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Depositional Environment of Neogene Foreland Deposits (Manchar Formation) from the Bara Nai Section of the Southern Indus Basin, Pakistan

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Abstract. Study of depositional environment of the Neogene deposits are important for their potential to uncover the paleogeography of the foreland basins. The paleogeography on the other hand is the sum of interactions between the tectonism, climate and sedimentary processes in a basin. The depositional environment of the Neogene foreland deposits exposed in Bara Nai section of Southern Indus Basin is poorly understood. The present study is aimed to understand the broad depositional environment of these deposits through analysis of primary sedimentary features and textural characteristics of the sandstone. The primary sedimentary structures include cross bedding and strata containing planar-lamination. Other depositional features include oxidized beds, mammal bones and petrified wood. The studied sandstones are medium to fine grained. The sandstones are mostly moderately sorted with a few showing poor sorting. The skewness range of the studied sediments shows coarse-skewed to near symmetrical, while the average skewness curves are near asymmetrical in nature. The kurtosis of the studied samples shows platykurtic nature and some represent mesokurtic and leptokurtic feature. Field sedimentologic studies and granulometric analysis involving linear discriminate functions reveal that the Neogene Manchar formation in the Bara Nai section was deposited in a fluvio-deltaic environment during Neogene.

Keywords: depositional environment, neogene, foreland deposits, manchar formation, southern indus basin, Pakistan

Introduction

The study of depositional environment provides important constraints regarding the paleogeography, paleo-hydrography and tectonic evolution (Halepoto *et al*., 2023b; Coe *et al*., 2010). The sedimentary strata deposited in each category of depositional environment have unique characteristics, which provide significant information regarding the geologic history of that area (Boggs, 2006). Clastic sediments preserve the information of their source terrains, history of transportation and deposition in the form of lithology, texture, primary sedimentary structures and fossils. Texture and primary sedimentary structures of the clastic sedimentary rocks are not only fundamental indicator of depositional environment but it also provides significant information regarding the transportation and energy of the depositional environment (James and Dalrymple, 2010; Reading, 2009). Grain size is a valuable textural constraint of clastic sedimentary rocks since it provides the information regarding the transportation, sorting and deposition of the clasts and end up with some inferences for the record of events that took place in the depositional basin before to the lithification (Ahmedani *et al*., 2024; Duval, 2002). Grain size analysis of the clastic rocks has broadly been employed to evaluate their texture and depositional environments (Edwards, 2001). The statistical constraints of the grain size incorporated with primary sedimentary structures are used to understand the potential source of sediments, paleo-transportation direction and mechanism as well as depositional trend in the sedimentary basins (Blott and Pye, 2001).

The Indus Basin is located on the northwestern margin of Indian plate. It remained a passive margin basin from Precambrian to the Oligocene till the collision of Indian plate with Eurasia (Kazmi and Abbasi, 2008; Kadri, 1995). The northern and western part of the Indus Basin are conventionally anticipated as a foreland basin in response to collision of the Indian plate with Eurasia during 70–34 Ma (Hakro *et al*., 2021; Yin and Harrison, 2000). Southern Indus Basin of Pakistan is geologically rich and complex region, its stratigraphy preserve the

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dynamic history of earth's paleo-environmental evolution. The exposed stratigraphy of southern Indus Basin is dominated by Cenozoic sedimentary sequences (Fig. 1). The foreland sedimentation commenced during Miocene, continued through Pleistocene to recent (Halepoto *et al*., 2023a; Bender, 1995). Rapid uplift of Himalayas and Kirthar-Suleiman fold belts of Pakistan created strong influx of clastics, which were deposited in the associated foreland basins (Cheema *et al*., 2009; Bender, 1995). The Neogene foreland deposits forms a regional belt parallel to the Kirthar-Suleiman fold belts of Pakistan and Himalayas from the Arabian sea in south, Potwar Plateau of Pakistan in the west to Arunachal Pradesh of India in the east. These deposits are designated as the "Siwalik Group" in both India and Pakistan, with Nepal (Churi group) being an exception (Chutia *et al*., 2022; Nakayama and Ulak, 1999; Parkash *et al*., 1980; Medlicott, 1879). The term Manchar Group was proposed by Blanford (1867) for Siwalik Group exposed in the southern Indus Basin, after famous Manchar lake, Sindh. In the later works Manchar Group was refined as Manchar series (Williams, 1959; Manchar (Vredenburg, 1901; Blanford, 1876) and Manchar formation (Cheema *et al*., 1977; Hunting Survey Corporation, 1960) included it in the "Siwalik Group". Siwalik Group attains its maximum thickness in the Sibi foreland basin in Pakistan and its thickness decreases southward (Ahmed *et al*., 1992). Manchar formation is dominantly composed of sandstone interbedded with shale, claystone, rudite and some evaporites (Cheema *et al*., 2009; Hunting Survey Corporation, 1960). Manchar formation has unconformable lower contact with Eocene Laki formation and conformable upper contact with Pleistocene Dada Conglomerate (Cheema *et al*., 2009) in the studied section.

Neogene was the time of rapid uplift of Himalayas, cooling of global climate and start of the Pleistocene ice age (Retallack, 1997; Bender and Raza, 1995; Dolan *et al*., 1987). The understanding of the depositional environment of Neogene foreland deposits will enable to understand the geomorphic evolution and tectonic setup of the northwestern margin of the Indian plate during the Neogene. Manchar formation is previously studied in terms of it vertebrate fossils (Raza *et al*., 1984; Pilgrim, 1908), paleo-magnetism (Khan *et al*., 1984) mineralogical, geochemical and economic potential (Agheem *et al*., 2020) depositional environment (Hakro *et al*., 2024; Samtio *et al*., 2020) from northern Laki and Kirthar ranges. These studies suggested that Manchar formation contains rich assemblage of vertebrate fossils. It is dominantly composed of sandstone, siltstone and shale, being rich in quartz (SiO_2) and clay minerals (Al_2O_3). Fluvial to shallow marine depositional environment is reported by previous workers from their studied sections. However, specific depositional environment of Manchar formation, exposed in Laki range in general and at Bara Nai section of southern Indus Basin in particular is poorly understood. This research is aimed to thoroughly understand the depositional environment of Manchar formation (foreland deposits) exposed at Bara Nai section (Fig. 1). The detailed results of geological fieldwork and statistical textural data of sandstone during this work. The depositional environment of the Manchar formation is discussed based on the primary sedimentary structures and statistical constraints of grain size such as mean, median, standard deviation (sorting), skewness and kurtosis. This study will not only improve our understanding of the Neogene geological history of the study area but also will contribute valuable insights into the broader context of foreland basin evolution.

Materials and Methods

Stratigraphic section of the Manchar formation was measured in the Bara Nai secion along the forelimb of Ranikot anticline (Fig. 1b). The section was measured using tape and Brunton compass as well as Jaccob's staff, depending upon the outcrop morphology. During measurement of stratigraphic section eighteen different lithofacies were identified and sampled (Fig. 2), including ten loose and friable samples. Total measured thickness of the Manchar formation in the Bara Nai section is 200m (Fig. 2). Different primary sedimentary structures, such as cross-bedding, planar laminations and other depositional features were identified during field observations. The grain size investigation of the studied samples was carried out at sedimentology laboratories, Centre for Pure and Applied Geology, University of Sindh, Jamshoro, Pakistan. According the standard methods illustrated by Folk and Ward (1957) to organize various groups of grain size data.

Ten loose sample of sandstone was further disintegrated and crumbled by putting it on the paper sheet. Then sample is mixed by folding the corner of the paper sheet to get well mixture of all grain sizes. Then 100 g sample was weighted and used for the sieve analysis. The pile of sieves were shaken by sieve shaker, for 20 min to segregate each clast size appropriately. The with held

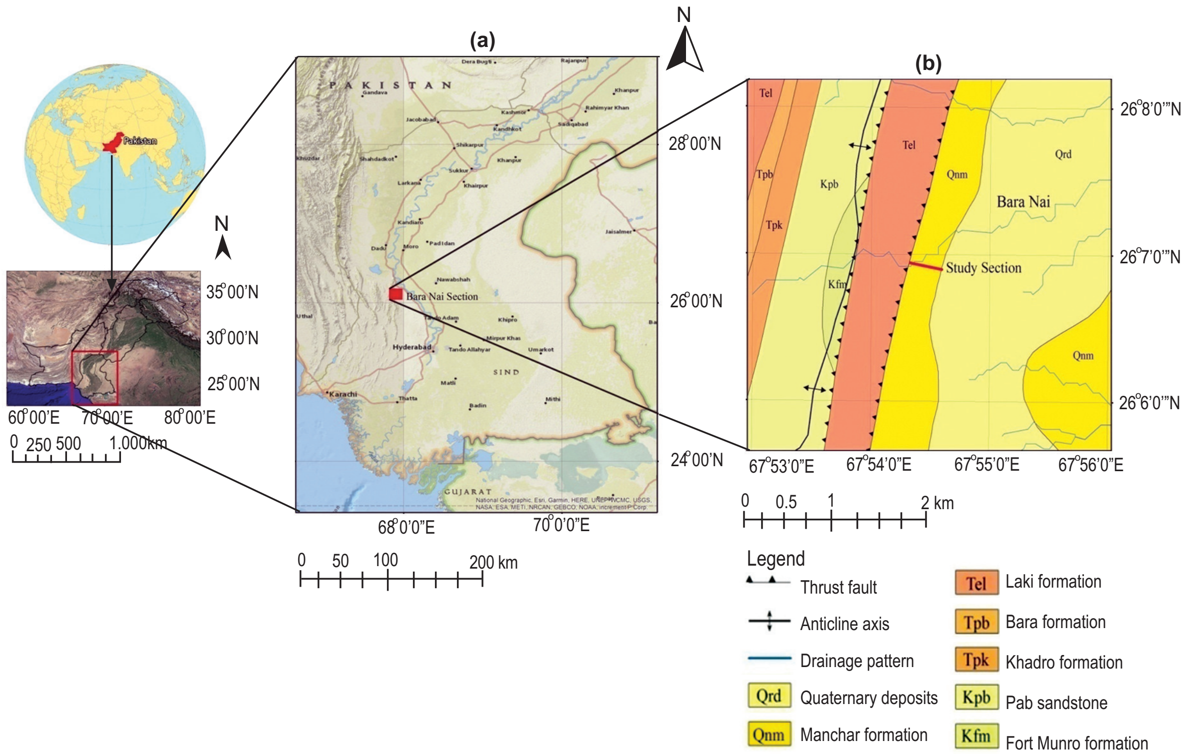

Fig. 1. Location and geology of the study area **(a)** map of Sindh, showing the location of Bara Nai section, **(b)** geological map of the Bara Nai section (satellite image source: National Geographic, Esri, Garmin, HERE, UNEPWCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp, gisgeography.com); Geological map modified after (Halepoto *et al*., 2022; Akhtar *et al*., 2012; Schelling, 1999; Abdullah, 1980; Hunting Survey Corporation, 1960).

weight in each mesh is then weighted and packed separately. The cumulative weight was computed using the weight of grains withheld by each mesh. The Udden-Wentworth standard classes were used to determine grain size group and the frequency of grain size distribution was computed. The grain size constraints obtained in millimeters were then transferred to Phi (Φ) scale as proposed by Krumbein (1934). Various grain size variables are then calculated from obtained data as per procedures suggested by Boggs (2009). Different interpretational diagrams have been employed to identify the depositional environment of Manchar formation after the (Friedman, 1967; Sahu, 1964; Passega, 1964). Relative boundaries of different depositional environments has been placed in columnar section on the basis of field observations and results obtained from grain size analysis (Fig. 2).

Results and Discussion

Field observations and interpretations. During the field studies and measurement of the Manchar formation in the Bara Nai section, different primary sedimentary structures such as planar cross-bedding, strata containing planar-lamination and other depositional features such as oxidized beds, gravely sandstone, petrified wood and mammal bones are identified. Planar cross-bedding and strata containing planar-lamination are commonly observed in sandstone of the Manchar formation (Fig. 3a-c). High angle cross bedding indicates the depositional environment with unidirectional flow, such as rivers and delta. These structures are formed due to the migration of bedforms of different types under lower or upper flow regime conditions on paleo-slopes (Leeder, 2011; Nichols, 2009). Planar laminated sand-stone usually indicates high energy deposition, such as in ephemeral channels or beach/swash zone in the sandy coastal plain. Planar cross bedded sandstone associated with planar laminated sandstones indicates probably braided fluvial or marine influenced fluvial environment of deposition (Ahmed *et al*., 2020; Ahmad *et al*., 2017; Allen, 1982). Presence of oxidized beds of sandstone and claystone in the Manchar formation indicates exposure to sub-aerial exposure and depositional Haitus (Fig. 3d). Metal-bearing minerals facilitate the process of oxidation under sub-aerial conditions in the presence of water, which produce oxidized beds in stratigraphic record (Halepoto *et al*., 2023b; Nichols, 2009). Gravely sandstone units are generally identified in middle and upper part of the Manchar formation (Fig. 3e). Gravely sandstone indicates high-energy depositional conditions, probably associated with braided river systems. The gravel component may be indicative of proximity to sediment source (Tucker, 2001; Blatt *et al*., 1980). The coarsest material in a river dominated environment is usually concentrated near thalweg and these deposit probably represent thalwegs of Manchar rivers. Presence of petrified wood and mammal bones suggest continental environment of deposition, typically fluvial or lacustrine, where organic remains preserved by rapid burial and subsequent petrification (Fig. 3f-g) (Raza *et al*., 1984).

Statistical grain size parameters. Numerous statistical grain size parameters are proposed by Folk and Ward (1957) to appraise the environment of deposition of sandstone. These parameters are obtained by plotting frequency curves of weight percentage of individual sieved samples. During present study these parameters are determined and tabulated in Table 1. Frequency curves are than combined on a single graph to obtain cumulative frequency curve (Fig. 4). The cumulative frequency curve help to visualize the trend of grain size distribution. Almost all frequency curves show the similar trend, which represent generally similar nature of sorting. The central slope of the S-shaped curves indicates the sorting. Steep slope indicates well sorting, while gentle slope indicates poor sorting (Folk and Ward, 1957). The cumulative frequency curves of the studied samples are neither steep nor gentle but they are intermediate, which indicates the moderate sorting of the sandstone.

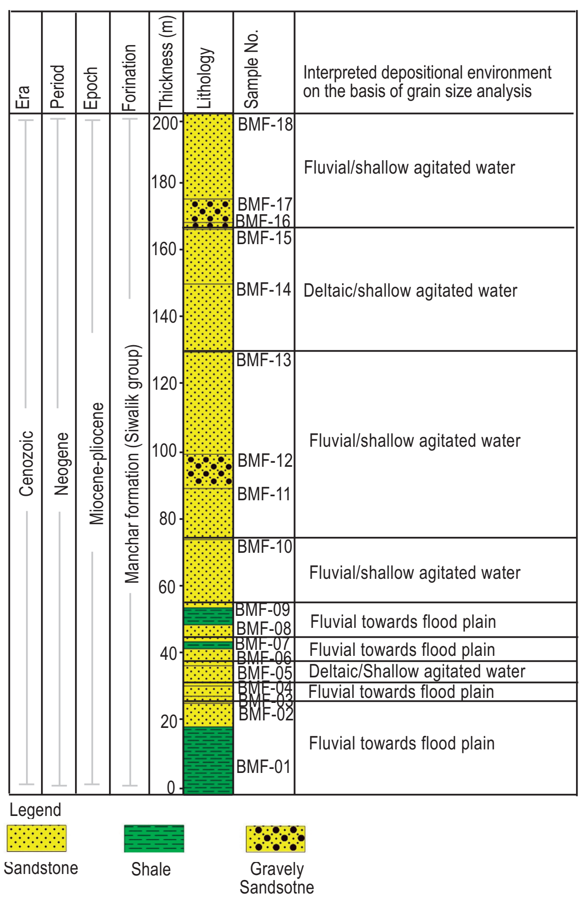

Fig. 2. Column section of the Manchar formation from Bara Nai section, southern Indus Basin, Pakistan.

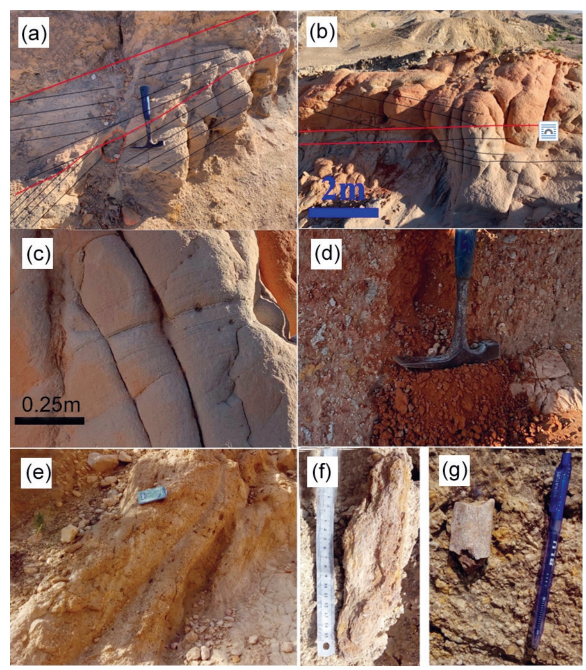

Fig. 3. Depositional features of the Manchar formation in Bara Nai section **(a)** cross bedded sandstone, **(b)** oxidized cross bedded sandstone, **(c)** sandstone strata containing planar-lamination **(d)** oxidized claystone, **(e)** gravely sandstone, **(f)** petrified wood and **(g)** mammal bone. Red lines in figure a and b corresponds with bedding planes and black lines indicate cross beds.

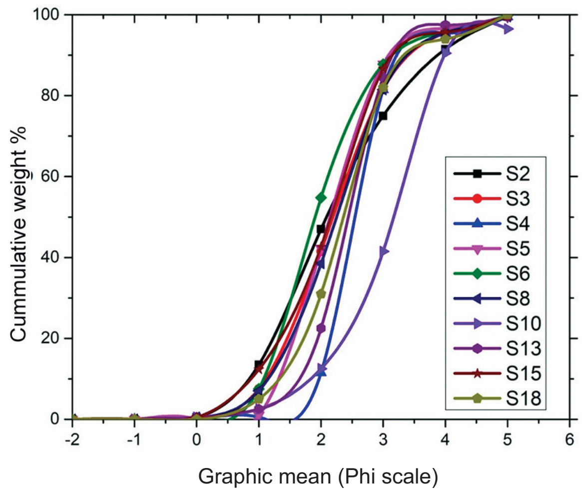

Fig. 4. Cumulative frequency curve of the studied samples.

Graphic mean (Mz). Primarily, graphic mean values suggest the relative size of clasts. The studied samples (Table 1) show generally a uniform mean size value in the range of 2.00-2.59, except sample number BMF 10, which have mean value of 3.06 (Fig. 5a-c). Average mean size of the studied samples is 2.33, which indicates the medium to fine grained sand with little variation in the grain size. These variations in the mean size value indicate fluctuations in the energy level during depositional process (Baiyegunhi *et al*., 2017; Boggs, 2009).

Inclusive graphic standard deviation (sorting). This statistical parameter determines level of sorting of the sediments (Boggs, 2009). Sorting in turn is used to understand the hydrodynamic mechanism in the depositional system. The sorting (standard deviation) values of the Manchar formation ranges between 0.66 to 1.23, having average of 0.94 (Table 1). Standard

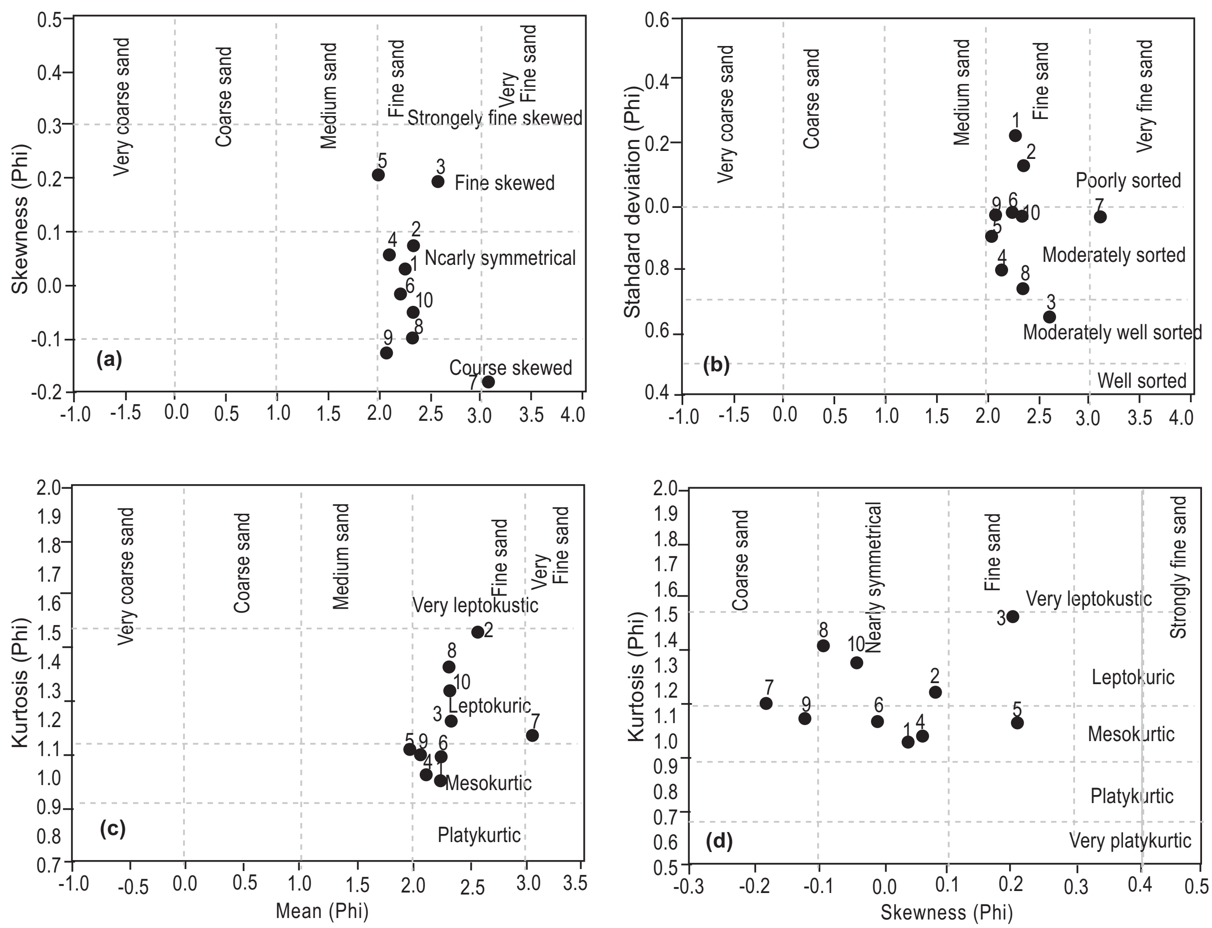

Fig. 5. Plots of statistical grain size parameters **(a)** mean versus skewness, **(b)** mean versus standard deviation, **(c)** mean versus kurtosis and **(d)** skewness versus kurtosis.

Table 1. Calculated statistical grain size constraints of the Manchar formation from Bara Nai section, southern Indus basin, Pakistan

Sample no.	Sample name	Graphic mean	Median	Standard deviation	Graphic skewness	Graphic kurtosis	C	M
1	BMF-02	2.24	2.10	1.23	0.04	0.99	870.55	233.26
2	BMF-03	2.34	2.30	1.13	0.08	1.19	812.25	203.06
3	BMF-04	2.59	2.50	0.66	0.20	1.50	707.11	176.78
4	BMF-05	2.12	2.17	0.81	0.06	1.01	500.00	222.21
5	BMF-06	2.00	1.90	0.91	0.21	1.08	659.75	267.94
6	BMF-08	2.25	2.28	0.99	-0.01	1.07	757.86	205.90
7	BMF-10	3.06	3.20	0.97	-0.18	1.14	812.25	108.82
8	BMF-13	2.33	2.43	0.75	-0.09	1.37	870.55	185.57
9	BMF-15	2.06	2.20	0.98	-0.12	1.07	933.03	217.64
10	BMF-18	2.33	2.40	0.98	-0.04	1.30	812.25	189.46

deviation value of 0 is taken as very well sorted sediments and any positive integer more than 2 is considered as very poorly sorted (Boggs, 2009). The standard deviation range of studied sediments of the Manchar formation indicates moderate sorting with minor poor sorting. Eight out of ten studied samples shows the moderate sorting, while only two remaining sample number 1 and 2 show poor sorting (Fig. 5b). Sorting is determined by transport processes, deposition and post-depositional processes such as winnowing or re-working (Boggs, 2009; Selley, 2000). Therefore, it could be concluded that depositional environment experienced winnowing or re-working due to energy fluctuations during the deposition of Manchar formation.

Inclusive graphic skewness. Skewness is another statistical parameter of sorting, which scrutinize the symmetry of grain size distribution in the studied sample. Measured skewness values of the studied sediments ranges from -0.18 to 0.21 (Table 1) which having average of 0.01. The skewness range of the studied sediments shows coarse-skewed to near symmetrical, while average skewness represent near symmetrical nature of sandstone of the Manchar formation (Fig. 5a and d). The coarse-skewed to near symmetrical nature of the sediments was reported from the middle Paleocene Bara formation (Samtio *et al*., 2021a; Hakro and Baig, 2014; 2013; Khokhar *et al*., 2014), Oligocene Nari formation (Hakro *et al*., 2021; Samtio *et al*., 2021b; Khokhar *et al*., 2016) and Neogene Manchar formation (Hakro *et al*., 2024; Samtio *et al*., 2020). They concluded that coarse-skewed to near symmetrical nature of the sediments demonstrate the presence of medium to fine grained clasts, which deposited in medium to low energy medium.

Graphic kurtosis. The kurtosis range of the Manchar formation ranges from 0.99 to 1.50 with average 1.17 (Table 1). Most samples of the Manchar formation show platykurtic nature, while some represent mesokurtic and leptokurtic nature (Fig. 5c-d). Kurtosis pattern indicates the intermittent inconsistency in the turbulence of the depositional medium (Selley, 2000). This intermittent inconsistency in the turbulence can be attributed by the alternate fluvial regime and ingression of marine realm in the depositional environment.

Bivariate statistical diagrams. Bivariate statistical diagrams of grain size distribution in sedimentary rocks are valuable to recognize the characters of loose sediments, their depositional environment and energy of depositional agent (Friedman, 1967; Passega, 1964; Sahu, 1964; Stewart, 1958; Folk and Ward, 1957). Simultaneously different statistical constraints of grain size are also effectively being used to differentiate between aeolian, fluvial and beach depositional environments (Friedman, 1967; Sahu, 1964; Passega, 1964; Stewart, 1958; Folk and Ward, 1957). These statistical parameters of grain size distribution have been employed (Khokhar *et al*., 2016; Hakro *et al*., 2016; Hakro and Baig, 2014; 2013; Naseem *et al*., 2005; 2003; 2002) for the unconsolidated sediments of different cretaceous and tertiary formations of the southern Indus Basin of Pakistan to work out the depositional environment during these periods.

Median versus standard deviation diagram. Stewart (1958) suggested two interpretational diagrams of median diameter plotted against standard deviation to differentiate three depositional processes of “river”, “wave-dominated” and “quite water” (Fig. 6). Four of the ten samples (4, 5, 6 and 9) fall within river deposited domain, two samples (3 and 8) fall within the wave field and remaining four samples (1, 2, 7 and 10) fall out of river-wave dominated processes but very close to river field in median versus standard deviation diagram (Fig. 6a). Five out of ten samples (1-5) occupy the position between "river-wave" and "quite water slow deposition" fields and three samples (7, 8 and 10) fall within "wave" field, while only two samples (6 and 9) fall on the boundary of river and wave fields on the median versus skewness diagram (Fig. 6b). These diagrams reveal that the Manchar formation is deposited in a setting that was dominated by rivers and waves.

Passega diagram (CM Plot). Passega diagram (CM plot) was suggested by Passega (1964) to understand the mechanism of depositional processes. The Passega diagram is a bivariate diagram based on the log probability scale. It epitomizes the correlation between 1% or one percentile (C) on the frequency curve of each sample and median grain size (M). Both these variables are first converted from Φ (phi) in to µm and then M is plotted on x-axis and C is plotted on y-axis (Table 1). To understand the mechanism of sediment transport and deposition CM plots function efficiently. On the CM plot diagram for transporting mechanism (Fig. 7a), all the analyzed samples fall on 2 field between 1 and 3 fields. This indicates the rolling and suspension mode of sediment transport and deposition. CM plot

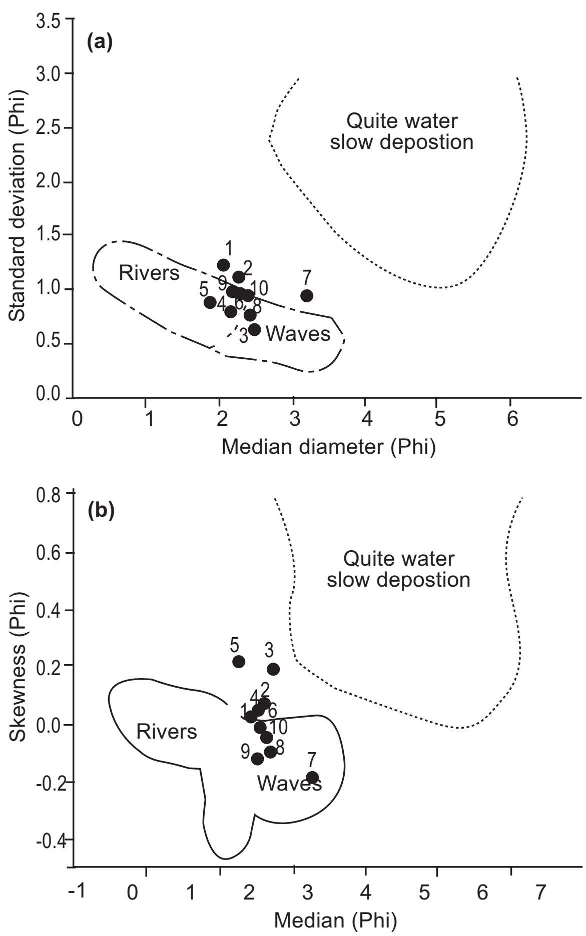

Fig. 6. Stewart (1958) plots **(a)** median diameter *vs* standard deviation and **(b)** median diameter *vs* skewness.

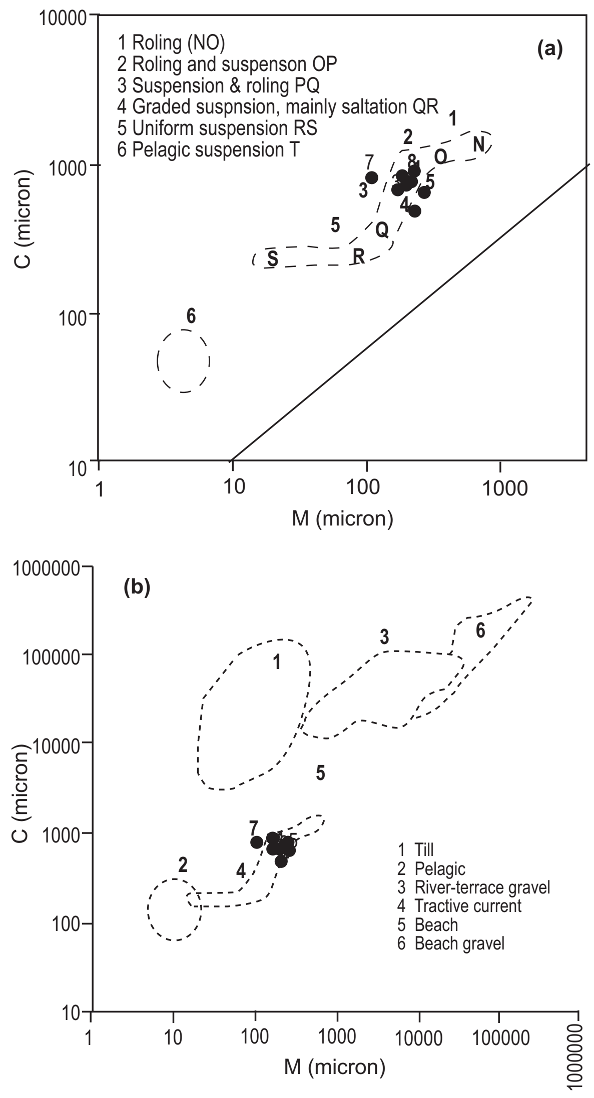

Fig. 7. Passega CM plots showing **(a)** transportation mechanism for sandstone of the Manchar formation and **(b)** depositional mechanism for sandstone of the Manchar formation.

diagram for depositional mechanism (Fig. 7b) shows that all the studied samples fall between 4 and 5 fields. Therefore, the CM plots indicate that the Manchar formation is deposited in fluvial to wave dominated delta by the traction, rolling and suspension. The results of CM plots also aid to the results of bivariate plots of statistical parameters and multivariate multi-group discriminate diagrams.

Conclusion

The present study conclude that Neogene Manchar formation exhibit planar cross-bedding, strata containing planar-lamination and other depositional features such as oxidized beds, gravely sandstone, petrified wood and mammal bones. Sandstone of the Manchar formation consists of medium to fine grains, moderately sorted, coarse-skewed to near symmetrical, platykurtic, with minor mesokurtic and leptokurtic nature. Field studies and grain size analysis results demonstrate that sandstone of the Manchar formation was deposited in fluvial to wave-dominated deltas during Neogene.

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Conflict of Interest. The author declare that thay have no conflict of interest.

References

Abdullah, M.M. 1980. Geological map of Amri-Bara (35 N/16), Lasbela district, Baluchistan, -Scale 1:50,000. *Geological Survey of Pakistan Map Series*, Quetta, Pakistan.

Agheem, M.H., Markhand, A.H., Dars, H., Solangi, S.H., Sahito, A., Thebo, G. 2020. Mineralogical studies of Manchar formation (Pliocene), Laki range, Pakistan: source and possible occurrence of Bauxite. *Sindh University Research Journal (Science Series)*, **52:** 21-30.

Ahmed, Z., Khan, A.S., Ahmed, B. 2020. Sandstone composition and provenance of the Nari formation, central Kirthar fold belt, Pakistan. *Pakistan Journal of Geology*, **4:** 90-96.

Ahmad, F., Quasim, M.A., Ghaznavi, A.A., Khan, Z., Ahmad, A.H.M. 2017. Depositional environment of the Fort member of the Jurassic Jaisalmer formation (western Rajasthan, India), as revealed from lithofacies and grain-size analysis. *Geologica Acta*, **15:** 153-167.

Ahmed, R., Ali, S.M., Ahmed, J. 1992. Structural styles and hydrocarbon prospects of Sibi foreland Basin. *Pakistan Journal of Hydrocarbon Research*, **4:** 31-40.

Ahmedani, S.B., Agheem, M.H., Hakro, A.A.A.D., Halepoto, A.A., Lashari, R.A., Thebo, G.M. 2024. Integrated petrographical, mineralogical and geochemical investigation to evaluate diagenesis of sandstone: a case study of the Oligocene Nari formation from southern Kirthar range, Pakistan. *Journal of Himalayan Earth Sciences*, **57:** 1-22.

Akhtar, M.J., Rizvi, Y., Muhammad, A., Tagar, M.A. 2012. Geological map of Sindh, Pakistan, -scale 1:500,000. *Geological Survey of Pakistan Map Series*, Quetta, Pakistan.

Allen, J.R.L. 1982. *Sedimentary Structures: Their Character and Physical Basis*, *Development in Sedimentology*, vol: **1,** pp. 593, Elsevier Amsterdam, USA.

Baiyegunhi, C., Liu, K., Gwavava, O. 2017. Grain size statistics and depositional pattern of the Ecca group sandstones, Karoo supergroup in the eastern cape province, south Africa. *Open Geosciences*, **9:** 554-576.

Bender, F.K. 1995. Paleogeographic and geodynamic evolution. In: *Geology of Pakistan*, Bender, F.K., Raza, H.A. (eds.), pp. 162-181, Gebruder Borntraeger, Berlin, Germary.

Bender, F.K., Raza, H.A. 1995. *Geology of Pakistan*, pp. 414, Gebruder Borntraeger, Berlin, Germany.

Blanford, W.T. 1876. On the geology of Sind. *Geological Survey of India Records*, **9:** 8-22.

Blanford, W.T. 1867. Note on the geology of the neighbourhood of Lyngan and Runeekot, north-west of Kotree in Sindh, India. *Geological Survey of India Memoir*, **6:** 1-15.

Blatt, H., Middleton, G.V., Murray, R.C. 1980. *Origin of Sedimentary Rocks*, pp. 782, Prentice Hall, New Jersey, USA.

Blott, S.J., Pye, K. 2001. GRADISTAT: A grain size distribution and statistics package for the analysis of un-consolidated sediments. *Earth Surface Processes and Landforms*, **26:** 1237-1248.

Boggs, S.J. 2009. *Petrology of Sedimentary Rocks*, pp. 600, Cambridge University Press, New York, USA.

Boggs, S.J. 2006. *Principles of Sedimentology and Stratigraphy*, 4th edition, pp. 662, Pearson Prentice Hall, New Jersey, USA.

Cheema, M.R., Ahmed, H., Raza, S.M. 2009. Cenozoic. In: *Stratigraphy of Pakistan*, Shah, S.M.I. (eds.), *Geological Survey of Pakistan*, pp. 237-308, Quetta, Pakistan.

Cheema, M.R., Raza, S.M., Ahmed, H. 1977. Cenozoic. In: *Stratigraphy of Pakistan*, Shah, S.M.I. (eds.), *Geological Survey of Pakistan*, pp. 56-97, Quetta, Pakistan.

Chutia, A., Gogoi, M.P., Taye, C.D., Bordoloi, A. 2022. Petrography and clay mineral study of Siwalik Group, east Siang district, Arunachal Pradesh: implications for tectonic setting and depositional environment. *Indian Journal of Geosciences*, **76:** 371-384.

Coe, A.L., Argles, T.W., Rothery, D.A., Spicer, R.A. 2010. *Geological Field Techniques*, pp. 323, Wiley-Blackwell, USA.

Dolan, P., Edgar, D.C., Brand, C., Shevlin, B.J. 1987. Pakistan Regional Geology and Petroleum Exploration Potential: Dolan and Associates, Non-Exclusive Report, London, UK.

Duval, B.B. 2002. *Sedimentary Geology: Sedimentary Basins, Depositional Environments, Petroleum Formation*, pp. 642, Technip, Paris, France.

Edwards, A.C. 2001. Grain size and sorting in modern beach sands. *Journal of Coastal Research*, **17:** 38-52.

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.

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

Hakro, A.A.A.D., Halepoto, A.A., Samtio, M.S., Rajper, R.H., Mastoi, A.S., Lashari, R.A., Rahoo, M.A. 2024. The comparative depositional heterogeneity of Manchhar formation (Siwalik Group), southern Indus Basin, Pakistan. *Journal of Mountain Area Research*, **9:** 1-15.

Hakro, A.A.A.D., Xiao, W., Mastoi, A.S., Yan, Z., Samtio, M.S., Rajper, R.H. 2021. Grain size analysis of the Oligocene Nari formation sandstone in the Laki range, southern Indus Basin, Pakistan: implications for depositional setting. *Geological Journal*, **56:** 5440-5451.

Hakro, A.A.A.D., Khokhar, Q.D., Solangi, M.A., Bhutto, I.A.S., Khokhar, I.A. 2016. Depositional environment of sohnari member sandstone of Laki formation from southern Indus Basin, Pakistan. *Sindh University Research Journal (Science Series)*, **48:** 227-232.

Hakro, A.A.A.D., Baig, M.A.A. 2014. Depositional environments of the Bara formation sandstone from Lakhra areas Sindh, Pakistan. *Pakistan Journal of Scientific and Industrial Research Series A: Physical Sciences*, **57:** 20-31.

Hakro, A.A.A.D., Baig, M.A.A. 2013. Depositional environment of the Bara formation, Fort Ranikot area, Sindh. *Sindh University Research Journal (Science Series)*, **45:** 83-94.

Halepoto, A.A., Agheem, M.H., Lashari, R.A., Hakro, A.A.A.D., Ahmedani, S. B. 2023a. Development and synclinal-anticlinal breakthrough of fault-propagation fold: insights from Borr Dhoro section of the Ranikot anticline, southern Kirthar fold belt, Pakistan. *Sindh University Research Journal (Science Series)*, **55:** 32-41.

Halepoto, A.A., Lashari, R.A., Sahito, A.G., Ahmedani, S.B., Mastoi, A.S. 2023b. Microfacies of Nari formation from Hundi anticline, Karachi Embayment, southern Indus Basin, Pakistan. In: *Proceedings of SPE-PAPGAnnual Technical Conference-2023*, pp. 1-16.

Halepoto, A.A., Ahmed, S., Agheem, M.H., Hakro, A.A.A.D., Lashari, R.A., Ahmedani, S.B. 2022. Assessment of suitability for hydrcarbon entrapment in the Ranikot anticline, southern Kirthar fold belt (SKFB), Pakistan. In: *Proceedings of PAPG-SPE Annual Technical Conference 2022*, pp. 35-48.

Hunting Survey Corporation, 1960. Reconnaissance geology of part of west Pakistan, pp. 540, a colombo plan co-operative project, Toronto, Canada.

James, N.P., Dalrymple, R.W. 2010. *Facies Models*, Geological Association of Canada, **4:** 667, Canada.

Kadri, I.B. 1995. *Petroleum Geology of Pakistan*, Pakistan Petroleum Limited, Karachi, pp. 275, Pakistan.

Kazmi, A.H., Abbasi, I.A. 2008. *Stratigraphy and Historical Geology of Pakistan*, National Centre of Excellence in Geology, University of Peshawar, pp. 524, Pakistan.

Khan, M.J., Hussain, S.T., Arif, M., Shaheed, H. 1984. Preliminary paleomagnetic investigations of the Manchar formation, Gaj river section, Kirthar range, Pakistan. *Geological Bulletin of University of Peshawar*, **17:** 145-152.

Khokhar, Q.D., Hakro, A.A.A.D., Solangi, S.H., Siddiqui, I., Abbasi, S.A. 2016. Textural evaluation of Nari formation, Laki range, southern Indus Basin, Pakistan. *Sindh University Research Journal*

(Science Series), **48:** 633-638.

Khokhar, Q.D., Hakro, A.A.A.D., Solangi, S.H., Brohi, I.A., Markhand, A.H. 2014. Textural maturity and depositional environment of Bara formation at Ranikot, Sindh. *Sindh University Research Journal (Science Series)*, **46:** 71-76.

Krumbein, W.C. 1934. Size frequency distributions of sediments. *Journal of Sedimentary Research*, **4:** 65-77.

Leeder, M.R. 2011. Tectonic sedimentology: sediment systems deciphering global to local tectonics. *Sedimentology*, **58:** 2-56.

Medlicott, H.B. 1879. *A Manual of the Geology of India: Chiefly Compiled from the Observations of the Geological Survey*, pp. 166, Peninsular area, Trübner, London, UK.

Nakayama, K., Ulak, P.D. 1999. Evolution of fluvial style in the Siwalik Group in the foothills of the Nepal himalaya. *Sedimentary Geology*, **125:** 205-224.

Naseem, S., Sheikh, S.A., Bashir, E., Shirin, K. 2005. Geochemistry and depositional setting of Fort Munro formation, middle and lower Indus Basin, Pakistan. *Journal of China University of Geosciences*, **16:** 160-169.

Naseem, M., Sheikh, S.A., Naseem, S. 2003. Sedimentology of Chitarwata formation, Rakhi Nala, Sulaiman range, Pakistan. *Journal of Applied Sciences*, **3:** 256-265.

Naseem, S., Sheikh, S.A., Qadeeruddin, M., Shirin, K. 2002. Geochemical stream sediment survey in Winder Valley, Balochistan, Pakistan. *Journal of Geochemical Exploration*, **76:** 1-12.

Nichols, G., 2009. *Sedimentology and Stratigraphy*, 2nd edition, pp. 419, Wiley-Blackwell, USA.

Parkash, B., Sharma, R.P., Roy, A.K. 1980. The Siwalik Group (molasse) - sediments shed by collision of continental plates. *Sedimentary Geology*, **25:** 127-159.

Passega, R. 1964. Grain size representation by CM patterns as a geological tool. *Journal of Sedimentary Petrology*, **34:** 830-847.

Pilgrim, G.E. 1908. The tertiary and post-tertiary freshwater deposits of Baluchistan and Sindh: with notices of new vertebrate. *Geological Survey of India Records*, **37:** 139-166.

Raza, S.M., Barry, J.C., Meyer, G.E., Martin, L. 1984. Preliminary report on the geology and vertebrate fauna of the Miocene Manchar formation, Sindh, Pakistan. *Journal of Vertebrate Paleontology*, **4:** 584-599.

Reading, H.G. 2009. Sedimentary environments: processes, facies and stratigraphy, pp. 704, John Wiley & Sons, USA.

Retallack, G.J. 1997. Neogene expansion of the north American Prairie. *PALAIOS*, **12:** 380-390.

Sahu, B.K. 1964. Depositional mechanisms from the size analysis of clastic sediments. *Journal of Sedimentary Petrology*, **34:** 73-83.

Samtio, M.S., Hakro, A.A.A.D., Agheem, M.H., Mastoi, A.S., Rajper, R.H., Lashari, R.A., Noonari, M.W., Junejo, Y., Otho, A.A. 2021a. Textural characterization of middle paleocene sediments from Thar coalfield southern Indus Basin Pakistan. *Sindh University Research Journal (Science Series)*, **53:** 245-256.

Samtio, M.S., Hakro, A.A.A.D., Lashari, R.A., Mastoi, A.S., Rajper, R.H., Agheem, M.H. 2021b. Depositional environment of Nari formation from Lal bagh section of Sehwan area, Sindh Pakistan. *Sindh University Research Journal (Science Series)*, **53:** 67-76.

Samtio, M.S., Hakro, A.A.A.D., Mastoi, A.S., Rajper, R.H., Nangraj, A.R. 2020. Depositional pattern of the Siwalik Group (Manchar formation) southwest of Lal bagh, Sehwan area, Sindh, Pakistan. *Sindh University Research Journal (Science Series)*, **52:** 363-368.

Schelling, D.D. 1999. Frontal structural geometries and detachment tectonics of the northeastern Karachi Arc, southern Kirthar range, Pakistan. *Special Paper of the Geological Society of America*, **328:** 287-302.

Selley, R.C. 2000. *Applied Sedimentology*, 2nd edition, pp. 523, Academic Press, London, UK.

Stewart, H.B. 1958. Sedimentary reflections of depositional environment in San Miguel Lagoon, Baja California, Mexico. *Bulletin of American Association of Petroleum Geologists*, **42:** 2587-2618.

Tucker, M.E. 2001. *Sedimentary Petrology: An Introduction to the Origin of Sedimentary Rocks*, 3rd edition, pp. 262, Blackwell Science Limited, USA.

Vredenburg, E.W. 1901. A geological sketch of the Baluchistan desert and part of eastern persia. *Geological Survey of India Memoir*, **31:** 179-302.

Williams, M.D. 1959. Stratigraphy of the lower Indus Basin, west Pakistan. In: *Proceedings of 5th World Petroleum Congress Section I*, pp. 377-391.

Yin, A., Harrison, T.M. 2000. Geologic evolution of the Himalayan-Tibetan Orogen. *Annual Review of Earth and Planetary Sciences*, **28:** 211-280.