategy for hydrocarbons in ONGC acreages of Jaisalmer Basin, Rajasthan–Proceedings of the National Seminar on Oil, Gas & Lignite Scenario with special Reference to Rajasthan held on 20-21 April: 53–68; Jaipur.

Srivastava, S.K., 1966. Jurassic microflora from Rajasthan, India. Micropaleontology, 12(1), 87-103.

Stewart, H.B. Jr., 1958. Sedimentary reflections of depositional environments in San Miguel Lago, Baja California, Mexico. American Association of Petroleum Geologists Bulletin, 42, 2567-2618.

Swaminathan, J., Krinshnamurthy, J.G., Verma, K.K., Chandiak, G.J., 1959. General geology of Jaisalmer area, Rajasthan. Bangkok (ECAFE, UN), Proceedings of the Symposium of

Development in Petroleum Resources of Asia and the Far East, Mineral Resources Development Series (10),

Swift, D.J.P., Figueiredo, Jr.A.G., Freeland, G.L., Oertel, G.F., 1983. Hummocky cross-stratification and megaripples, a geological double standard. Journal of Sedimentary Petrology, 53, 1295-1318.

Udden, J.A., 1898. Mechanical composition of wind deposits. Augustana Library, 1, 1-69.

Van-Stratten, L.M.J.U., 1954. Composition and structure of recent marine sediments in the Netherlands. Leidse Geologische Mededelingen, 19, 1-110.

Visher, G.S., 1969. Grain size distributions and depositional processes. Journal of Sedimentary Petrology, 39, 1074-1106.

Walker, R.G., 1979. Shallow-marine sands. In: Walker, R.G. (ed.). Facies Models. Geoscience Canada reprint Series, 1, 211pp.

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