Sequence stratigraphic framework of the Maastrichtian shelfal to deep marine strata of Lower Indus Basin, Pakistan: implications for the petroleum potential

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Abstract

The present study integrates the facies and planktonic foraminiferal biostratigraphic data to construct a sequence stratigraphic model of the Mughal Kot Formation of Maastrichtian age in the Lower Indus Basin, Pakistan. The Mughal Kot Formation is comprised of 1000-m-thick sequence of hemipelagic sediments, interrupted by random influxes of coarse-grained sandy turbidites. The petrographic details revealed six sub-microfacies, indicating deposition in the middle shelf, slope and deep marine basin. The sequence stratigraphic model is based on the integration of biostratigraphic age and local depositional signals in the study area. The studied sedimentary succession is divided into one second-order and two third-order cycles while ten parasequences are identified within the complete cycles of transgressive, highstand and lowstand systems tracts. The depositional trends within the relative sea level curve of the Maastrichtian strata of the study area and the global sea level charts are quite dissimilar, which suggest a sustained transgression with pulsated tectonics in Lower Indus Basin. The integrated results of plug porosity/permiability and petrography reveal poor reservoir potential for the sandy turbidites and pelagic carbonates of the Mughal Kot Formation.

Keywords Sequence stratigraphy · Cretaceous · Indus Basin · Reservoir

Introduction

The Lower Indus Basin is an integral part of a giant Indus Basin which is a sedimentary depocenter located on the north-western margin of the Indian Plate (Shah 2009). The Cretaceous depositional packages of the Indus Basin match up to the Eastern Tethys (Khan 2013). The carbonate–siliciclastic succession of the Maastrichtian age corresponds to the Mughal Kot Formation; it is approximately 1000 m thick, however the thickness greatly varies in different stratigraphic sections as a result of tectonic forcing at the western margin of Indian Plate during the late Cretaceous time (Smewing

et al. 2002). The Mughal Kot Formation is composed of dark gray calcareous mudstone with scattered interlayers of quartzose sandstone and argillaceous limestone which were deposited in the outer ramp-open marine settings with basin floor lobes, submarine channel-fill and base of slope lobes (Umar et al. 2011; Williams 1959; Marks 1962; Shafique 2001; Dorreen 1974) while Malkani (2010) suggests a shallow marine, deltaic and post-deltaic environment of deposition. The planktonic foraminiferal biostratigraphic findings revealed a Maastrichtian age of the Formation (Dorreen 1974; Khan et al. 2017). Similarly, the diagenetic studies have demonstrated negative effect on the reservoir quality of this mix carbonate–siliciclastic unit (Wadood et al. 2019).

The previous stratigraphic analysis of the Mughal Kot Formation lacks the sequence stratigraphic information and trivial studies have been conducted to comment on the reservoir capability of the rock unit in the Lower Indus Basin. Therefore, present study aims to contribute by critically evaluating facies distribution and discuss the ambient depositional settings and petroleum reservoir potential of the unit.

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General geology of the study area

The Himalayan collision resulted in the development of several foreland basins and ranges in Pakistan and India (Acharyya 2007). The Sulaiman Range (Lower Indus Basin) is one of the manifestations of the Indian–Eurasian collision (Bender and Raza 1995). Before the collision of the Indian and Eurasian Plates, the parts of the Lower Indus Basin acted as passive margin until the early Eocene collision (Waheed and Wells 1990). The major collision in the area took place during Palaeocene time (Bannert et al. 1989) while various transform and wrench faults developed in the Early–Middle Miocene (Wang et al. 1996). The Indian Plate started movement towards north in late Cretaceous time as the western margin of the plate was separated from the Madagascar Plate (Scotese et al. 1988; Gnos et al. 1997). Because of this event, the Indian passive margin was greatly affected by faulting and fragmentation into basins including the Indus Basin. The tectonic influenced rock highs divided the Indus Basin into Lower and Upper Indus Basin. The Sulaiman Basin, part of Lower Indus Basin, is the largest sub-basin that covers about 170 thousand km^2 area with more than 40% area of Indus Basin (Malkani 2010). It can be divided into arc-shaped major tectonic zones including Sulaiman fold belt, Sulaiman foredeep and a monoclinal zone called as the Punjab Monocline.

The stratigraphy of Sulaiman Basin ranges from Triassic to recent (Shah 2009; Fig. 1) that starts from the rock unit Ferozabad Group of Triassic–Jurassic (Anwar et al. 1991). The Ferozabad Group is overlain by Cretaceous succession having disconfirmable contact with the overlying strata (Umar et al. 2011). The Cretaceous succession includes the Sembar, Goru and Parh limestone (Shah 1977). These units are successfully overlain by clastic dominated Mughal Kot and Pab Formations. These Cretaceous units are succeeded by the Paleocene and Eocene succession. The eradication of the Tethyan Ocean is recorded by the sequence of shale and limestones (Umar et al. 2011) while the angular unconformity separates the non-marine clastics of the Plio-Quaternary time.

Materials and methods

The stratigraphic thickness of the Mughal Kot Formation exposed in Mughal Kot Gorge, Sulaiman Range in the Frontier Region Dera Ismail Khan is measured and all visible sedimentological and textural variations are documented and a composite stratigraphic log is constructed (Fig. 1). For the biostratigraphic age constraints previous available data were used while the paleoenvironmental analysis was based on the study of the 101 petrographic thin sections. The carbonates were classified using Dunham (1962) classification and the microfacies were established using Flügel scheme (2004). On basis of these microfacies and variation in their depositional settings, various sequences were established. The representative photomicrographs were taken with the help of Olympus DP12 microscope with a digital camera installed at the Sedimentology Laboratory in the Department of Geology, University of Peshawar. The plug porosity and permeability of selected rock samples were determined by using PoreMaster Series, Porosimeter at the Hydrocarbon Development Institute of Pakistan.

Results and discussion

Lithostratigraphy

In this study the Mughal Kot Formation is documented as nodular marls, alternating with shale and lenticular sandstone interbeds. The marls are bluish at weathered surface while dark gray at fresh surface. Shales are internally laminated having pillow structures. The size of pillow ranges from 30 to 80 cm. Several turbidity sandstones are found in the vertical stratigraphic succession. The bioclastic limestone is demarcating the lower contact with the Parh Formation. Hard splintery shales with sandy filled matrix are also documented. The marls of the Mughal Kot Formation are blocky at places incorporating slumped carbonate blocks. The sandstone interbeds are thin- to thick-bedded, medium- to coarse-grained, gray to white quartzose. These turbidites have recorded the normal grading, however rare inverse-grading are also observed. The pyrite fambroids and phosphate nodules are also seen at places in the Mughal Kot Formation. In the study area the Mughal Kot Formation overlies the Parh Limestone while in turn it is conformably overlain by the Pab Sandstone. Based on lithological variation, the rock unit can be divided into the following three lithostratigraphical units.

Lower splintery shales unit with interbedded thin sandstone

This unit is almost 380 m thick which is mainly composed of hard splintery shales with interbedded thin sandstone (Fig. 2a). Marls are bluish on weathered surface while gray on fresh surface. Sandstones have filled sandy burrows (Fig. 2b). Marls are characterized by thinly laminated pillow structures that range from few centimeters up to 80 cm (Fig. 2c). Occasionally pyrite fambroids and phosphate
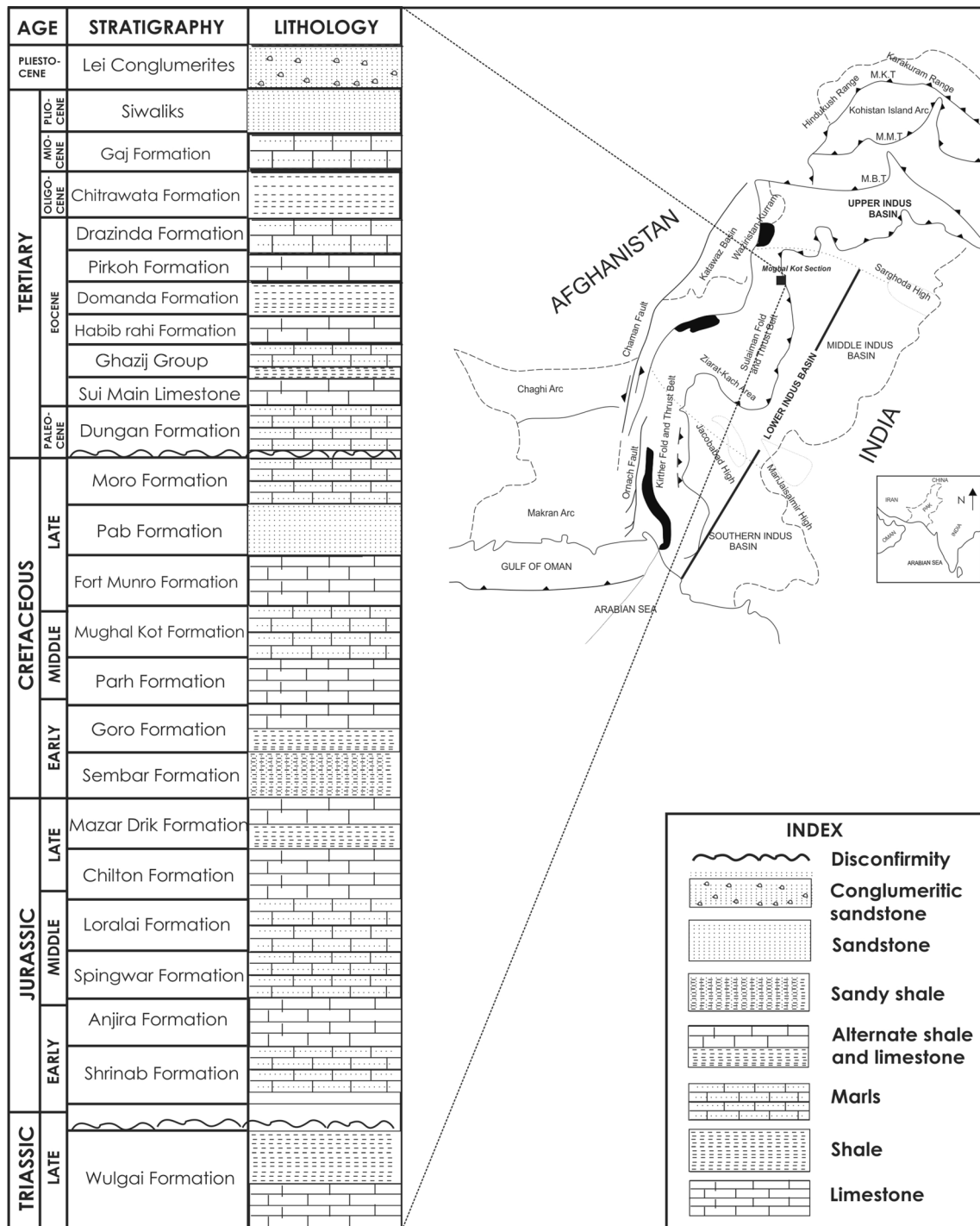
Fig. 1 Tectonic map of Pakistan and the study area is marked in black box (modified after Banks and Warburton 1986; Kadri 1995; Khan 2013; Wadood et al. 2019). The generalized stratigraphic column of the study area is also shown (Shah 2009)

nodules are seen at places (Fig. 2d). The complete Bouma sequence is also observed in the lower part of the Mughal Kot Formation (Fig. 2e).

Middle sandstone unit with alternate beds of shales

This unit is almost 370 m thick. The unit mainly comprised sandstone (turbidites). Several thin-bedded Bouma
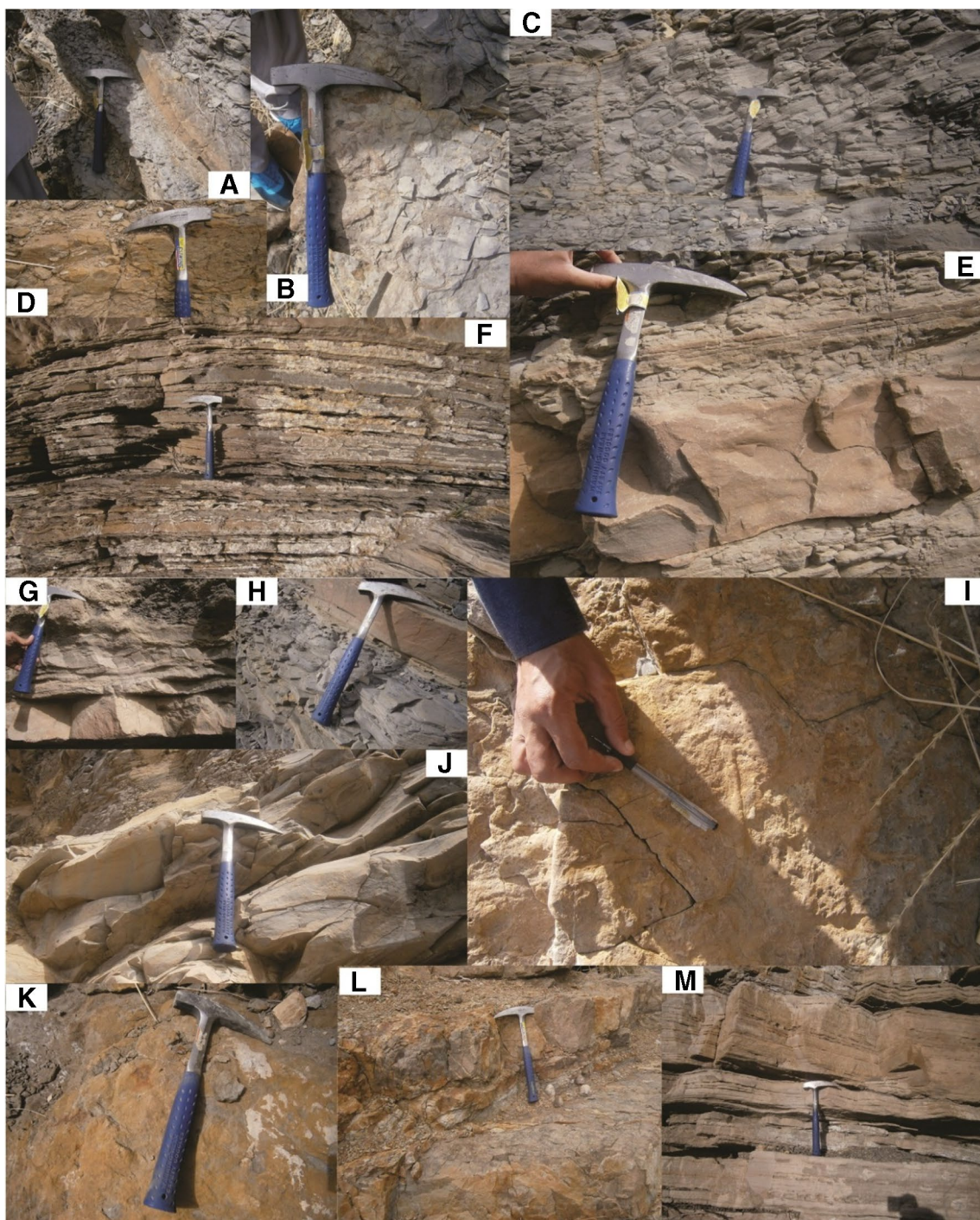
Fig. 2 Field photographs of Mughal Kot Formation. **a** Splintery shales with interbedded sandstone. **b** Filled burrows in sandstone. **c** Pillow structures in marls. **d** Pyrite fambroids and phosphate nodules in limestone. **e** Bouma sequence in lower part. **f** Several thin-bedded Bouma sequence in middle part. **g** Normal grading in turbidites. **h** Reverse grading in turbidites. **i** Ripple marks and burrows in sandstone. **j** Hard blocky beds of limestone. **k** Bioclastic sandy shale with nodules. **l** Channelized beds of sandstone. **m** Planar turbidite beds (hammer length = 35 cm for scale)

sequences are recognized (Fig. 2f).These turbidites have recorded the normal grading (Fig. 2g), however rare inverse-grading are also observed (Fig. 2h). Sedimentary structures like ripple marks and burrows have been examined at several places (Fig. 2i). Similarly, thin interbedded fissile shale is consistently present in this unit.

Upper nodular shale unit with interbedded sandstone and limestone

This rock unit is almost 250 m thick. This part consists of nodular shales having hard blocky limestone and interbedded thin layers of sandstone. The hard blocky beds of limestone are found (Fig. 2j). The bioclastic sandy shale with weathered phosphate nodules are also part of this unit (Fig. 2k). Some channelized sandstone beds are seen at places (Fig. 2l). The unit also consists of planar turbidite beds (Fig. 2m).

Petrographic analysis

The petrographic characteristics studied include type of grains, matrix and cement. The semi-quantitative data on percentages of these attributes are calculated by visual estimation. Consequently, such petrographic data are then used for microfacies analysis. The microfacies lead to the interpretation of the depositional environments of the Mughal Kot Formation.

Microfacies analysis

Following the Dunhum (1962) classification, three major depositional facies are identified including middle shelf facies, deeper slope facies and deep marine facies. Middle shelf facies is characterized by siliciclastic bioclastic orbitoidal wackestone sub-microfacies. The deep marine is further subdivided into pelagic mudstone and siliciclastic pelagic mudstone sub-microfacies while the slope facies include quartz wacke, quartz arenite, and calcareous quartz wacke sub-microfacies.

Middle shelf facies

Siliciclastic bioclastic orbitoidal wackestone sub-microfacies Field observations: At outcrop scale it is composed of coarse bioclastic limestone beds while at the top displaying inverse grading.

Microscopic observations: This microfacies exhibit wackestone texture. The total abundance of the grains is 65%, while the rest of 35% is micritic matrix. The dominant fauna are the larger benthic foraminifera which is 28% of the total rock. The bioclasts and planktonic foraminifera constitute 7% and 2% of the rock, respectively. The quartz grains constitute 28% of the total rock (Fig. 3).

Environmental interpretation: The bioclastic wackestone texture along with larger benthic foraminifera, i.e., orbitoides represents the middle shelf setting (see Flügel 2004).

Slope facies

Quartz wacke sub-microfacies Field description: Multiple turbidity sandstone units, with thinning and finning upward sequences are observed. These turbidites at places become channelized and conglomeritic.

Framework mineralogy: Quartz is the most abundant constituent in all the studied samples of this particular sandstone microfacies. The quartz is dominantly monocrystalline, and ranges from 10 to 70% with an average of 45.14%. The limestone rock lithics and accessory minerals are below 1%. The modal composition of the sandstones pertaining to this microfacies indicates quartz wackes (see Pettijohn et al. 1987). The quartz grains are dominantly medium grained. The sandstone of this sub-microfacies is poorly sorted because it includes fine and medium sand in addition to the fine-grained calcareous/clayey matrix. The grains of this microfacies are subangular to subrounded and show low-to-moderate sphericity. The grains are loose to tightly packed with pointed to sutured contacts (Figs. 3, 4).

Environmental interpretation: The poor sorting in the quartz wacke sub-microfacies suggest deposition in a relatively calm water conditions. The presence of graded bedding within this sandstone suggests deposition by turbidity currents (see e.g., Ricci-Lucchi 2003). These sandstone microfacies are interbedded with a thick succession of hemipelagic sediments, suggesting that such ambient calm water condition corresponds to the deeper slope turbidities. The subangular to subrounded quartz grains suggest that the framework components are derived from the nearby source. The thick bedded clastic sandstone pertaining to this microfacies suggests the extrabasinal hyperpycnal river flow transportation processes responsible for the deposition of such deeper slope turbidites (e.g., Stow et al. 1998; Zavala and Arcuri 2016).

Quartz arenite sub-microfacies Field description: In the field various planner beds of turbidities sequence are observed.

Framework mineralogy: Quartz is the most abundant framework grain of this sandstone, ranging from 88 to 94% with an average abundance of 91.2%. The quartz grains are mostly fine-to-medium grained and monocrystalline but rare polycrystalline grains are also seen. The limestone lithics and accessory mineral are below 1% each. Randomly oriented bioclasts are seen. The modal composition of this sub-microfacies falls in quartz arenite category of Pettijohn et al. (1987). The sandstone is fine-to-medium grained, however coarse-grains are randomly scattered within thin section. This sandstone displays moderate sorting. The grains are sub-angular to sub-rounded, and the overall sphericity is moderate but high. Clay matrix fills the pore spaces between
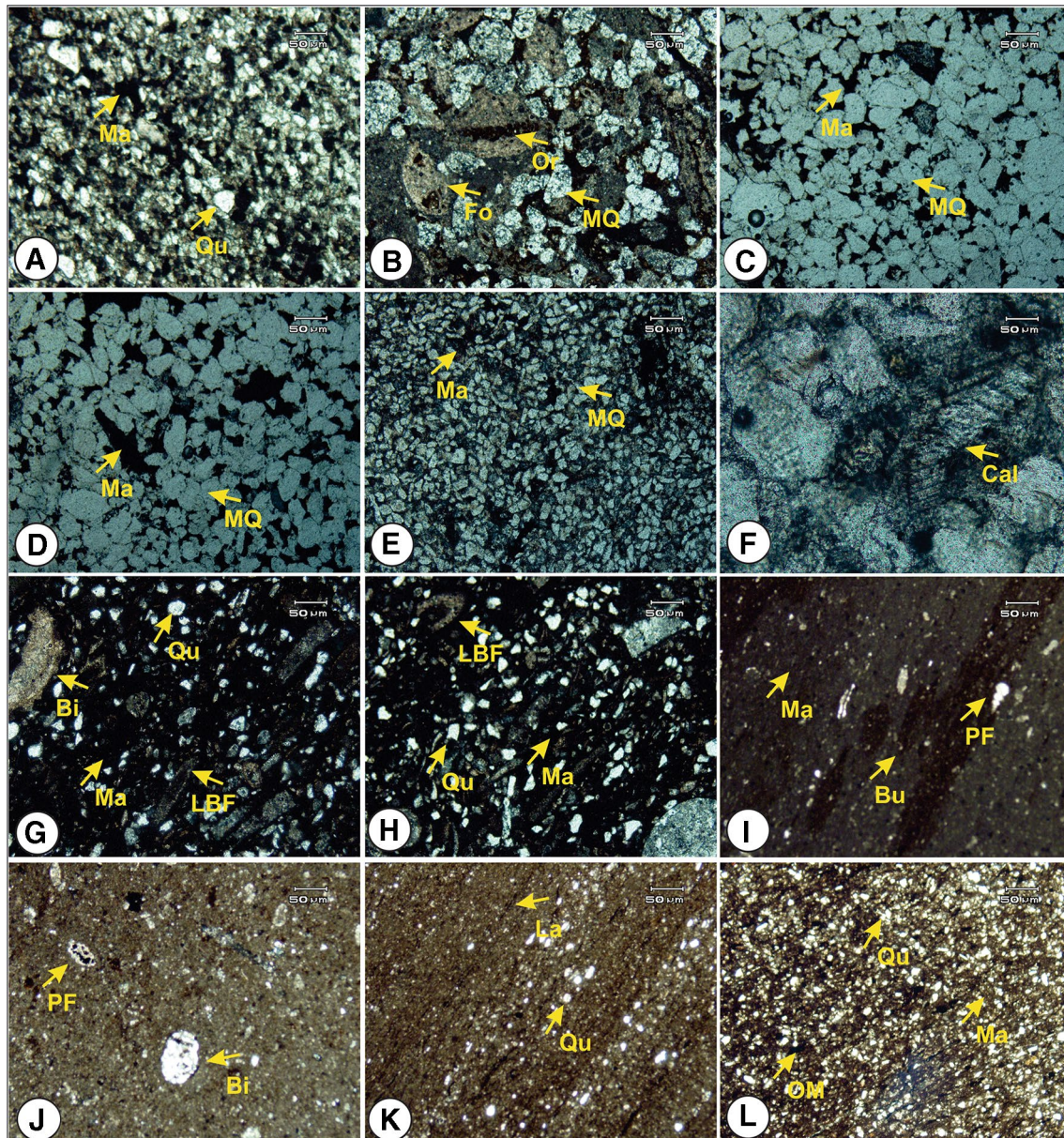
Fig. 3 Photomicrographs of sub-microfacies. **a**, **b** Quartz wacke; **c**, **d** quartz arenite; **e**, **f** calcareous quartz wacke; **g**, **h** siliciclastic bioclastic orbitoidal wackestone; **i**, **j** pelagic mudstone; **k**, **l** siliciclastic pelagic mudstone [matrix (M in **a**, **c**–**e**, **g**–**i**, **l**), quartz (Qu in **a**, **g**, **h**, **k**, **l**), microcrystalline quartz (MQ in **b**–**e**), forams (Fo in **b**), orbitoides (Or in **b**), calcite (Cal in **f**), bioclast (Bi in **g**, **j**), larger benthic foraminifer (LBF in **g**, **h**), burrows (Bu in **i**), planktonic foraminifera (PF in **j**, **i**) and organic matter (OM in **l**)]

the grains. The grains are tightly packed with dominant sutured contact (Figs. 3, 4).

Environmental interpretation: The moderate to well sorting suggests a high-energy depositional conditions, whereby the matrix is continually washed from the pore spaces of the grains. The interbedded thick sequence of the hemipelagic sediments shows deep bottom conditions. The graded bedding within the sandstone suggests deposition by turbidity currents on slope-deep basin. The quartz arenite fabric suggests high-energy water settings. From slope to deep basin such high-energy conditions can only be established at the onset of turbidites. This sub-microfacies is therefore interpreted to be deposited in the early phase of turbidites. The subangular to subrounded grains with moderate-to-high sphericity suggest that the sands were derived from the stable granitic craton of uniform composition located at considerable distance from the site of deposition. The rounding of the edges and corners of the grains may also be associated with high energy settings.

Fig. 4 The modal mineralogical composition of slope microfacies of the Mughal Kot Formation, after Pettijohn et al. (1987)
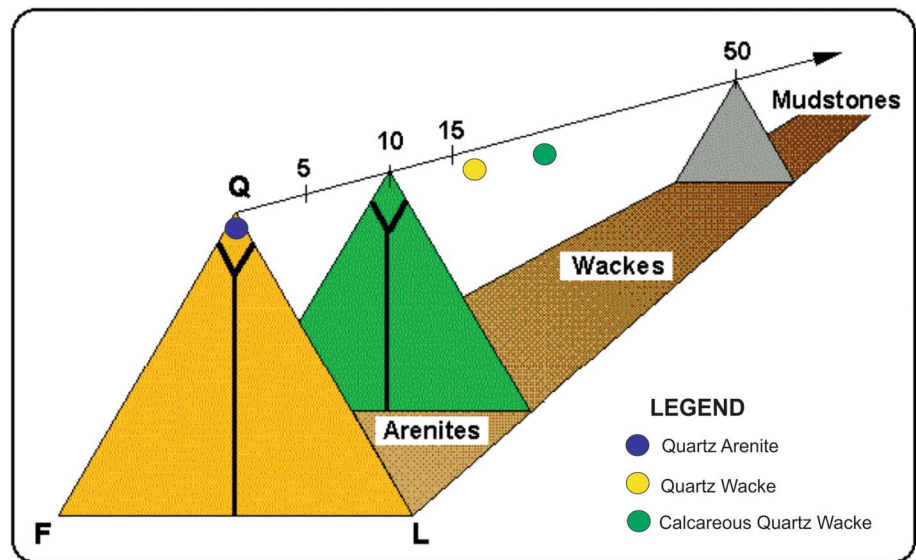
Calcareous quartz wacke sub-microfacies Field description: The field study revealed up to 3-m-thick bedded turbidite sequence encapsulated in the shale horizons.

Framework mineralogy: The fine-to-medium grained monocrystalline quartz constitutes 51.5% of this microfacies. The matrix supporting the quartz grain is lime mud. The modal composition of the sub-microfacies indicates calcareous quartz wacke. This microfacies is poorly sorted because of its wacke nature. The quartz grains are subangular to subrounded. The grains are loosely packed with point contacts (Figs. 3, 4).

Environmental interpretation: The graded sequence of this sub-microfacies suggests a turbidite origin on slope-deep basin. The poor sorting of the facies suggests deposition in the waning stage of turbidity currents. The decrease in grain size and the presence of calcareous matrix indicate the dominance of marine processes over the fluvio-deltaic. The subangular to subrounded grains of this facies suggest that the particles have been transported from reasonable distances.

Deep marine facies

Pelagic mudstone sub-microfacies Field observations: The macroscopic observations reveal that this sub-microfacies comprised hard splintery and nodular shale. The strata are dark gray color on fresh surface. In some intervals it has thick-bedded micritic limestone.

Microscopic observations: In thin sections, these rocks can be classified as mudstone. The total relative abundance of grains ranges from 2 to 6% with an average of 5%, while the relative abundance of matrix ranges from 94 to 98% with an average of 95%. The grains are composed of planktonic foraminifera, bioclasts and siliciclastic-rare quartz grains.

Intense burrows and extensive pyritization are seen in this microfacies (Fig. 3).

Environmental interpretation: The dominant presence of micritic matrix, rare planktonic foraminifera represent deposition in distal deep marine setting (e.g., Flügel 2004). The burrows represent benthic biological activity, suggesting the oxic bottom water conditions. The infaunal activity in the sediments is time dependent, i.e., lower rate of sedimentation provides sufficient colonization time for the burrowing organisms (Blatt 1992). However, the rare occurrences of planktonic foraminifera within foraminifera favored habitat suggest high rate of sedimentation for this microfacies. The deposition of 1000-m-thick strata during Maastrichtian shows overall high rate of sedimentation for the Mughal Kot Formation (Khan et al. 2017). The slumped beds in this sub-microfacies suggest the gravity induced contortion of the previously deposited rocks on such high-angle slope (see e.g., Chen et al. 2002).

Siliciclastic pelagic mudstone sub-microfacies Field observations: All the field features of this sub-microfacies are similar to the pelagic mudstone except no slumped blocks are seen in this facies. The associated sandstones are thinly laminated and are up to 3 cm thick. The mudstone contains weathered phosphate nodules.

Microscopic observations: The total grain content of the sub-microfacies ranges from 2 to 18% with an average of 10%, while the mixed carbonate and clay matrix ranges from 75 to 98% with an average of 90%. The planktonic foraminiferal component of the of this sub-microfacies ranges from 0 to 3% with an average of 1%, bioclast ranges from 0 to 3% with an average of 1.2% while peloids with an average of 2% constitute this microfacies. The quartz ranges from 2 to 18% with an average of 5.8% while sponges, calcisphere, organic

laths, glauconite are present in minor amount. Burrows and tempestites are observed under microscope (Fig. 3).

Environmental interpretation: The mudstones texture having pelagic fossils and clastic input indicates proximal deep marine setting (e.g., Flügel 2004). The presence of slumped calcareous mudstone suggests erosion from high angle slope settings, whereby the gravity contortion is dominant. The wavy to planer silt laminae suggest the reworking of prodelta storm activity (see e.g., Chen et al. 2002). The presence of tempestite, absence of slumped mudstone and the presence of quartz suggest proximal depositional settings probably the proximal part of the deep marine settings. The presences of organic rich horizons at places suggest localized anoxic water conditions.

Dynamic sequence stratigraphic model

Sequence stratigraphy is the relationship between eustasy, tectonics and sedimentation (Vail 1987). Generally, sequences are subdivided into system tracts on the basis of types of bounding surfaces, parasequence-set distributions and the position within sequences (Van Wagoner 1995). The sequence stratigraphic genetic units are lowstand systems tract (LST), transgressive systems tract (TST), highstand systems tract (HST) and maximum flooding surface (MFS) which are bounded by sequence stratigraphic surfaces (SB) (Emery and Myers 2009; Catuneanu et al. 2009). The sequence stratigraphic framework of the Mughal Kot Formation is established on the basis of the facies analysis and their interpretation. This framework is based on the fluctuation of sea level which is confirmed by the variation in depositional settings of the microfacies (give signals of fluctuation). The microfacies are subdivided based on the depositional settings which ultimately surmise the depositional sequences. Therefore, the facies variations are linked with the establishment of sequence stratigraphic framework.

The Mughal Kot Formation represents deposition in three different settings, i.e., middle shelf, deep slope and deep marine environment. The fluctuation in sea level causes the mix carbonate–sandstone deposits on three distinct depositional settings. The Pelagic mudstone sub-microfacies has been deposited in the distal part of deep marine environment while the Siliciclastic pelagic mudstone sub-microfacies has been deposited in the proximal part of deep marine environment. Siliciclastic bioclastic orbitoidal wackestone sub-microfacies shows deposition in the middle shelf environment. Similarly the Quartz Wacke, Calcareous Quartz Wacke and Quartz Arenite sub-microfacies have been deposited in the deep slope environment. In deep marine environment the energy conditions are low depositing fine-grained sediments. Middle shelf is relatively high energy environment and characterized by siliciclastic grains and orbitoides deposits. Microscopic

observations of these facies according to their suitable environments are given (see Fig. 3).

The planktonic foraminiferal biostratigraphy revealed a single biozone (Globotruncana, Globotruncanita and Heterohelix assemblage biozone) in the Mughal Kot Formation which designates that the rock unit is deposited in total time span of 6 million years (75–69 Ma; Khan et al. 2017). The ~ 1000-m-thick strata of the Mughal Kot Formation is divided into equal time slices by assuming the constant rate of sedimentation (see Khan et al. 2017). The Mughal Kot Formation is deposited in five different stages based on the sea level fluctuation and their effect on deposition (Fig. 5). The Stage-I represents the overall time of 0.4 Ma and shows an overall transgression and deposition of deep marine distal pelagic mud. This stage is succeeded by relatively sea level fall with deposition of middle shelfal facies along with proximal deep marine hemi-pelagic sediments of Stage-II with a time span of 1.4 Ma. The Stage-III shows fall in sea level below the offlap break point, resulting in the deposition of sandy turbidites on slope including sandstone. The total time of Stage-III deposition is 0.5 Ma. This stage of deposition is replaced by another rise in sea level and with reappearance of deep marine proximal hemi-pelagic sediments marking transgression. This transgression spans around 3.3 Ma. The sea level again falls and the sandstone on the slope setting shows the final stage, i.e., Stage-V of the deposition of Mughal Kot Formation representing 0.4 Ma.

Based on these stages of deposition and sea level fluctuation, we recognize that Mughal Kot Formation comprised one second and two third-order cycles. Local second-order cycle in Mughal Kot Formation is MLC-1 while it is comparable with global second-order cycle, i.e., UZA-4 (Haq et al. 1988; Fig. 6). The studied second-order supersequence is subdivided into two third-order depositional sequences that start from 75 to 69 Ma (Khan et al. 2017) with complete sets of Transgressive Systems Tract (TST), Highstand Systems Tract (HST) and Lowstand Systems Tract (LST). Two type-I sequence boundaries are marked based on facies that may represent correlative conformity (Fig. 6). The whole Mughal Kot Formation is marked by ten marine flooding surfaces with nine parasequences in fining upward sequence.

Sequence 1

The sequence 1 is 450 m thick. This sequence can be divided into TST, HST and LST. The deep marine Pelagic Mudstone is the basal part of sequence 1 which is overlain by mixed carbonate and sandstone of deep marine and slope deposits showing HST (Fig. 6). These sandstones have been deposited possibly during the waning stage of sea level after maximum rise in sea level. The final stage of this sequence is marked by LST showing clastic slope deposits which is
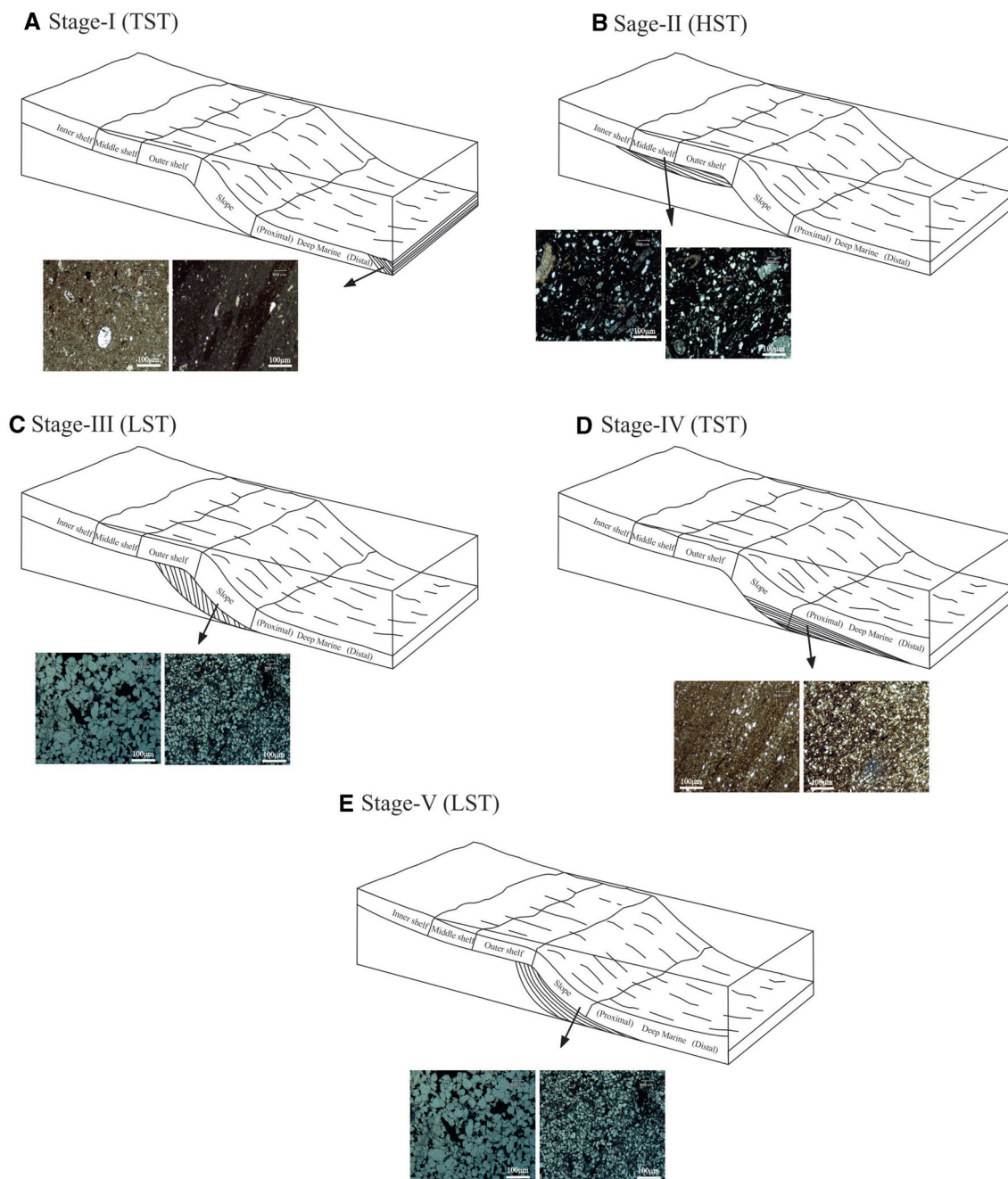
Fig. 5 Showing the deposition of Mughal Kot Formation in different stages with response to sea level fluctuation

marked by sequence boundary 1 with sea level fall below the offlap break point (Fig. 6).

Sequence 2

This sequence is thick up to 550 m. Similarly, it can also be divided into TST and HST/LST. The deep marine rocks of the Siliciclastic Pelagic Mudstone are interpreted as transgressive deposits formed during a period of sea level rise during TST (Fig. 6). The uppermost part of this sequence is marked by deep marine mudstone and slope sandstone with pulsated fluctuation in sea level showing HST/LST (Fig. 6). The evidence for the sequence boundary (SB2) is not prominent on outcrop scale because it corresponds to correlative part of the sequence boundary where the abrupt change in facies from deep marine to slope facies is recorded. Similarly, the upper part of Mughal Kot Formation shows the fall in sea level after maximum rise and may correspond to progradation associated with HST or LST (Fig. 6).
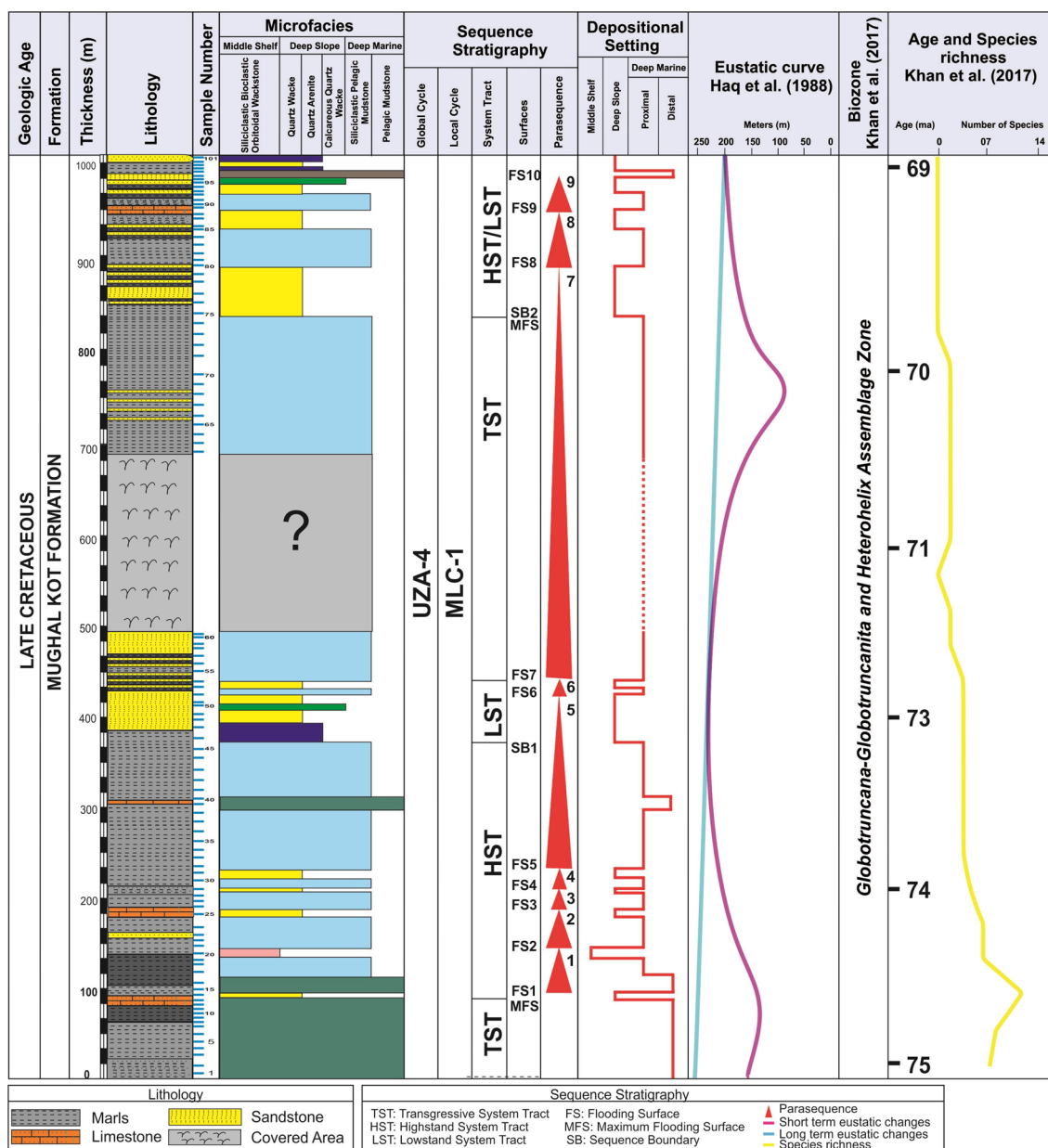
Fig. 6 Stratigraphic log showing varying lithology, distribution of microfacies types, sequence stratigraphy, eustatic curve, biozone and species richness of Mughal Kot Formation

Correlation with global sequence

The Mughal Kot Formation in the Mughal Kot section is deposited in 6 million years (75–69 Ma; Khan et al. 2017). The correlation of relative sea level constructed for the Mughal Kot Formation with eustatic curves in Fig. 6 shows a complete mismatch because of the local tectonic forcing of the cycles in the studied section. According to Carter et al. (1998) the global sea-level model comprises an assembly of local relative sea-level events which are widely recognizable within their parent sedimentary basin; and the sequence stratigraphic model is robust, and its application is therefore an insightful way to approach the interpretation of sedimentary rocks.

Table 1 Shows the plug porosity and permeability values of the lower, middle and upper part of the Mughal Kot Formation	Plugs poroperm				Reservoir potential
	Sample #	Lithology	Porosity %age	Permeability Ka Md	
	18	Sandstone	0.14	0	Nil
	17	Sandstone	0.31	0	Nil
	16	Shale	0.65	0	Nil
	15	Sandstone	0.09	0	Nil
	14	Sandy limestone	0.4	0	Nil
	13	Sandstone	2.99	1.63	Poor
	12	Sandstone	1.87	1.76	Poor
	11	Limestone	2.43	4.98	Poor
	10	Sandstone	0.02	0	Nil
	9	Sandstone	3.23	2.75	Poor
	8	Sandstone	0.01	0	Nil
	7	Shale	0.73	0.03	Very poor
	6	Sandy limestone	0.52	0	Nil
	5	Sandstone	0.076	0	Nil
	4	Limestone	0.032	0	Nil
	3	Sandstone	0.354	0.06	Very poor
	2	Sandy limestone	0.044	0	Nil
	1	Shale	0.05	0	Nil

Reservoir characterization

The hydrocarbon reservoir potential of a rock unit can be evaluated by various conventional methods and techniques. However, in the present study the reservoir characterization of the Mughal Kot Formation is occluded on the integration of petrographic studies and plug porosity and permeability data. According to the petrographic studies, low porosity and permeability is characteristic of carbonate microfacies while no significant porosity values have been observed in the sandstone facies, providing very less chances for the accumulation of hydrocarbons in this mix carbonate–sandstone hemi-pelagic sequence. Carbonate facies mainly comprised matrix with very less clastic inputs and no sign of secondary porosity (Fig. 3g–l). Bioturbation and organic laths have been observed in most of the carbonate microfacies which result in the destruction of original primary porosity in the strata (Fig. 3i, l). Siliciclastic bioclastic orbitiodal wackestone sub-microfacies exhibits abundance of clastic grains with pore spaces filled by micritic matrix, resulting in reduction in porosity (Fig. 3g, h). Sandstone facies of the Mughal Kot Formation mainly comprised quartz with matrix. Quartz wacke sub-microfacies is poorly sorted, having angular grains and less roundness with matrix favoring the less potential zone (Fig. 3a, b). Quartz arenite sub-microfacies, however shows rounded grains, good sorting and high content of quartz grains; pore spaces between the grains are vanished by suture contacts and clay matrix (Fig. 3c, d). The plug porosity and permeability tests of the 18 samples from the lower, middle and upper part of the formation were carried out. The quality of a reservoir as determined by permeability, in mD, may be judged as: very poor if $k < 1$, poor if $1 < k < 10$, fair if $10 < k < 50$, average if $50 < k < 200$, good if $200 < k < 500$ and very excellent if $k > 500$ mD (Peters 1986). The porosity/permeability tests of the Mughal Kot Formation show porosity range from 0 to 3.23% while permeability ranges from 0 to 4.98 Ka mD (Table 1). The plug porosity/permiability data suggest that the overall reservoir potential of Mughal Kot Formation may be ranked as very poor.

Conclusions

Based on detailed field investigations and petrographic studies, the following conclusions have been revealed:

- Three major depositional facies are identified from the Mughal Kot Formation at Mughal Kot section which is further subdivided into six sub-microfacies based on the depositional settings, i.e., siliciclastic bioclastic orbitoidal wackestone, pelagic mudstone, siliciclastic pelagic mudstone, quartz arenite, quartz wacke and calcareous quartz wacke.
- The siliciclastic bioclastic orbitoidal wackestone sub-microfacies was interpreted to be deposited in open middle shelf depositional setting. The quartz arenite, quartz wacke and calcareous quartz wacke show the deposition in the deep slope settings while the pelagic mudstone and siliciclastic pelagic mudstone show the deposition in the

distal and proximal deep marine environment, respectively.

- The Mughal Kot Formation is overall deposited in the five different stages which are based on the fluctuation of sea level in the Maastrichtian time due to local shift in tectonics.
- One second-order depositional cycle while two third-order cycles with complete sequence of TST, HST and LST has been recognized in Mughal Kot Formation.
- Ten marine flooding surfaces, nine parasequences and two type-I sequence boundary have been interpreted in the rock unit.
- The petrographic studies argumented by plug porosity/permeability data indicate low porosity/permeability in both carbonate and clastic part of the formation, hence the petroleum reservoir potential of the studied unit is very poor.

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