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Lithofacies analysis and economic mineral potential of a braided fluvial succession of NW Himalayan foreland basin Pakistan

Abbas Ali[1,2] · Jiayong Pan[1] · Jie Yan[1] · Ahmad Nabi[1,2]

Abstract

This study has described detailed lithofacies analysis, clay mineralogy, and depositional setting, and highlighted economic mineral potential of late Miocene to Early Pliocene mid Siwalik Dhok Pathan Formation. The Siwalik fluvial sedimentary succession is 5300 m thick in the NW Himalayan foreland fold-and-thrust belt known as Surghar-Shingar Range (SSR). The middle Siwalik (Dhok Pathan Formation) typically represents cyclic alternation of massive sandstones, siltstones, mudstones, and claystones in repeated fining upward rhythm with varied thicknesses from 807 to 1540 m. Detailed sedimentological investigations resulted in the identification of seven distinct lithofacies (Gt, St, Sh, Ss, Sl, Fm, and Fl) which had been deposited by sand-dominated bed load braided fluvial system. The facies Sh is hosting detrital uraninite identified through a scanning electron microscope (SEM). X-Ray diffraction analyses revealed that kaolinite, smectite (montmorillonite and saponite), illite, vermiculite, and chlorite (clinochlore and chamosite) are the main clay mineral suits present in the formation. The morphology of clay mineral suits is indicative of weathering products or contribution from the source areas. The absence of glass shards and mineral analcimolite evidenced that these smectite group clay minerals were not derived from the devitrification of volcanic ashes. The sedimentological analysis, mineralogical composition, and paleo-flow directions revealed that these sediments had been deposited by NS fluvial system presently known as Indus River system in this area. The rare earth element concentrations of sandstone and heavy minerals laminations (black sand) show enrichment of uranium (662 ppm), thorium (1374 ppm), La (975 ppm), Ce (2831 ppm), Pr (193 ppm), Nd (746 ppm), Gd (98 ppm), and Dy (50.8 ppm), which specify good indicative economic mineral potential of the formation.

Keywords Siwalik Group · Clay mineralogy · Depositional environments · Detrital uraninite · Surghar range

Introduction

Lithofacies analyses are significant to know the depositional environments of the sediments as characteristic lithofacies can only be produced by particular sediment depositional environments. Sedimentary lithofacies analysis has been considered an important exploration tool for many syndepositional mineral deposits such as pollymetallic gold and base metal, uranium, and rare earth element (REE) deposits. The detailed

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lithofacies analyses are helpful in predicting the favorable strata for certain mineral accumulation and estimation of their economic resource potential, thus providing basis for mineral exploration program.

The India-Eurasia collision created bending of slices of Indian plate due to collisional tectonic loading resulted in the form of a peripheral basin south of the emerging Himalayan Ranges (Valdiya 2016). This peripheral basin is known as Himalayan foreland basin. This basin spans over > 2000 km from Nepal in the east to Pakistan in the west (Ullah et al. 2009; Goswami and Deopa 2018; Fig. 1d). The SSR is a part of NW Himalayan foreland basin (fold-and-thrust belt) lying west of the Indus River, apparently as western extension of the Salt Range displaced by an active dextral strike-slip fault known as Kalabagh Fault (Fig. 1c). The SSR is the north-south-oriented parallel ranges flanking the northeastern margin of Bannu Basin (Fig. 1c). The Surghar Range is characterized by pre-Siwalik sediments, escarpment ridges facing
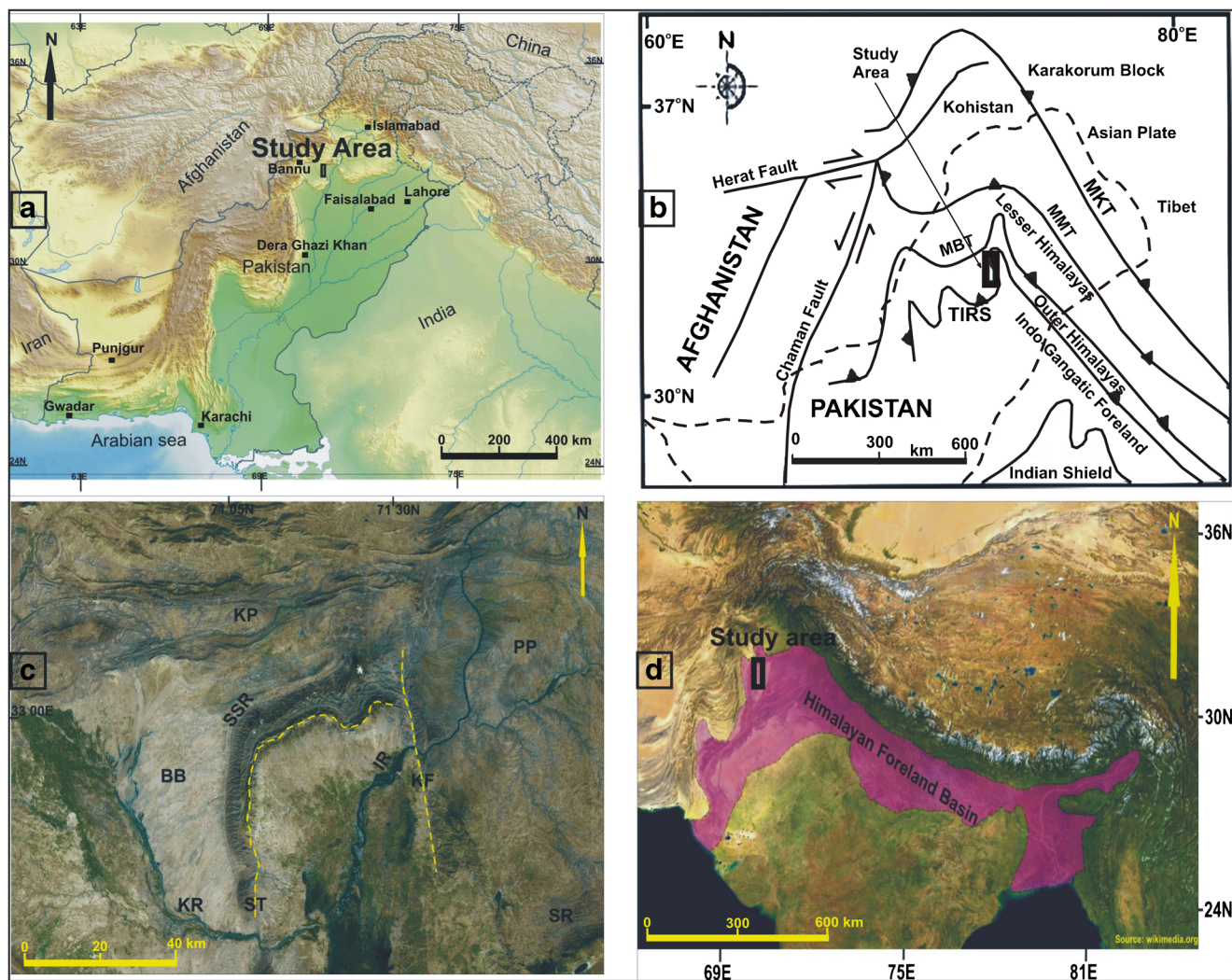
Fig. 1 **a** Regional map of Pakistan depicting location of the study area. **b** Tectonic map of NW Pakistan (after Ali et al. 2014). **c** Zoom earth satellite image of SSR and surrounding areas. BB Bannu Basin, PP Potwar Plateau, KP Kohat Plateau, KF Kalabagh Fault, IR Indus River, KR Kurram River, SR Salt Range, ST/SF Surghar Thrust/Fault, SSR Surghar Shingar Range, MKT Main Karakoram Thrust, MMT Main Mantle Thrust, MBT Main Boundary Thrust, MFT Main Frontal Thrust, TIRT Trans-Indus Range Thrust. **d** Himalayan foreland basin (purple color)

the Indus River towards the east, and the Shingar Range mostly comprises Siwalik sediments facing the Bannu Basin towards the west. Thus, the term Surghar-Shingar Range is applied for the same range (Danilchik and Shah 1987). The SSR is also termed as Trans-Indus Salt Range. The India-Eurasia collision has produced plenty of detritus which has subsequently deposited in the foreland basin and recorded precious information of Himalayan orogeny in terms of paleo-climate and drainage frameworks in time and space (Najman 2006). The molasse sediments accumulated in Himalayan foreland basin during the third and most intense phase of deformation during the middle Miocene to Pleistocene. These freshwater molasse sediments after deposition underwent tectonic phases and emerged as distinct identity known in literature as the "Siwaliks" or "Siwalik Hills" (Chauhan 2003).

Stratigraphy committee of Pakistan has divided Siwalik Group rocks into three subgroups: lower, middle, and upper in accordance with their lithological make-up and further subdivided into formations (Shah 2009). The lower Siwaliks (Kamlial and Chinji Formations) represent mudstone-dominated sandstone-mudstone succession. The middle Siwaliks (Nagri and Dhok Pathan Formations) are mainly sandstone dominated over siltstone-mudstone and clay. The sandstone units are coarse to fine grained (generally medium grained), light gray, bluish gray, massive, and multistoried. The upper Siwalik (Soan Formation) is mainly conglomeratic in nature. These sedimentary deposits are 5300 m thick while the thickness of the Dhok Pathan Formation varies from 807 to 1540 m in study area. The formation shows alternate fining upward sedimentary rhythms of shale, siltstone, and sandstone units. According to magnetostratigraphy studies of Khan and

Opdyke (1987), age of this formation in this area is 7.5–2.5 Ma. The formation is also well developed and exposed in other parts of the country like Kohat-Potwar plateau and Kirthar and Suleiman fold-and-thrust belts (Shah and Hafeez 2009; Ullah et al. 2009). Barry et al. (2002) have assigned 10.1–3.5 Ma age to this formation in Potwar Plateau based on faunal study.

Placer deposits are the secondary deposits formed due to the accumulation of economic detrital mineral grains under the action of gravity or by the tractional current of flowing water of streams and rivers and deposited as heavy mineral accumulations within sedimentary sequences mostly low grade and small in size. The lowest cut-off of grade from bulk sand is about 1% heavy minerals. Worldwide > 360 placer REE deposits have been identified (Orris and Grauch 2002). Monazite is one of the most important REE-bearing mineral found in placers along with certain amounts of allanite, pyrochlore, loparite, xenotime, euxenite, knopite, fergusonite, and samarskite (Möller 1986).

The provenance of Siwalik sediments of this area is considered to be the Himalayan rocks. The NW Himalaya has diverse geological environments with complex evolution history. The placer/detrital concentration of thorian-uraninite, scheelite, and gold has already been reported many hundred miles downstream of river Indus (Davidson 1962; Malik et al. 2004). From the feeding streams of Indus River, the extraction of gold by gold washers using primitive tools has been practiced since a long period in the region (Shah and Khan 2004). The Siwalik group rocks of the Kohat-Potwar province have been studied by many researchers in different perspectives (Johnson et al. 1985; Quade et al. 1989; Flynn et al. 1995; Barry et al. 2002; Basu 2004; Shah and Hafeez 2009; Ullah et al. 2009 etc.), but the Siwaliks of SSR have not been paid much attention to evaluate their economic potential to host placer mineral deposits. Previously, Azizullah and Khan (1997) reported high radioactivity and carnotite mineralization from this formation in the northern part of the present study area. After the identification of uranium mineralization, this area was partially studied for its potential to explore sandstone or surficial uranium deposits. But still, this area is virgin in terms of placer/economic mineral exploration. We have made an effort on this segment of SSR with the aim to contribute detailed database on lithofacies characters, clay mineralogy, depositional settings, and potential for placer mineral as well as sandstone-type uranium deposit exploration.

Geological setting

The continent-continent collision of India-Eurasia which had started in the Paleogene time gave rise to the mighty Himalaya (Powell 1979; Beck et al. 1995, 1996). The continual southward folding and overthrusting of Indian plate blocks during this India-Eurasia collision resulted in the formation of NW Himalayan foreland fold-and-thrust belts (Blisniuk et al. 1998). From latest Cretaceous to early Tertiary, due to this collisional tectonics, the thrusting has been progressively being shifted southwards (Yeats and Hussain 1987) and transpired youngest frontal thrust system, i.e., the Salt Range and the Trans-Indus Salt Range (TISR) to the east and west of modern Indus River respectively (Fig. 1b, c).

In north Pakistan, the SSR is characterized by outermost Himalayan foreland fold-and-thrust belt (Powell 1979). The range displays NS configuration on bordering the eastern boundary of Bannu Basin and transforms into EW trend while margining the southern periphery of Kohat-Plateau (Rehman et al. 2017; Fig. 1b).

The SSR forms asymmetrical, overfolded anticlinal structure plunging to the south near the Kurram River, with Permian strata exposed in the core, overlain by Mesozoic and Paleogene rocks (Akhtar 1983). The western limb of the range is well exposed (present study area), while its eastern limb is deeply eroded exposing older formations. The Surghar thrust corresponding to the Salt Range Thrust is expected to continue along the axis of the Surghar anticline bringing Punjab foreland alluvium in contact with Neogene rocks in the south to Permian and Mesozoic rocks in the north (Gee 1989). After uplift of the area, headward erosion of streams produced the steep cliffs and rugged topography of the SSR, and the material eroded from these mountains is being deposited on the adjacent Bannu and Indus plains (Danilchik and Shah 1987). The end of marine sedimentation in SSR is marked by the deposition of fluvial rock units of Siwalik Group. The base of lower Siwalik is discernible by the presence of a thick conglomerate bed mainly composed of pebbles and boulders of Eocene formations.

Materials and methods

i. Twenty surface sandstone and heavy mineral samples collected along sections (marked A, B, C; Fig. 2) were analyzed for uranium, thorium, and REE concentration on ICP-MS analysis at Beijing Research Institute of Uranium Geology (BRIUG), Beijing, China, and Pakistan Atomic Energy Commission analytical labs. The same samples were also studied on SEM (scanning electron microscope). With due care, 14 grain-mounted thin sections were prepared as the sandstones were soft and friable and studied under a petrographic microscope for their modal composition.

ii. Geological map (Fig. 2) has been prepared with the help of high-resolution satellite data (2.5 m per pixel Spot-5, and ArcGIS 10.2). Three (3) lithostratigraphic cross sections were studied at appropriate places where the formation is well exposed (marked as A, B, and C on Fig. 2).

Various depositional cycles and fluvial facies associations were recorded. Detailed analysis of lithofacies characteristics of different sandstone and mudstone units were carried out by following the facies model of Miall 1978. The paleo-current studies were carried out according to the method of DeCelles et al. (1983). NL-372 Nikon total station was used for measuring lithostratigraphic profiles to achieve higher accuracy levels and data were plotted by using AutoCAD 2015 software.

iii. Clay-mineral analyses of mudstones and sandstones (20 samples), representing different stratigraphic units of Dhok Pathan Formation were carried out. To deduce the original clay mineral composition of the source areas, unweathered samples were collected with due care. To understand the bulk mineralogy, all these samples were ground to 200 μm size by using non-iron manual grinder (mortar and pestle). Oriented clay slides were prepared following the Stock's law. The XRD analyses were carried out on natural (powder 200 μm), oriented, glycolated, and heated (400–550 °C) samples on Bruker D-8 X-ray unit with Ni-filtered Cu-radiation (Cu tube with 1.5418 Å) target. The associated diffraction peaks were studied according to the Carroll 1979. Additionally, for better visualization of mineral replacements and authigenic grain coatings (18 gold-coated samples), morphological behavior of clay mineral images were taken by using SEM (Nova NANOSEM 450).

The XRD, SEM, and petrographic analysis were carried out at "State key laboratory, Breeding Base of Nuclear Resources and Environment, East China University of Technology" (ECUT), Nanchang, China.

Results

Lithofacies analysis

The formation is generally comprised of seven distinct lithofacies such as gravely sandstone (Gt), coarse-grained sandstone (St), fine- to medium-grained sandstone (Sh), fine sandstone facies (Sl), scour fill coarse sand (Ss), massive mudstone (Fm), and siltstone and claystone (Fl) typically representing repeated fining upward sedimentary succession. The sand/clay ratio varies from top to bottom and north to south of the studied sections. The lithofacies recognized are described as below:

Gravely sandstone

The facies is marking the base of each fining upward cycle as erosive basal surface (Fig. 3c, d). Trough cross-bedding is present in the facies. The thickness of the facies varies from north to south in the studied sections. It is present as stratified gravel bed in the northern part and as matrix supported gravel unit towards the south. Their thickness and frequency both decrease towards south. It is mainly composed of clasts of igneous-metamorphic origin with some claystone clasts. The facies is poorly sorted and the clast size varies from less than 1 cm to more than 5 cm. These clasts are generally rounded in shape with some exception of spheroidal, tabular, to elliptical. The upper contact with coarse-grained sandstone facies St is generally gradational while the lower contact is always sharp and erosive. The clasts are generally stacked parallel to bedding; however, imbrications are also present. The extra-formational nature of the clasts differentiates it from the overlain coarse-grained sandstone facies St.

Coarse-grained sandstone

The thickness of this facies varies from 2 to 40 m with maximum thickness (40 m) in the middle part of the formation. It is less thick in the upper part of the formation ranging from 3 to 6 m. Weathered color is yellowish gray, reddish gray, or greenish gray due to strong limonitic/hematitic alterations while fresh color is ash gray to light gray (Fig. 4d). The sandstone is generally medium to coarse grained, occasionally very coarse grained containing intra-formational clay clasts and rounded to subrounded extra-formational lithic clasts of igneous-metamorphic origin which may range up to 7 cm in size. The facies is soft to friable; however sedimentary concretions in the form of rounded balls of up to 4-cm diameter (Fig. 4c) and concordant, lenticular hard bands of maximum 20-cm thickness are present throughout the formation. The facies is packed into cross-bedded sets and cosets with moderate to poor sorting (Fig. 3e, f). The small scale cross-bedded units (< 0.5 m wide) commonly present though large scale troughs (> 1 m wide) are dominant. Usually, a thin lag of poorly sorted sand with intra-clasts of siltstone-claystone is present at the base of troughs and rarely isolated igneous-metamorphic clasts occur within the bodies of sets. The facies is typically displaying multistorey nature in which thickness of each storey varies from few meters to tens of meters. The facies occurs as sheets of sandstone that are stacked into trough cross-bedded cosets. Its lateral extension is several hundreds of meters. The upper contact with facies Sh is flat and gradational while the lower contact with facies Gt is either gradational or erosive with facies Fm of underlying cycle.

Fig. 2 Detailed geological map of NS segment of Surghar-Shingar Range, the study area
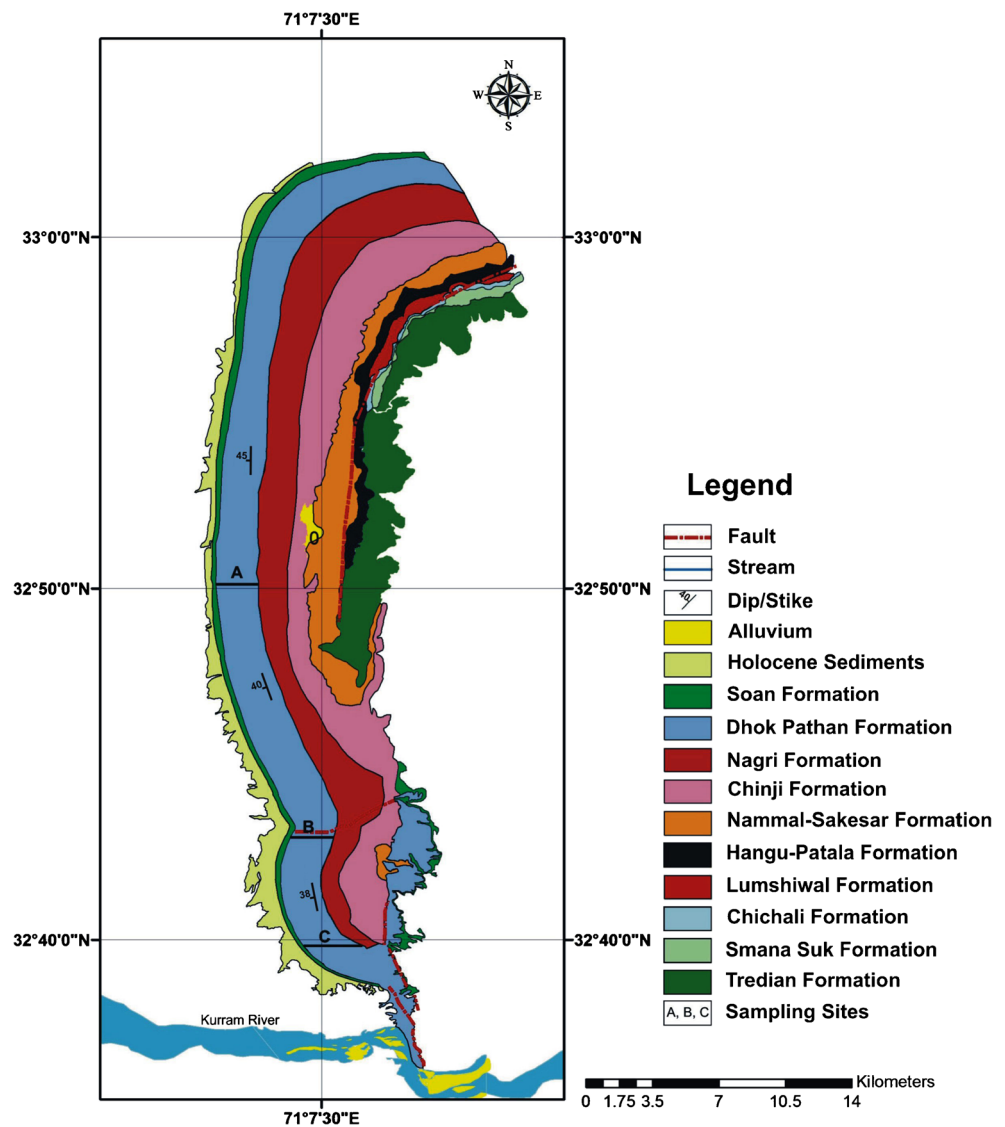

Fine- to medium-grained sandstone

This facies varies in thickness from 2 to 71 m with maximum thickness in the upper part of the formation. Weathered surfaces are yellowish gray or reddish gray or greenish gray due to limonitic/hematitic alterations while fresh color is ash gray to light gray. The sandstone is generally fine to medium grained, occasionally locally derived intra-formational clasts are present. The facies is soft to friable; however, occasional sedimentary concretions in the form of concordant, lenticular hard bands of maximum 40-cm thickness are also observed. The facies is moderately sorted and packed into flat, parallel, horizontal laminated sandstone units (Fig. 4b). The micaceous siltstone laminae are present as parting lineation within sandstone units exhibiting a sheet-like as well as tabular geometry. Individual beds are traceable over several tens of meters. The upper and lower contacts of this facies with the overlying and underlying facies are gradational. This facies contains detrital uraninite in sandstone and thick layers of heavy mineral accumulation (black sand) which are rich in urano-thorite and light REEs (Figs. 3b and 4b; Table 2).

Fine sandstone facies

The facies (Sl) occurs as wedge-shaped, tabular, or lenticular beds with variable thickness from 1 to 6 m. Generally, medium- to fine-grained sandstones predominate but very fine–grained sandstones also occur locally. Intra-formational debris, granules, and extra-basinal clasts are uncommon. The bedding characteristics of this facies are similar to the facies Sh. The distinguishing factor is the presence of low-angle cross-beds (8–11˚). The parting lineations are present and their orientation is usually slanted to the dip of cross-beds.

Fig. 3 Characteristic features of Dhok Pathan Formation: **a–b** thick, massive sandstone units; **c** gravelly horizon, facies Gt; **d** intra- and extra-formational conglomerates along erosional surfaces; **e** mosaic of large scale trough cross-bedding, facies St; **f** multiple small-scale trough cross-bedding in facies St
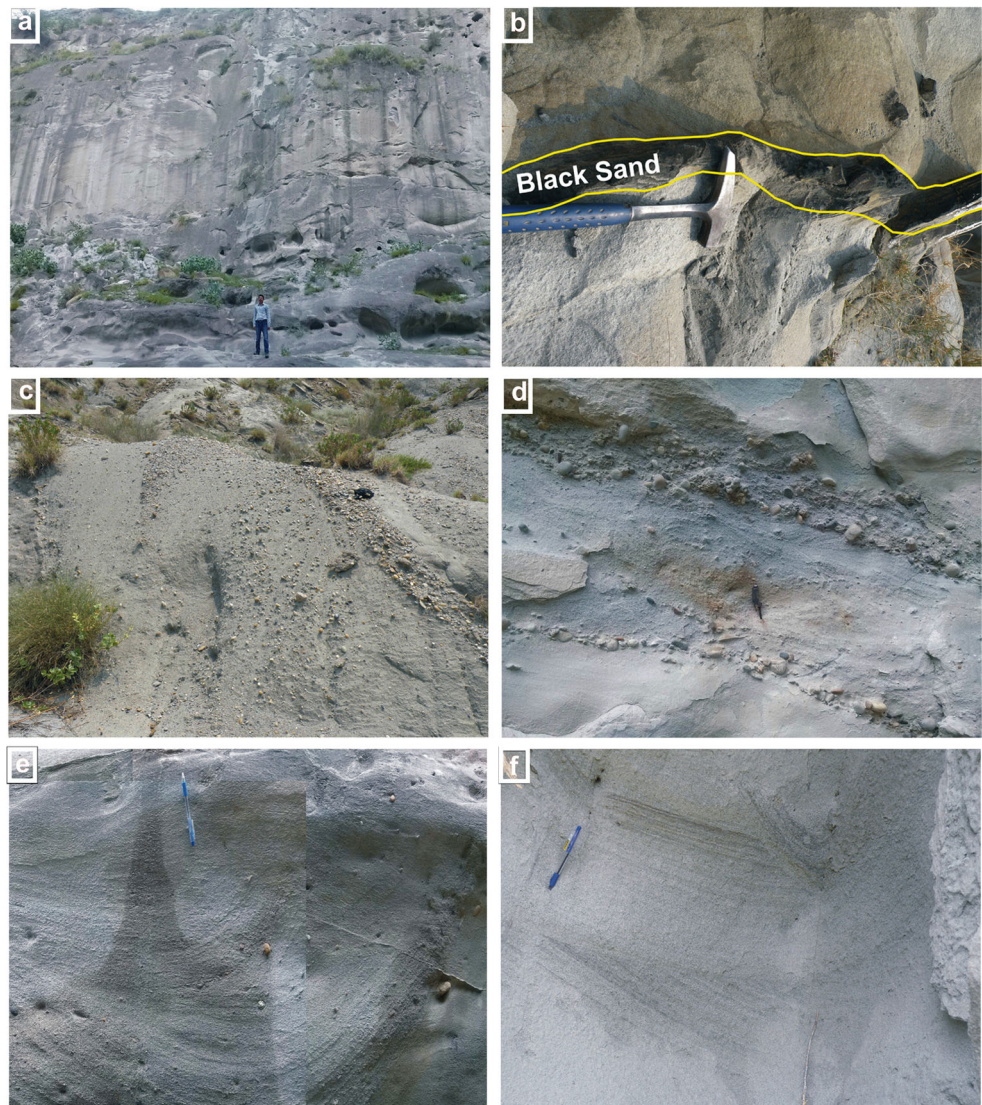
Scour fill coarse sand

The thickness of this facies range from < 1 m to ≳ 4 m. Thesandstone is generally coarse to very coarse grained, soft to friable and poorly sorted (Fig. 3d). Weakly developed cross-bedding and abundant intra-formational clasts, exotic pebbles, and granules of claystone are observed. At places, it is hard to distinguish between facies St and Ss. Individual beds are traceable over several tens of meters. The upper contact with the overlying facies is generally gradational while the lower contact with underlying facies Gt is sharp.

Siltstone and claystone

This facies consists of parallel-laminated claystone interbedded with siltstone. The contact relationships of facies Fl are mostly gradational with underlying facies Sh or Sl and overlying facies Fm. The facies exists as thick sheet-like bodies and laterally persistent for hundreds of meters. Variable thickness of strata of this facies is observed from north to south in the study sections. In the northern part, laterally persistent thin beds of fine-grained sandstone are observed. Weak sedimentary structures (ripple marks) are present in the sandstone horizons.

Massive mudstone

This facies is thin to thick bedded present with different thickness at different intervals from bottom to top of formation. The thickness ranges from less than 1.0 m to more than 100 m (Fig. 4e) with extensive sheet-like geometry. The color varies from orange red to reddish brown to maroon, at some places greenish gray and greasy. It becomes dirty brown, gray, and silty with strong limonitic alteration along fracture planes. The upper contact is always sharp and erosive while the lower contact with facies Fl is gradational. Desiccation cracks,

Fig. 4 a Planner cross-bedded sandstone facies. b Horizontally bedded/laminated sandstone facies Sh. c Rounded and lenticular sedimentary concretions. d Strong hematite alterations along wood logs and clay balls. e Massive mudstone facies Fm. f Load structure at shale/sandstone contact
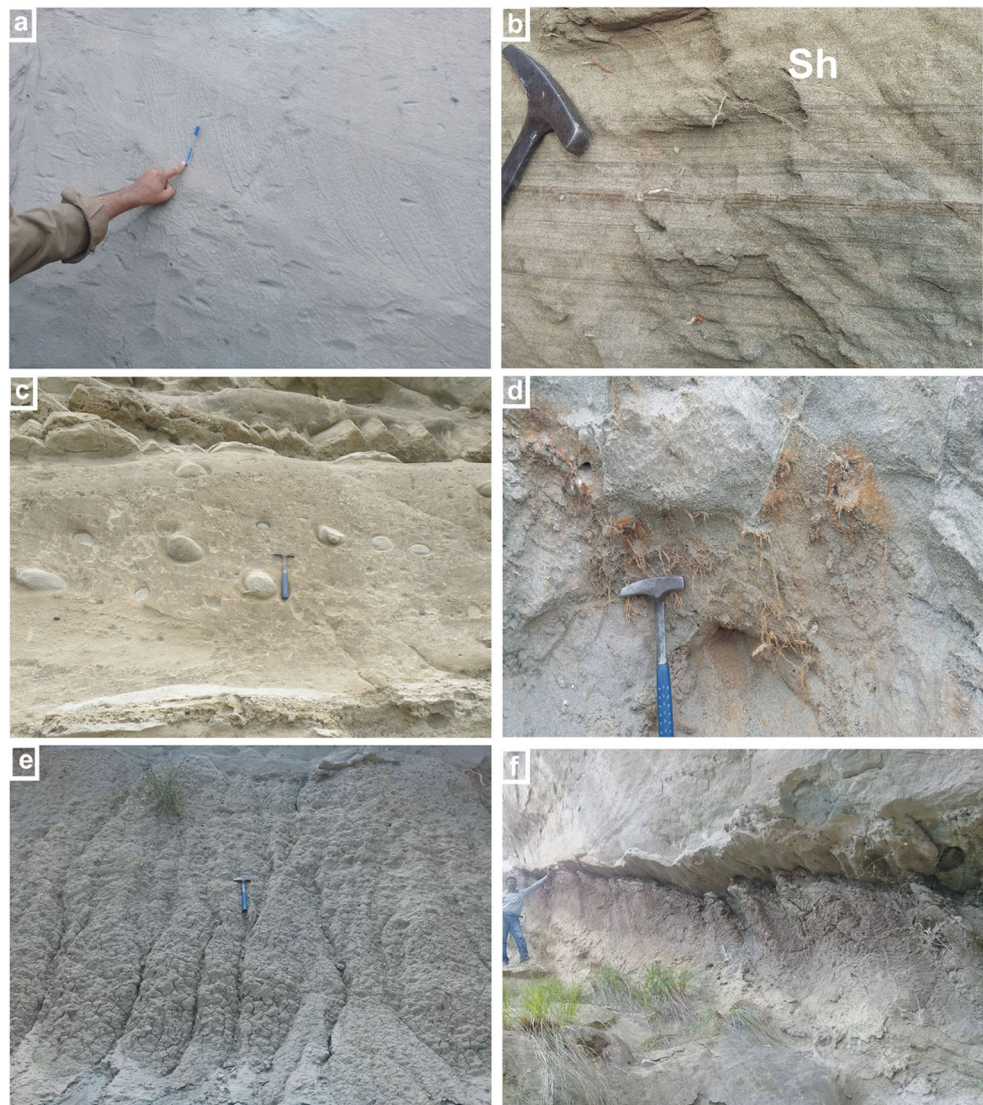
carbonaceous streaks, plant roots, and burrows are commonly observed.

Clay mineralogy

Both allogenic and authigenic clay minerals occur in the Dhok Pathan Formation. Kaolinite, smectite (montmorillonite, saponite), illite, vermiculite, and chlorite (clinochlore, chamosite) are the main clay mineral suits identified occurring in varying amounts and different morphologies. Allogenic clay minerals were emplaced during the deposition of Dhok Pathan Formation. Their distribution, shape, and size are plausibly controlled by physical and biogenic process while authigenic clay minerals were formed during the diagenesis from rapidly altering minerals such as potassium feldspar. The different clay minerals suits present in Dhok Pathan Formation are as described below:

Kaolinite

The prominent clay mineral in Dhok Pathan Formation is kaolinite occurring in both forms, i.e., authigenic and allogenic. The X-ray powder diffractogram profiles with 7.098 Å, 7.076 Å, and 3.539 Å reflections (Fig. 5) are characterized by kaolinite which became amorphous upon heating at 500 °C and remained unaffected with glycol saturation. The conversion of crystalline variety into amorphous upon heating is one of the confirmatory tests of kaolinite (Carroll 1979; Ghazi and Mountney 2009). SEM images show different morphologies of kaolinite. Allogenic kaolinite encrusted on silt-sized quartz grains are associated with channel and bar facies and thus form component of matrix. In floodplain facies association, it occurs as mixture with illite and smectite. The authigenic kaolinite in channel and bar facies association occurs in book-like morphology (Fig. 6a). The kaolinite occurs in association with feeble amounts of quartz, illite, and organic
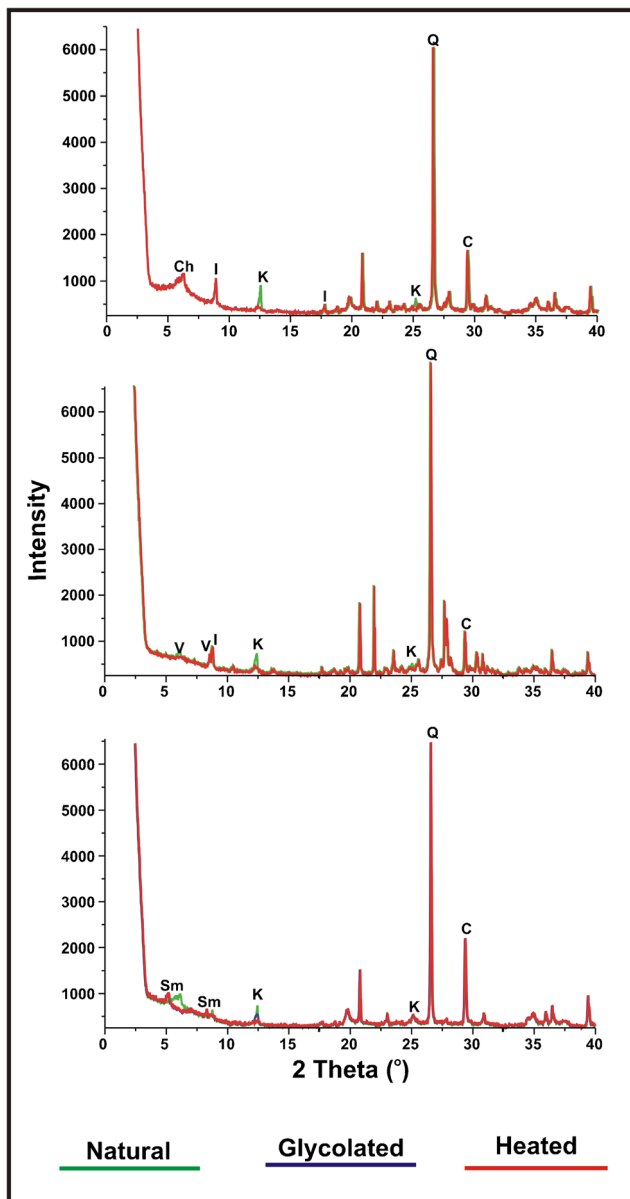
Fig. 5 XRD analysis of Dhok Pathan Formation, SSR, Pakistan. Kaolinite (K), smectite (Sm), vermiculite (V), illite (I), chlorite (Ch), quartz (Q), and calcite (C)

matter at the top of depositional cycles which is weakly crystalline. The diagnostic feature of crystallinity of kaolinite is resistance to heat treatment and sharp XRD patterns (Ghazi and Mountney 2011). The low-pH groundwater action on detrital alumino-silicate (feldspars, micas, rock fragments, heavy minerals, and mud intra-clasts) in continental sediments form kaolinite in humid climate (Emery et al. 1990). The main variables which control the amount and distribution of kaolinite are fluid flow rates, concentration of unstable detrital silicates, hydraulic conductivity, and annual precipitation. In permeable channel sand deposits, eogenetic grain dissolution is most common. Potassium feldspar is less prone to the process

of kaolinization than albite and calc-plagioclase (Worden and Morad 2003). In humid conditions, large quantities of meteoric waters are available that support the formation of kaolinite.

Smectite

Montmorillonite and saponite are two main smectite group minerals identified on XRD patterns by 14.573 Å reflections which show transformation to 17.541 Å on glycol saturation and collapse to 10 Å on heating at 450 °C (Fig. 5). The smectite crystallites in smectite aggregates show a wide range of variations in the morphological features. Distinctions among smectite aggregates can be made on the basis of the habit and arrangement of individual crystallites. In this regard, a distinction should be made between internal (structural) and external factors. The internal factors are related to the crystal structure and to its imperfections such as dislocations. The major external factors are temperature, pressure (hydrostatic), degree of disequilibrium (super saturation, concentration, and diffusion gradients) and viscosity of the medium, and the presence of impurities. During the crystallization of layer silicates, the internal factors seem to be strongly effective, leading to the prominence of lamellar forms (Güven and Pease 1975).

SEM images reflect different morphological features, modes of aggregations, and crystal structures of smectite minerals which are significantly related to their rheological behavior and other physical properties. Different habits of smectite crystallites are depicted in Fig. 6c–e with their predominant forms as: (a) lath-shaped particles: these are genuine laths or laths formed by folding of thin lamellae; (b) cellular dendrites: these dendrites resemble a honeycomb in which the branches have strictly defined orientations; (c) spherulites: these consist of a bundle of radiating needles or lamellae according to the classification of dendrites Saratovkin (1959).

In some cases the morphological features of the aggregate may be inherited from the parent volcanic glass, with the devitrification process altering the mineralogy but not the texture. The smectite minerals seem to be developed under the effect of seasonal climate changes or transported with the sediments to the basin from the stream catchment areas which are also evident from the absence of any glass shreds in the studied samples.

Illite

The X-ray powder diffractogram profiles with 10.048 Å, 10.018 Å, 4.996 Å, and 3.567 Å reflections (Fig. 5) are characterized by illite. Illite minerals remained unchanged upon glycol saturation. However, samples profiles slightly collapsed upon heating at 400 °C. Illite is present as detrital grain as an authigenic phase and as alteration product of kaolinite, micas, and feldspars. It showed irregular flakes with lath-like

Fig. 6 Scanning electron micrographs of different clay minerals. **a**–**b** Stacked plates and lath-like morphology of kaolinite. **c**–**e** Dendritic, spherulite, and honeycomb morphologies of smectite clay minerals. **f** Cabbage head–like morphology of chlorite. **g** Lath-like morphology of vermiculite. **h** Adsorption of illite clay mineral around quartz grain
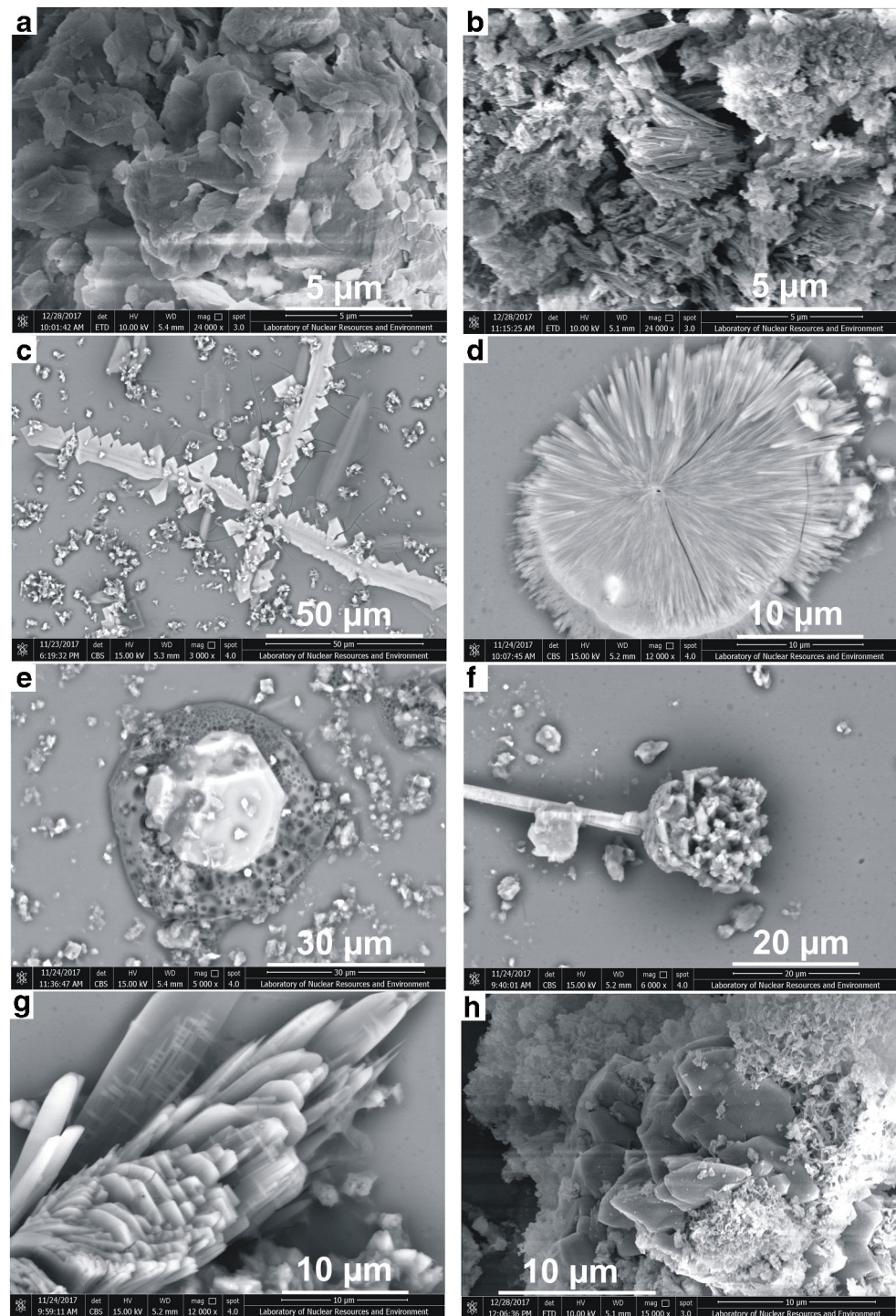
morphologies on SEM images (Fig. 6h). The lath morphology of illite depends on its development mechanisms whether it has developed as sheets which bend from attachment point or attached to sand-grain surfaces. At increasing temperatures and under alkaline conditions, illite is stable in the presence of kaolinite. Illite may also be formed around 100 °C temperature due to smectite degradation. The main source of potassium for illitization process during diagenesis was the potassium feldspar (Bertier et al. 2008).

Vermiculite

The X-ray powder diffractogram profiles with 14.24 Å reflections that collapse to 10 Å on heating at 400 °C and remained

unaffected on glycol saturation (Fig. 5) are characterized by vermiculite. SEM images show lath-like morphology (Fig. 6g). Clay-sized vermiculite and vermiculite layers interstratified with mica or chlorite layers are quite common in soils where weathering is not overly aggressive (Barshad and Kishk 1969). The removal of potassium from biotite, muscovite, and illite or the brucite sheet from chlorite generally gives rise to the formation of these clays. Some of the expanding physils in soils have the attributes of vermiculite, some of smectite, and some have features of both (Weaver 1989).

Artificial weathering of biotite (Ismail 1969) showed that oxidation of ferrous iron was independent of pH; however, under neutral and alkaline conditions, iron oxidation caused a large decrease in layer charge and a smectite formed; under acid conditions, the charge decrease due to the oxidation of ferrous iron was balanced by the loss of octahedral Fe and Mg and a highly charged vermiculite material was formed. Therefore, vermiculite formed in more humid environments. This suggests development of vermiculite under humid conditions due to the removal of potassium from micas.

Chlorite

Clinochlore and chamosite are the chlorite clay group minerals identified through XRD and fall at 14.244 Å and 3.543 Å reflections on diffractogram (Fig. 5). The clay-minerals remained unchanged upon heating at 400 °C and treating with glycol. In the sandstones, it occurs as pore lining or may change its form as plates which attached to detrital sand particles (Hayes 1970). SEM images of samples revealed cabbage-head-like morphology (Fig. 6f). There are three recognized processes of authigenic chlorite in sandstones. These are transformation of clay minerals, replacement of non-clay minerals, and precipitation from pore fluids, i.e., neoformation. The ferromagnasium minerals such as basic volcanic rock clasts, biotite, amphibole, heavy minerals, and also feldspars can be replaced with chlorite on reaction with pore waters (Anjos et al. 2003). Smectite group clay minerals gave birth to magnesium-chlorite while ferroan-chlorite owes their origin from 7 Å verdine-chamosite-odinite clays (Hillier 1994). The syngenetic alteration of basic volcaniclastic materials or replacement of non-clay substrates (feldspar, biotite etc.) were plausibly produced chlorite group minerals in Dhok Pathan Formation.

Petrographic, ICP-MS, and EDS analysis

The sandstones of Dhok Pathan Formation are composed of quartz, lithic fragments, feldspars, and micas (biotite predominate over white mica). The monocrystalline quartz represents the main framework grains constituting 30% (on average) of the total volume of rock. The feldspars' (orthoclase, K-feldspar, and plagioclase) share is up to 14%. Lithic grains are the second abundant framework grains after quartz and constitute 21% (on average) of the rock volume. Lithic fragments are dominantly igno-metamorphic and sedimentary in origin. The igno-metamorphic lithic grains include low-grade metamorphic carbonaceous schist, quartz mica schist, phyllite, volcanic rock fragments, and siliceous fragments while dolomite, calcite, and claystones occur as sedimentary lithic fragments. Biotite (ferran phlogopite 5% on average) is more common than white mica (2%). About 3% of the total rock volume is constituted by phyllosilicates. Calcite, clay, and oxides/hydroxides of iron are the main cementing material. Calcite may contribute up to 11% to the rock volume. Higher calcite value is due to development of secondary calcite.

Garnet, epidot, amphibole, magnetite, tourmaline, rutile, zircon, monazite, and urano-thorite are heavy mineral assemblages present in the studied mid-Siwalik sandstones. These sandstones have feldspathic-lith arenite to lithic arenite composition on QFL (quartz-feldspar-lithic fragments) classification diagram (Fig. 7) after McBride (1963). The results are tabulated in Table 1.

The maximum concentrations of uranium, thorium, and REEs recorded on ICP-Ms are as follows: uranium 662 ppm in sandstone and 107 ppm in heavy minerals, thorium 1374 ppm, La 975 ppm, Ce 2831 ppm, Pr 193 ppm, Nd 746 ppm, Gd (98 ppm), and Dy (50.8 ppm) from heavy mineral samples. The results are tabulated in Table 2. We have identified detrital uraninite in surface sample of sandstone through EDS on SEM (Fig. 8a). Good concentrations of magnetite (Fe) were observed from samples of black sand (heavy mineral accumulations).

Discussion

Interpretation of lithofacies

Gravely sandstone The degree of roundness and sphericity, poor sorting, and imbrication pattern entail quick sedimentation in fairly energetic flow regime. The facies characters are similar with deposition from deepest portion of the stream with energetic flow (Miall 1988; Collinson 1996; Ghazi and Mountney 2009). The relatively energetic flow in the deepest portion of the stream deposit similar facies in fluvial channels and interpreted as channel lag deposits. The tractional currents transported the sediments. The dominance of extra-basinal clasts over intra-basinal mud clasts, normal grading, and frequent existence of roughly developed cross-bed sets with erosional basis are all clues for deposition of facies by downstream migrating 3-D dunes or obliquely shifting longitudinal bars.
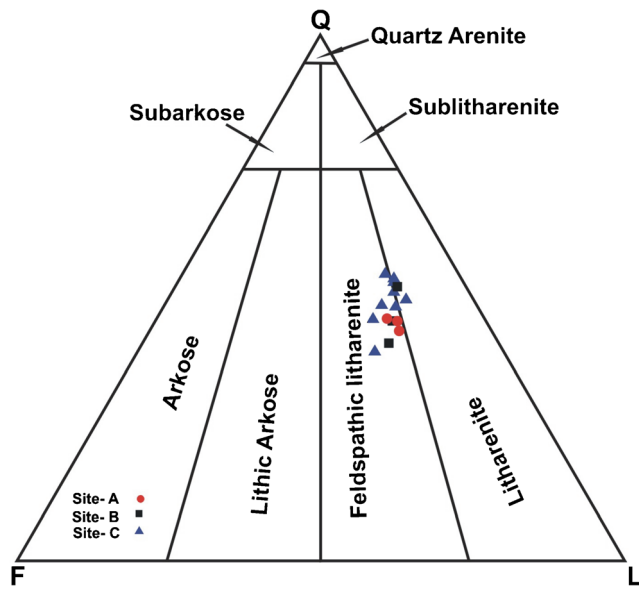
Fig. 7 QFL classification diagram of sandstones of Dhok Pathan Formation (after McBride 1963)

Coarse grained sandstone The dominance of large scale trough cross-bedding over small scale and planar cross stratification along with lateral continuity of sandstone sheets can be inferred as the deposition of sand-moved braided fluvial system (Ullah et al. 2009). The superposition or lateral migration of various bars in the channel belt gave rise to channel bar deposits decipher as mega-scale multistorey-inclined strata. In the fluvial system, the filling or superposition of channel bars within large aggrading stream result in the formation of multistorey sandstone units (Gordon and Bridge 1987;

Bridge and Mackey 1993). Along the erosional surfaces the intra-formational clasts are cut bank materials produced due to lateral stream migration (Ullah et al. 2009). The presence of large-scale trough cross-bedded strata is evident of greater water depths. Although, the large-scale trough cross-bedding (> 1 m wide) are rare in fluvial systems but still present and correspond to greater dune heights and water depths (Miall 2006).

Fine- to medium-grained sandstone The parting lineation along bedding planes, and flat and parallel laminations are the distinguishing characteristics of this facies deposition under high and low-flow conditions as plane beds (Miall 1985, 2006). The intercalation of finer facies with horizontally laminated sandstone units recorded as fast change in flow regime. i.e., high energetic flow; the flood regime and low flow as waning flow stage deposited finer sediments (Olsen 1988). Conversely, during the flooding of main stream within the fluvial system, the energetic sheet floods upon dropping their energies could have deposited this facies. The parting lineation associated with flat bedding, typical fine-medium-grained sandstone that may have been sorted and deposited from micro-vortices action during high-energy stream flow conditions (Fielding 2006). The deposition of this facies is interpreted as bar top sand sheet or channel deposit in lower and upper flow regime.

Fine sandstone facies Lithofacies Sl characterizes deposition either by individual bedform geometries or on primary dipping surfaces, i.e., the scour hollows. This facies

Table 1 Modal composition of sandstone samples of Dhok Pathan Formation, Himalayan foreland basin

Sample No.	Quartz	Feldspar			R.F	Biotite	Muscovite	Chlorite	Epidote	Other Acc.	Voids/wash out	Clay	Calcite	Total
		Orth.	Kfs	Plag.										
170-802	29	2	4	7	23	5	2	1	1	2	13	3	8	100
171-802	31	3	5	6	19	4	2	–	1	3	14	2	10	100
177-802	30	2	4	6	21	6	3	2	1	3	13	2	7	100
179-808	28	3	5	8	22	5	3	1	1	3	9	3	9	100
180-808	32	4	5	6	20	6	2	–	–	4	11	2	8	100
181-808	30	4	3	5	22	4	1	1	–	3	16	2	9	100
182-808	28	5	5	7	19	6	3	1	–	4	12	2	8	100
1871-808	29	2	4	7	21	4	2	1	1	3	12	3	11	100
196-805	32	3	5	8	20	5	1	–	–	3	13	2	8	100
197-805	31	2	3	7	23	5	2	1	1	2	13	3	7	100
198-805	31	4	5	5	18	6	2	–	–	4	14	2	9	100
199-802	29	4	5	7	24	4	2	1	1	3	12	2	6	100
2001-802	32	2	4	7	21	5	2	1	1	4	11	2	8	100
202-808	30	2	5	8	20	4	2	1	1	2	15	3	7	100

Orth. orthoclase, *Kfs* potassium feldspar, *Plag.* plagioclase, *R.F* rock fragments, *Acc.* accessory

Table 2 Rare earth elements, U and Th concentrations of sandstone and heavy minerals (black sand) of the Dhok Pathan Formation

Sample No.	Th ppm	U	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
170-802	6.93	1.83	19.9	37.4	4.32	16.9	3.12	0.714	2.7	0.475	2.62	0.534	1.41	0.265	1.61	0.225
171-802	10	2.67	26.6	48.8	5.7	21.6	3.93	0.793	3.26	0.536	2.7	0.504	1.32	0.209	1.32	0.181
177-802	12.4	14.9	35.9	65.7	7.67	28.1	5.36	1.13	4.61	0.77	4.06	0.77	2.08	0.346	2.23	0.322
179-808	8.35	1.65	19.9	37.6	4.38	17.4	3.25	0.737	2.66	0.434	2.21	0.409	1.03	0.172	1.07	0.146
180-808	8.85	1.86	21.7	41.2	4.75	18.5	3.31	0.739	2.76	0.462	2.35	0.442	1.18	0.182	1.2	0.161
181-808	7.34	19.7	19.1	36.5	4.14	17	3.04	0.73	2.45	0.406	2.14	0.385	1.07	0.17	1.08	0.152
182-808	7.89	34.9	19.9	36.7	4.36	16.9	3.06	0.721	2.6	0.441	2.22	0.415	1.11	0.185	1.12	0.148
1871-808	19.9	662	45.6	82.9	9.57	37	6.83	1.22	5.46	0.893	4.59	0.788	2.13	0.353	2.2	0.306
196-805	15	3.96	38.7	70.8	7.98	29.3	5.08	0.95	4.41	0.75	3.99	0.81	2.24	0.384	2.49	0.413
197-805	7.93	1.33	16.3	31.1	3.72	14.3	2.66	0.615	2.27	0.378	2	0.378	0.98	0.166	1.01	0.137
198-805	7.33	3.73	19.9	36.5	4.25	16.3	3.04	0.699	2.53	0.424	2.14	0.399	1.08	0.181	1.1	0.149
199-802	10.8	107	29.8	53.8	6.23	24	4.16	0.965	3.59	0.606	3.17	0.572	1.56	0.259	1.56	0.203
2001-802	22.8	87.1	40.9	77	9.03	35.3	6.65	1.09	5.26	0.901	4.65	0.84	2.25	0.381	2.44	0.32
202-808	12.5	28.8	31.2	58.9	6.79	25.5	4.58	0.834	3.88	0.641	3.14	0.577	1.57	0.261	1.68	0.239
Heavy mineral (black sand) analytical data																
213-802	1374	107	975	2831	193	746	127	6.16	98.7	12.8	50.8	6.67	17.6	2.21	14.5	1.88
2132-802	1236	103	934	2674	169	713	120	5.96	95.4	12.3	50.3	6.12	15.4	2.11	14.3	1.66
2135-802	1148	99	856	2543	183	732	124	6.04	93.2	11.4	46.8	5.88	16.7	1.99	13.9	1.72
2136-802	1352	102	896	2448	178	708	113	5.89	96.7	10.8	48.9	6.51	14.9	2.04	14.4	1.8
2138-802	1030	105	963	2791	189	729	119	6.09	94.1	12.2	44.7	6.24	15.8	2.07	12.9	1.82
2139-802	1298	101	971	2822	180	712	122	5.98	97.4	11.8	49.36	5.96	16.4	2.1	13.4	1.58

typically formed at the transition between supercritical and subcritical flow regimes where washed out dunes and humpback dunes occur (Miall 2006). According to DeCelles (1986), the crevasse splays of distal, sand-moved braided fluvial system in allied flood plains can deposit this sandstone facies. The recurrent avulsion and crevassing produced these crevasse splay channels (Smith et al. 1989). It can be inferred that the crevasse splay channels of a sand-dredged braided fluvial system in allied floodplains have deposited this facies.

Fig. 8 **a** SEM image of detrital uraninite (in circle). **b** EDS spectrum of detrital uraninite. **c** SEM image of LREE-bearing monazite. **d** Field photograph of carnotite mineralization (circle)
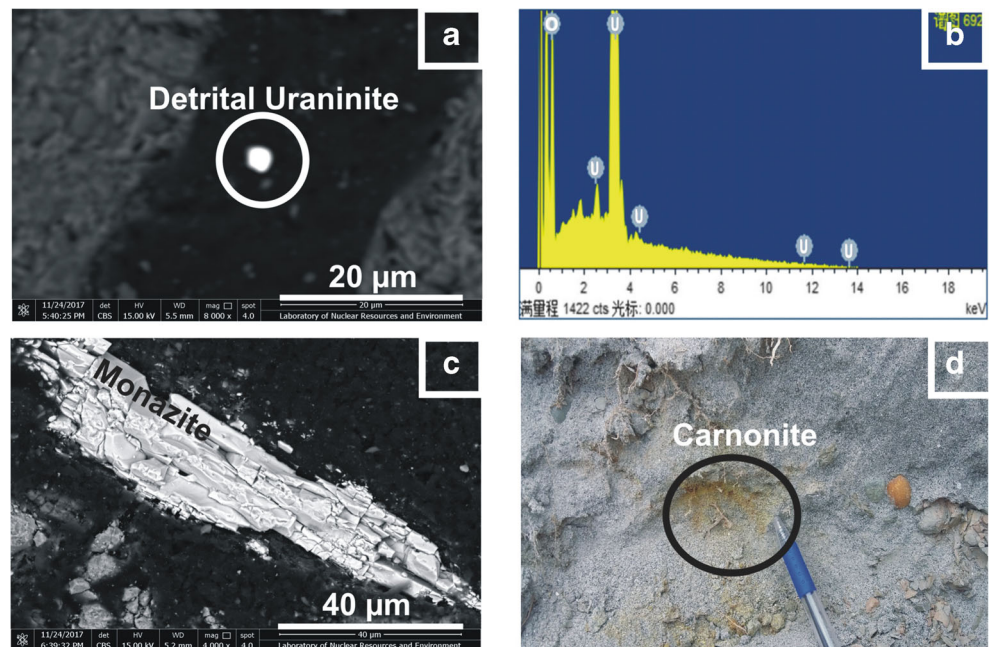
Scour fill coarse sand Usually, a few decimeter to a meter poorly sorted, coarse to very coarse–grained sand with poor cross stratification containing plenty of intra-clasts and other lag material is present above the fluvio-erosional surfaces. It may be complicated or more plausibly erratic to distinguish between migrating large solitary St sets along a stream floor and facies Ss (Miall 2006). The sandstone geometry, poorly sorted coarse-grained texture, and abundance of lag material suggest fast deposition of coarse bed-load material as scour fill under high-energy upper flow regime in a sand-dominated fluvial system.

Siltstone and claystone The deposition from suspended load under weak traction currents in flood plain areas can be reflected by the intercalation of very fine-grind sand, silt, and mud (Miall 2006). The deposition from suspended load in abandoned low relief flood plain areas and upper part of sandy bar forms shows alternate siltstone-claystone thin lamination along with sheet geometry (Allen 1965). The presence of thin sandstone beds is interpreted as more energetic flood-plains traction current such as of crevasse splays. The facies Fl is interpreted as deposits of overbank areas at waning stage flood deposition. The orange-red color of mudstone indicates well-oxygenated environment and subaerial exposure.

Massive mudstone At low stage of stream abandonment, the standing pools of water commonly in sandy/gravelly braided sedimentary deposits lithofacies Fm form the mud drapes (Miall 1977). It is interpreted that the facies Fm is deposited from suspension load in overbank setting during the low-stage channel abandonment. The thicker units of this facies in the northern part suggest the deposition in floodplain ponds. The orange-red color with widespread lateral extension advocates deposition in good subaerial exposure and oxygenated environment in a well-developed flood plain basin.

Depositional environments of Dhok Pathan Formation

The temperature and humidity, snow and rainfall disparities, flowing water, wave, and wind direction and velocity are the substantial constraints of a sedimentary environment. The formation is comprised of repeated sandstone-shale sequences with few pebbly horizons stacked in fining-upward fashion. The lithological attributes of formation are characteristically indicating laterally migrating streams in a fluvial system (Allen 1965, 1970). The channel bars or superposition of different bars through lateral accretion deposited sandstone units while the mudstone units were deposited through vertical accretion after overbank flooding in flood plain areas. The gravelly horizons are associated with erosional surfaces and are interpreted as channel lag sediments transported through traction current. As the stream relocates, the vertically accreted deposits are underlain by laterally accreted deposits bringing about a fining-upward cycle (Abbasi et al. 1983; Allen 1997). The sandstone units are generally medium to fine grained with subordinate coarser facies and are moderately sorted which ascribed the vitality of the depositing stream. The Siwalik sedimentation was coupled with the fluctuating basinal tectonism which is reflected by the variation in grain sorting coefficient (Abbasi et al. 1983). Generally, medium sand–sized sediments are best sorted while fine and coarse-grained sediments are poorly sorted. Likewise sorting relies on mean size, not on transported distance. Usually, very fine -to coarse-grained sediments even gravels are incorporated as suspended load in a river system.

Enormously thick sandstone units can be attributed to the continual sinking of depositional basin which is obvious from the cyclic deposition of gravelly beds. These gravelly horizons are bounded with the cross-bedded sandstones. These gravels were spread just when the basin was totally topped off, and streams still energetically dredged the gravelly material (Abbasi et al. 1983; Miall 2000). This proposes that the basin was never deeper than the thickness between two consecutive gravel beds. Towards the beginning of a cycle, the rate of deposition initially surpassed the rate of steady sinking of the basin. The gravelly units marked the break in deposition. At the point when persistently sinking basin accomplished some depth, re-deposition of sand started (Abbasi et al. 1983; Einsele 1992). No doubt, the environment has experienced variable conditions with the distinctive periods of tectonism (Tandon 1972).

Paleosol sequences demonstrate revamping of geography and drainage networks associated with a regular to changed seasonal climate (Fatmi 1973). A couple of paleosols have formed under water-logged and grassy woodland conditions; however, most of the paleosols developed under close vegetation and drier conditions. They clay minerals of the middle Siwaliks have abundant illite and smectite group clay minerals (Raiverman 2002). During the late Neogene (7.4–0.5 Ma), the Himalayan foreland sediments and modern Bengal fan sediments have incorporated high proportion of smectite (Suresh et al. 2004). A decline in sedimentation rate has been recorded in the Himalayan Foreland Basin and Bengal fan at about 8 Ma even with escalated monsoon in the Himalayan foreland basin (Quade et al. 1989; Burbank et al. 1993). This amassing rate of sedimentation was most likely to be controlled by exogenic factors as opposed to moderating tectonism. Due to thick vegetation cover, slope stability had enhanced which reduced the mechanical disintegration of mountain ranges under intensified monsoonal climate (Quade et al. 1989; Burbank et al. 1993). Different clay-mineral suits can be originated due to variable climatic conditions of the source areas. Warm, humid, and more hydrolyzing conditions are favorable for kaolinite and smectite clay group minerals while illite and chlorite clay minerals originate under cold-dry and less hydrolyzing conditions (Suresh et al. 2004). The chemical

weathering became more profound under warm and humid climatic conditions. This implies that not only the basic rocks exposed in the catchment zones yet additionally; a higher precipitation rate may have assumed an imperative part in the appropriation of smectite clay minerals in the Siwalik sediments. Temporal changes in the Siwalik fluvial system have been documented, but the degree to which they are related to climate or subsidence, or to which they are simply due to auto cyclic dynamics of the fluvial system, is not clear (Barry et al. 2002). Saponite clay mineral of smectite group was observed in the sediments of Dhok Pathan Formation of Shingar Range as high as up to 15% which owes its origin by the devitrification of volcanic glass/ashes (Azizullah and Khan 1997). The smectite clay group minerals may be contributed by the depositing river as source area lithology or due to several other factors such as topography, physical and chemical disintegration, diagenesis, or climatic conditions. In floodplain areas, under warmer conditions of temperature, chemical weathering can form smectite; however, it essentially originates with elevated swell-shrink properties in wet-dry climatic conditions. This formation of smectite required less water percolations as that for kaolinite (Suresh et al. 2004). A variety of clay-minerals suits may have developed due to weathering of non-crystalline rocks such as altered volcanic rocks can generate smectite group clay minerals (Chamley 1989). The absence of glass shards suggests that the smectite group clay minerals in this part of Siwalik sediments mainly derived from physical processes (weathering of rocks or climatic and diagenetic alterations) other than the devitrification of volcanic ashes/glass.

Hence, the vertical stacking of massive, multistoried sandstone units with various facies associations, their sheet geometry, recurrence of erosional surfaces, and presence of diverse clay-mineral suits revealed that the Dhok Pathan Formation in the study area has been deposited by sand-moved braided river system.

Depositional model of Dhok Pathan Formation

The Indus River is one of the oldest known rivers. As indicated by Clift et al. (2001), the Indus River was shaped soon after the India-Eurasia collision before 45 Ma and streaming around a similar route since then. The paleo-Indus initially drained the foreland basin through the Himalaya at about 18 Ma ago when it adopted its modern course (Najman et al. 2003). Since the early Eocene, the course of river Indus has been pushed about 200–300 km towards south (Clift 2002) and 100 km towards east (Inam et al. 2007) due to the development of Suleiman Range. This relative stability in the course of Indus River is either because of its strike-slip alignment towards the western margin of Indian plate or its position in the Indus-Tsangpo suture zone. The Himalayan foreland basin has received a thick pile of molasse sediments through Indus River system. This process of detritus generation and deposition has been a moderately steady component of the Indus River system for the previous 18 million years (Johnson et al. 1985). The sedimentary succession of Dhok Pathan Formation (middle Siwaliks) in the Surghar-Shingar Range show multistorey sandstone units with sheet geometry suggesting deposition in large braided river fluvial system (Miall 1978; Gordon and Bridge 1987). Each storey is representing a channel bar. Similarly, different other parts of the subcontinent additionally uncover that the Siwalik sedimentation took place in the Himalayan foreland basin due to a large fluvial framework (Goswami and Deopa 2018). The low sinuosity migrating streams across an alluvial plain can deposit multistorey sandstone units as a mark of channel bar and channel fill (Gordon and Bridge 1987). The multistorey nature of sandstone units with sheet geometry proposed that numerous streams with braided character and larger stream depths have actively contributed to the depositional process (Rust 1978; Jones and Frostick 2002). The suspended material during slack flooding was deposited as siltstone-mudstone facies (the finer facies).

The braided stream deposits can resemble in numerous characteristics with high sinuosity river deposition in rapidly sinking sedimentary basins (Bentham et al. 1993). The neotectonic activity, climatic conditions, and various sedimentation rates can produce vertically stacked units (Singh et al. 1990). In this case, either the varied climatic conditions or the uplift of source areas (resulting high relief, more catchment areas, and subsequently more detritus production) assumed to be the controlling factors of fluvial architecture. What the case may be, in bigger river systems, a high discharge can be deduced from sedimentation patterns (Kumar et al. 2004). A broad stream inside demonstrating a braided morphology of small streams entirely encased inside a fine-grained overbank can excellently define the depositional model of Miocene molasse sediments in the Himalayan foreland basin (Ullah et al. 2009). On the other hand, this Siwalik sedimentation was due to a single large braided river similar to Brahmaputra river where an assortment of depositional style can be seen (Bristow 1987). Based on heavy mineral analysis by Cerveny et al. (1989) along the Himalayan front, the paleo-Indus that had deposited these molasse sediments in the foreland has kept relatively stationary position over an extended time period. The paleo-Indus River has drained over a vast area covering the central Potwar Plateau and the Trans-Indus areas with time. However, the sedimentary architecture and thickness of middle Siwalik molasse sediments suggested that the most plausible position of Indus River was the present Trans-Indus region (present study area).

The detailed paleo-current analysis of Dhok Pathan Formation has shown a regional NE-SW paleo-flow direction.

The paleo-flow directions of Miocene to recent Siwalik sediments exposed to the east and west of modern Indus River are different. The paleo-flow directions of exposures are SE and NS towards east and west of present Indus River. The paleo-flow direction in the northern part of Surghar Range was NS (Friend et al. 1999). The enormous thickness of multistoried sandstone units, their sheet geometry, lateral and vertical stacking, and paleo-current directions suggest that these sediments were deposited by sand-dominated larger river system. The positions of paleo and modern Indus in the perspective of tectonics also depict that it had deposited a thick pile of molasse sediments in the foreland. The fluvial architecture of sandstone and shale units, their thickness, and position of Indus River in time and space, we propose that the molasse sediments of Surghar-Shingar Range most plausibly belong to Indus River. This model is also supported by the presence of detrital uraninite in sandstone which is a unique feature of Indus River. This interpretation contrasts with the previous model of Azizullah and Khan (1997) based on visual comparison of some conglomerates that these sediments were deposited by Siwalik or Indo-Brahm River streamed along the Himalayan mountain front.

Economic mineral potential

The catchment areas of river Indus have diverse geological environments and evolution history. Tectonically, the Kohistan-Ladakh island arc is surrounded by Shyok suture zone to the north and Indus suture zones to the south. The Indus suture zone is positioned to the north by Karakoram block and south by Indian plate. This region host good prospects for valuable commodities such as precious metals (including gold), gem stones, and minerals (Ahmad et al. 2013). The placer gold-uraninite-scheelite occurrences from the upper reaches of Indus River as well as many 1100 miles downstream (Davidson 1962) are well known for decades. The gold washers are extracting gold using primitive techniques (Malik et al. 2004; Shah and Khan 2004). The sediments under study host high radioactivity along with yellow secondary uranium mineralization identified as carnotite (Azizullah and Khan 1997).

The present study has revealed that the sediments of Dhok Pathan Formation are of Indus River affinity. These sediments have 80–100 cm thick layers of heavy mineral accumulation (black sand) that extends for > 1 km and are rich in REEs, uranium, and thorium. The present studies have successfully identified the presence of detrital uraninite in surface sample of sandstone. The ICP-MS analytical results of sandstone and heavy mineral accumulations (black sand) of Dhok Pathan Formation show promising concentrations of uranium, thorium, and light REEs (Table 2). In this perspective, these Himalayan molasse sediments hold a good potential for placer mineral exploration.

Conclusion

The Dhok Pathan Formation of middle Siwalik in SSR is 807–1540 m thick, comprised of cyclic alternation of massive, multistoried sandstones, and shale units in fining-upward fashion. The formation hosting seven distinct lithofacies (Gt, St, Sh, Sl, Ss, Fm, Fl) which had been deposited by sand-dominated bed load braided fluvial system most plausibly the Indus River system. Clay-mineral suits are mostly indicative of weathering products or the contribution from source areas. The absence of volcanic glass shards and mineral analcimolite suggests that the smectite group clay minerals were not derived from the devitrification of volcanic ashes. Sandstone and heavy mineral accumulation (black sand) samples showed promising concentrations of radioactive minerals (uranium 662 ppm and thorium 1374 ppm) and light REEs. Detrital uraninite has also been identified from the surface sample of sandstone. Hence, we can safely conclude that the Dhok Pathan Formation of Surghar-Shingar Range holds good potential for economic minerals exploration.

References

Abbasi IA, Abid IA, Khan MA (1983) Statistical study of the Dhok Pathan Formation, Puki Gudikhel, Surghar Range, Karak. Geol Bull Univ Peshawar 16:85–96

Ahmad L, Shah MT, Khan S (2013) Gold mineralization in northern areas of Pakistan. In: 125th Anniversary Annual Meeting & Expo, 27–30 October, Denver, Colorado, USA. Geol Soc Am Abstract with programs 45(7):539

Akhtar M (1983) Stratigraphy of the Surghar Range. Geol Bull Punjab Univ 18:32–45

Ali F, Khan MI, Ahmad S, Rehman GR, Rehman I, Ali TH (2014) Range front structural style: an example from Surghar Range, North Pakistan. J Himalayan Earth Sci 47(2):193–204

Allen JRL (1965) A review of the origin and characteristics of recent alluvial sediments. Sediment 5:89–191

Allen JRL (1970) Studies in fluviatile sedimentation: a comparison of fining upwards cyclothems, with particular reference to coarse member composition and interpretation. J Sediment Petrol 40:298–323

Allen PA (1997) Earth surface processes. Blackwell science, Oxford

Anjos SMC, Derose LF, Silva CMA (2003) Chlorite authigenesis and porosity preservation in the upper Cretaceous marine sandstones

of the Santos Basin, offshore eastern Brazil. Int Assoc Sedimentol Spec Publ 34:291–316

Azizullah, Khan MA (1997) Petrotectonic framework of the Siwalik Group Shingar Range with special reference to its petrography. Geol Bull Univ Peshawar 30:165–182

Barry JC, Morgan ME, Flynn LJ, Pilbeam D, Behrensmeyer AK, Raza SM, Khan IA, Badgley C, Hicks J, Kelley J (2002) Faunal and environmental change in the late Miocene Siwaliks of northern Pakistan. Paleobiology Memoirs 3((Supplement to Paleobiology 28 (2)):1–55

Barshad, Kishk FM (1969) Chemical composition of soil vermiculite clays as related to their genesis. Contrib Mineral Petrol 24(2):136–155

Basu PK (2004) Siwalik mammals of the Jammu sub-Himalaya, India: an appraisal of their diversity and habitats. Quat Int 117(1):105–118

Beck RA, Burbank DW, Sercombe WJ, Riley GW, Barndt JK, Berry JR, Afzal J, Khan AM, Jurgen H, Metje J, Cheema A, Shafique NA, Lawrence RD, Khan MA (1995) Stratigraphic evidence for an early collision between northwest India and Asia. Nature 373:55–58

Beck RA, Burbank DW, Sercombe WJ, Khan AM, Lawrence RD (1996) Late cretaceous ophiolite obduction and Paleocene India-Asia collision in the westernmost Himalaya, proceedings of the 10th Himalaya- Karakoram-Tibet workshop, Monte Verità Switzerland. Special Volume, Geodinamica Acta 9(2):116–144

Bentham PA, Talling PJ, Burbank DJ (1993) Braided stream and floodplain deposition in a rapidly aggrading basin: the Escanilla Formation, Spanish Pyrenees. In: Best JL, Bristow CS (Eds) Braided rivers. Geol Soc London Spec Publ 75:177–194

Bertier P, Swennen R, Lagrou D, Laenen B, Kemps R (2008) Palaeoclimate controlled diagenesis of the west phalian C & D fluvial sandstones in the Campine Basin (north-east Belgium). Sedimentology 55(5):1475–1417

Blisniuk PM, Sonder LJ, Lillie RJ (1998) Foreland normal fault control on thrust front development northwest Himalayan. Tectonics 17(5): 766–779

Bridge JS, Mackey SD (1993) A revised alluvial stratigraphic model. In: Marzo M, Puigdefabregas C (eds) Alluvial sedimentation. Int Assoc Sedimentol Spec Pub 17:319–336

Bristow CS (1987) Brahmaputra River: channel migration and deposition. In: Ethridge G, Flores RM, Harvey MD (eds) Recent developments in fluvial sedimentology. SEPM Spec Publ 39:63–74

Burbank DW, Derry L, France-Lanord C (1993) Lower Himalayan detrital sediment delivery despite an intensified monsoon at 8 Ma. Nature 364:48–50

Carroll D (1979) Clay minerals: a guide to their X-ray identification. Geol Soc Am Spec Pap 126:80

Cerveny PF, Johnson NM, Tahirkheli RAK, Bonis NR (1989) Tectonic and geomorphic implications of Siwalik Group heavy minerals, Potwar Plateau, Pakistan. Geol Soc Am Spec Pap 232:129–136

Chamley H (1989) Clay sedimentology. Springer-Verlag, New York

Chauhan PR (2003) The importance of India in human origins studies with special reference to the Siwalik Hills & the Narmada Basin. In National Workshop on Pleistocene environments and hominin adaptations in South Asia: problems & prospects, march 29–31, Delhi, India

Clift PD (2002) A brief history of the Indus River. Geol Soc Lond, Spec Publ 195:237–258. https://doi.org/10.1144/GSL.SP.2002.195.01.13

Clift PD, Shimizu N, Layne GD, Blusztajn J, Gaedicke C, Schluter HU, Clark MK, Amjad S (2001) Development of the Indus Fan and its significance for the erosional history of the western Himalaya and Karakoram. Geol Soc Am Bull 113:1039–1051

Collinson JD (1996) Alluvial sediments. In: Reading HG (ed) Sedimentary environments and facies, 3rd edn. Blackwell Publishing, Oxford

Danilchik W, Shah SMI (1987) Stratigraphy and coal resources of the Makerwal area, Trans-Indus Mountains, Mianwali District, Pakistan. U S Geol Survey Prof Pap 1341:39

Davidson FC (1962) Uraninite-scheelite placers of the river Indus. Econ Geol 57:456–457

DeCelles PG (1986) Sedimentation in a tectonically partitioned, non marine foreland basin: the Lower Cretaceous Kootenai Formation, southwestern Montana. Geol Soc Am Bull 97:911–931

DeCelles PG, Langford RP, Schwartz RK (1983) Two new methods of paleocurrent determination from the trough cross stratification. J Sediment Petrol 53(2):629–642

Einsele G (1992) Sedimentary basins: evolution, facies and sediment budget. Springer-Verlag, Berlin Heidelberg New York

Emery D, Myers RJ, Young R (1990) Ancient subaerial exposure and freshwater leaching in sandstones. Geology 18:1178–1181

Fatmi A (1973) Lithostratigraphic units of the Kohat-Potwar Province, Indus Basin, Pakistan. Geological Survey of Pakistan Memoir 10, GSP, Quetta

Fielding CR (2006) Upper flow regime sheets, lenses and scour fills: extending the range of architectural elements for fluvial sediment bodies. Sediment Geol 190:227–240

Flynn LJ, Barry JC, Morgan ME, Pilbeam D, Lindsa EH (1995) Neogene Siwalik mammalian lineages: species longevities, rates of change, and modes of speciation. Palaeogeogr Palaeoclimatol Palaeoecol 115(1–4):249–264

Friend PF, Raza SM, Baig MAS, Khan IA (1999) Geological evidence of the ancestral Indus from the Himalayan foothills. In: Meadows A, Meadows PS (eds) The Indus River, Biodiversity, Resources, Humankind. Oxford University Press, Oxford, pp 103–113

Gee ER (1989) Overview of the geology and structure of the Salt Range, with observations on related areas of northern Pakistan. In: Malinconico LL, Lillie RJ (eds) Tectonics of western Himalaya. Geol Soc Am Spec Pap 232:95–112

Ghazi S, Mountney NP (2009) Facies and architectural element analysis of a meandering fluvial succession: the Permian Warchha sandstone, Salt Range, Pakistan. Sediment Geol 221(1–4):99–126

Ghazi S, Mountney NP (2011) Petrography and provenance of the early Permian fluvial Warchha sandstone, Salt Range, Pakistan. Sediment Geol 233(1–4):88–110

Gordon EA, Bridge JS (1987) Evolution of Catskill (Upper Devonian) river systems: intra and extrabasinal controls. J Sediment Petrol 57: 234–249

Goswami PK, Deopa T (2018) Litho-facies characters and depositional processes of a Middle Miocene lower Siwalik fluvial system of the Himalayan foreland basin, India. J Asian Earth Sci 162:41–53

Güven N, Pease RW (1975) Electron optical investigation on montmorillonite-II: morphological variations in the intermediate members of the montmorillonite-beidellite series. Clay Clay Miner 23:187–191

Hayes JB (1970) Polytypism of chlorite in sedimentary rocks. Clay Clay Miner 18:285–306

Hillier S (1994) Pore-lining chlorites in siliciclastic reservoir sandstones: electron microprobe SEM and XRD data, and implications for their origin. Clay Miner 29(4):665–679

Inam A, Clift PD, Giosan L, Tabrez AR, Tahir M, Rabbani MM, Danish M (2007) The geographic, geological and oceanographic setting of the Indus River. In: Gupta A (ed) Large rivers: geomorphology and management. John Wiley & Sons Ltd, Hoboken, pp 333–346

Ismail FT (1969) Role of ferrous iron oxidation in the alteration of biotite and its effect on the type of clay minerals formed in soils of arid and humid regions. Am Mineral 54:1460–1466

Johnson NM, Stix J, Tauxe L, Cerveny PF, Tahirkheli RAK (1985) Palaeomagnetic chronology, fluvial processes and tectonic implications of the Siwalik deposits near Chinji Village, Pakistan. J Geol 93: 27–40

Jones SJ, Frostick LE (eds) (2002) Sediment flux to basins: causes, controls and consequences: geological society special publication 191. The Geological Society, London 284 p

Khan MJ, Opdyke ND (1987) Magnetic-polarity stratigraphy of the Siwalik Group of the Shingar and Surghar ranges, Pakistan. Geol Bull Univ Peshawar 20:111–127

Kumar R, Sangode SJ, Ghosh SK (2004) A multistorey sandstone complex in the Himalayan foreland basin, NW Himalaya, India. J Asian Earth Sci 23:407–426

Malik IA, Cohen DR, Dunlop AC (2004) Geochemical aspects of uranium in the Sumayar valley, northern areas of Pakistan. Geol Bull Univ Peshawar 37:1–25

McBride EF (1963) A classification of common sandstones. J Sediment Petrol 33(3):664–669

Miall AD (1977) A review of the braided river depositional environment. Earth Sci Rev 13:1–62

Miall AD (1978) Litho-facies types and vertical profile models in braided river deposits. In: Miall AD (ed) Fluvial Sedimentology 5. Canadian Society of Petroleum Geologists Calgary, Calgary, pp 597–604

Miall AD (1985) Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth Sci Rev 22:261–308

Miall AD (1988) Architectural-element and bounding surface in fluvial deposits: anatomy of the Kayenta Formation (Lower Jurassic), southwest Colorado. Sediment Geol 55:233–262

Miall AD (2000) Principles of sedimentary basin analysis. Springer, Berlin

Miall AD (2006) The geology of fluvial deposits. Springer, Berlin

Möller P (1986) Rare earth mineral deposits and their industrial importance. In: Möller P, Cerny P, Saupe F (eds) Lanthanides, Tantalum and Niobium. Proceedings of a workshop. Spring-Verlag, Berlin

Najman Y (2006) The detrital record of orogenesis: a review of approaches and techniques used in the Himalayan sedimentary basins. Earth-Sci Rev 74(1–2):1–72

Najman Y, Garzanti E, Pringle M, Bickle M, Stix J, Khan I (2003) Early-Middle Miocene paleodrainage and tectonics in the Pakistan Himalaya. Geol Soc Am Bull 115:1265–1277

Olsen H (1988) The architecture of a sandy braided-meandering river system: an example from the Lower Triassic Solling Formation (M. Buntsandstein) in W-Germany. Geol Rundsch 77(3):797–814

Orris GJ, Grauch RI (2002) Rare earth element mines, deposits and occurrences: U.S. Geological Survey open file report 02-189, USGS, Tucson, Az

Powell CMA (1979) A speculative tectonic history of Pakistan and surroundings: some constraints from the Indian Ocean. In: Farah A, DeJong KA (eds) Geodynamics of Pakistan. Geological Survey of Pakistan, Quetta, pp 5–24

Quade J, Cerling TE, Bowman JR (1989) Development of Asian monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan. Nature 342:163–166

Raiverman V (2002) Foreland sedimentation in Himalayan tectonic region: a relook at the orogenic process. Bishen Singh Mahendra pal Singh, Dehra Dun

Rehman NU, Ahmad S, Ali F, Alam I, Shah A (2017) Joints/fracture analysis of Shinawah area, district Karak, Khyber Pakhtunkhwa, Pakistan. J Himalayan Earth Sci 50(2):93–113

Rust BR (1978) Depositional models for braided alluvium. In: Miall AD (ed) Fluvial sedimentology. Canadian society of Petroleum Geologists, Memior 5, Calgary, pp 605–625

Saratovkin DD (1959) Dendritic crystallization. Consultants Bureau, New York

Shah SMI (2009) Stratigraphy of Pakistan. Geological Survey of Pakistan Memoirs 22, GSP, Quetta, p 400

Shah SMA, Hafeez A (2009) Sedimentology of Dhok Pathan Formation from Thathi area, northeast Potwar, district Rawalpindi. Geol Bull Punjab Univ 44:131–137

Shah MT, Khan H (2004) Exploration and extraction of placer gold in the terraces of Bagrot valley, Gilgit, northern Pakistan. Geol Bull Univ Peshawar 37:27–40

Singh H, Parkash B, Gohain K (1990) Facies analysis of the Kosi megafan deposits. Sediment Geol 85(1–4):87–113

Smith ND, Cross TA, Dufficy JP, Clough SR (1989) Anatomy of an avulsion. Sedimentology 36:1–24

Suresh N, Ghosh SK, Kumar R, Sangode SJ (2004) Clay-mineral distribution in late Neogene fluvial sediments of the Subathu sub-basin, central sector of Himalayan foreland basin: implications for provenance and climate. Sediment Geol 163(3–4):265–278

Tandon SK (1972) Mechanical analysis of middle Siwalik sandstones from Ramnagar, Nainital District, Kurnaon Himalaya. J Geol Soc India 13:51–58

Ullah K, Arif M, Shah MT, Abbasi IA (2009) The lower and middle Siwaliks fluvial depositional system of the western Himalayan foreland basin, Kohat, Pakistan. J Himalayan Earth Sci 42:61–85

Valdiya KS (2016) The making of India; geodynamic evolution. Springer, London

Weaver CE (1989) Clays, muds and shales. Elsevier, New York, p 819

Worden RH, Morad S (2003) Clay minerals in sandstones: controls on formation, distribution and evolution. Int Assoc Sedimentol Spec Publ 34:3–41

Yeats RS, Hussain A (1987) Timing of structural events in the Himalayan foothills of northwestern Pakistan. Geol Soc Am Bull 99:161–176