Fluvial Facies and Provenance of the Early Permian Warchha Sandstone Salt Range, Pakistan

Shahid Ghazi[1]*and Nigel P. Mountney[2]

1. Institute of Geology Punjab University, Lahore-54590, Pakistan
2. School of Earth and Environment, the University of Leeds, LS2 9JT, UK
Received 10 February 2010; accepted 9 April 2010

Abstract

Deposits of the Warchha Sandstone in the Salt Range, Pakistan are characterised by a range of fluvial facies and architectural elements that together preserve a record of both the proximal and distal parts of a meandering river system that drained the northern margin of Gondwanaland. Several fining-upward cycles are recognised and completely preserved cycles can be divided in to three parts; a lower part composed of an erosive base with gravel- and coarse sand-grade trough cross-bedded facies, a middle part composed of planar cross-bedded, ripple cross-laminated and horizontally laminated sandstone facies, and an upper part composed predominantly of horizontally laminated and massive mudstone facies. Nine architectural elements are recognised within these cycles and these record the presence of channels, downstream and laterally accreting barforms, laminated sand sheets, crevasse splays, levees, over-bank floodplain units and shallow lakes. A broad range of sedimentary structures is recognised, including different forms of bedding, cross bedding, ripple marks and stratification, channels, flute casts, load casts, desiccation cracks, rain prints, cone-in-cone structures, a variety of concretions and bioturbation.

The occurrence and abundance of these structures varies in a systematic manner throughout the vertical thickness of the succession. Cross bedding is the most prominent and consistent sedimentary structure, including various trough and planar varieties. The clasts are mainly of plutonic and low-grade metamorphic origin, with an additional minor sedimentary component. Textural properties of the sandstone are fine- to coarse-grained, poorly to moderately sorted, sub-angular to sub-rounded and with generally loose packing. Based on modal analyses, the sandstone is dominantly a sub-arkose to arkose. Detrital constituents of this formation are mainly composed of monocrystalline quartz, feldspars (more K-feldspar than plagioclase) and various types of lithic clasts. XRD and SEM studies indicate that kaolinite is the dominant clay mineral. Detailed palaeocurrent analysis reveals a broad unimodal palaeocurrent pattern within each cycle but significant changes in local migration direction between each vertically stacked cycle, supporting the notion of a high-sinuosity system with an overall dominant flow direction to the north-northwest. Petrographic analysis indicates the provenance of the Warchha Sandstone to have been the Aravalli Range to the southeast and the Malani Range to the south of the Salt Range, suggesting northward transport across a broad alluvial plain towards the margin of the Tethys Ocean in the north.

Keywords: *Fluvial, Early Permian, Warchha Sandstone, Provenance, Salt Range.*

1. Introduction and Geological setting

The Salt Range of Pakistan is located to the south of the Potwar Basin and east of the Jhelum River where it forms a southwardly-convex outcrop belt with a general east-west trend (Fig. 1). The Salt Range forms a complex anticlinorium with a series of pronounced salt anticlines at its core. It is widest in its central part, between the Khewra and the Warchha areas, where a sequence of Precambrian to Neogene strata is exposed. Outcrops exposing the base of the formation are numerous and tend to be present across the entire Salt Range region. By contrast, however, the top of the formation is only exposed in central and western parts of the Salt Range. Aside from trace fossils, no fossils have been recorded although pollen grains could conceivably be present in the Warchha Sandstone succession [1].

This study describes and interprets both the small-scale lithofacies organisation and the larger-scale geometry of depositional units in terms of architectural elements.

Additionally, the significance of the petrographic analysis and arrangement of recognised depositional sequences are considered in terms of their provenance and palaeoenvironmental significance. Vertical lithological profiles of the Warchha Sandstone were measured in eight areas across a 160 km-long east–to-west transect across the Salt Range (Fig.1). Facies analysis of the succession was carried out using a modified version of Miall's facies schemes [2, 3]. Detailed petrographic overviews of the Warchha Sandstone through analysis of textural and mineralogical properties have enabled the provenance of the succession to be established. Both petrographic

----
*Corresponding author.
E-mail address (es): ghazigeo@yahoo.com

analysis and field characteristics of the sandstone indicate that the source areas were characterized by uplift of a moderate to high relief continental block that was weathered under the influence of hot and humid climatic conditions. The rock weathered from the source areas included primary granites and gneisses, together with metamorphic basement rocks and minor amounts of sedimentary rocks. This paper endeavours to draw together field evidence on the grain size, composition and outcrop geometry of the Warchha Sandstone. This evidence is used to suggest a broad palaeoenvironmental setting of the Warchha Sandstone in the Salt Range. Additionally, the petrographic interpretations made here, when used in conjunction with facies analysis, provide valuable information that enable determination of the palaeogeography and palaeoclimate of the broader region from which the sediment was derived and in which the succession accumulated.

2. Fluvial lithofacies

The Warchha Sandstone can be informally divided into several conglomerate, sandstone and claystone units, with roughly equal proportions of sand and clay and rather less conglomerate. Conglomerate units are composed of rounded, sub-rounded and sub-angular clasts of igneous, metamorphic and sedimentary origin, which are dark-pink, dark-brown, maroon, white and green in colour. Clasts within the conglomerates mostly range from 0.5 cm to 2 cm, though large, rounded to sub-rounded, pink granite boulders up to 20 cm are also present. The clasts lie in poorly sorted sand-, silt- and clay-grade matrix of varied composition. In places, intraformational clasts of claystone are also present. Sandstone units are arkosic to sub-arkosic, medium- to thick-bedded, mainly light-brown to pinkish-white and grey in colour, fine- to coarse-grained, poorly- to moderately-sorted, with grains that are sub-angular to sub-rounded. The sandstones commonly contain 1-3 cm-thick, dark-brown, grey and green coloured claystone layers. Additionally, granule and pebble lags composed of pink granite are common. The sandstone units are locally speckled in appearance and, in places, contain carbonaceous material. Argillaceous claystone units are red, maroon, dark-brown, grey and light-green in colour. They are commonly massive-bedded, blocky and splintery, though in places are interlaminated with thin, red, maroon, dark grey and dark green siltstone layers to form shales. Seven lithofacies, arranged into a series of discrete separate fining-upward cycles, are recognised in the Warchha Sandstone (Fig. 2) and areas described based on the classification scheme of Miall [2,3].

3. Architectural elements

A variety of architectural elements are recognised, with coarse sand and conglomerate-dominated units representing channel fills, sandstones representing lateral accretion bar deposits, and finer-grained units largely representing overbank and crevasse splay deposits. A summary of the characteristics of architectural elements recorded in the Warchha Sandstone is shown in Fig. 3.

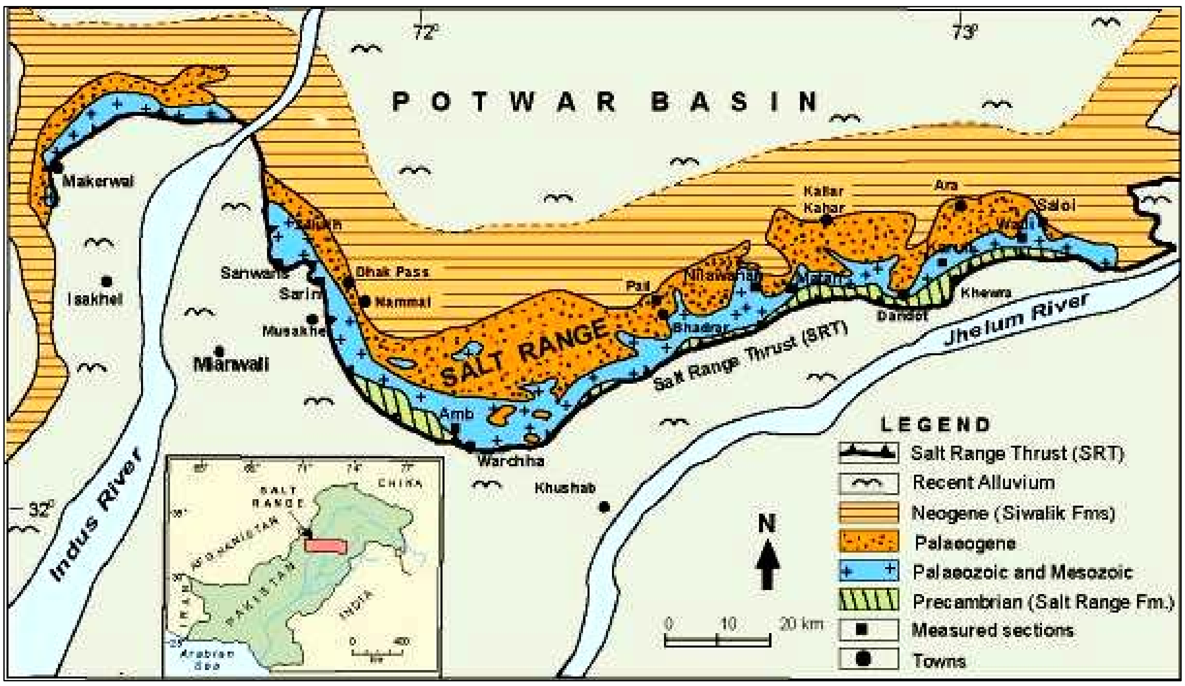


Fig. 1. Outcrop belt of the Warchha Sandstone in the Salt Range of Pakistan showing the location of eight measured sections.

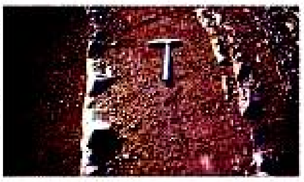
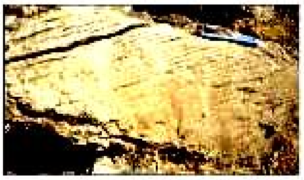
Characteristic features		Interpretation
Massive claystone / mudstone facies (Fm): Red, dark-brown, green and yellow claystone and shale with occasional grey to greenish-grey siltstone interbeds. The facies contains abundant bioturbation, clay balls, iron concretions, desiccation cracks, rain-drop imprints and caliche nodules up to 10 cm in diameter. The lower contact of this facies is typically gradational, whereas the upper contact is usually sharply truncated by the erosive base of the overlying cycle.		This facies is interpreted to represent deposition from suspension in overbank settings where the fine-grained sediments drape underlying deposits.
Parallel laminated siltstone and claystone facies (Fl): Laminated siltstone and/or massive claystone. Its lower contact with facies Sh or Sr and upper contact with facies Fm are gradational. Geometrically, this facies is arranged into thin but laterally extensive sheet-like bodies.		This facies is interpreted to represent the deposits of waning stage flood deposition, chiefly in overbank areas, with the majority of deposition occurring from suspension settling.
Very fine- to medium-grained sandstone with flat bedding facies (Sh): Very fine- to medium-grained, horizontally laminated sandstone arranged into thin beds with a sheet or tabular geometry.		Deposited as a plane bed under conditions of either upper or lower flow regime, either on bar top surfaces or as isolated sand sheets in overbank flood plain areas.
Ripple cross-laminated sandstone facies(Sr): Overlies facies Sp and consists of fine- to coarse-grained sandstone, which is interlaminated with thin siltstone and claystone horizons. The sandstone is medium- to thick-bedded. It occurs as thin wedge-shaped bodies which pinch out laterally within few metres and which contain abundant ripple marks, flat bedding, and small-scale trough and planar cross-stratification and load casts.		This facies likely represents the temporary abandonment of bars during periods of elevated water level and/or the product of deposition in areas of slack or sluggish water between bars or in overbank areas
Medium- to coarse-grained planar cross-bedded sandstone, facies (Sp): Medium- to coarse-grained, poorly sorted, arkosic sandstone arranged into lenticular or tabular sets, which are characterised internally by planar cross-bedding. The lower contact of this facies is sharp and flat, whereas the upper contact is erosional either with facies Sr or Fl.		Deposited as dunes or bars under conditions of lower flow regime.
Coarse-grained trough cross-bedded sandstone facies (St): Overlies facies Gt and consists of medium- to very coarse-grained sandstone arranged into trough cross-bedded sets and cosets. Geometrically, this facies occurs as lenticular or wedge-shaped bodies that are pebbly in places and which are commonly arranged into stacked trough cross-bedded cosets. The lower boundary is either gradational with facies Gt or is erosional with facies Fm, whereas the upper contact is sharp and flat with facies Sp.		Deposited as dunes or bars under conditions of lower flow regime.
Stratified gravely sandstone facies (Gt): Trough cross-bedded, stratified gravels that commonly infill channel-like erosive basal surfaces. Geometrically, the facies consists of lens- or ribbon-shaped bodies, commonly interbedded with sandy deposits.		Deposited as channel lag under conditions of lower flow regime, with sediment transport occurring via traction currents.

Fig. 2. Summary of the characteristic features of the lithofacies types encountered in the Warchha Sandstone, Salt Range, Pakistan.

4. Fluvial cyclicity

Cyclicity of the Warchha succession is divided into two groups [4]: small-cycle sedimentary cycles and large-cycles. Small-scale cycles are attributed to fluvial process of channel migration and avulsion and are generally considered to be controlled by autogenic processes [4, 5]. By contrast, large-cycles are generally attributed to be products of allogenic processes [4, 5]. Small-scale cycles in the Warchha Sandstone are each 2 to 40 m thick and exhibit a fining-upward trend. Complete examples of such cycles (Fig. 4) are characterised by seven lithofacies (Gt, St, Sp, Sr, Sh, Fl and Fm). The large-scale cycle within which the smaller-scale cycles of the Warchha Sandstone are developed, represents part of a large scale regressive-transgressive phase of sea-level change that occurred during Permian time in the northeast part of

Gondwanaland. The Warchha Sandstone succession represents a wedge or tongue of non-marine strata bounded by marine deposits. Both the top and bottom boundaries of the Warchha Sandstone are marked by regional unconformities, which are traceable throughout the Salt Range. The lower contact with the underlying marine fossiliferous strata of an alternating mudstone and shale, siltstone and sandstone sequence of the Dandot Formation is marked by sub-aerial surfaces. The upper boundary represents a marine flooding surface due to transgression of a regressive-transgressive cycle and varies in its stratigraphic position. In the eastern Salt Range it is between the top of the Warchha Sandstone and overlying Palaeocene rocks. In central and western Salt Range, the upper boundary of the regressive-transgressive cycle is between the top of the Sardhai Formation and lower part of the overlying Amb Formation.

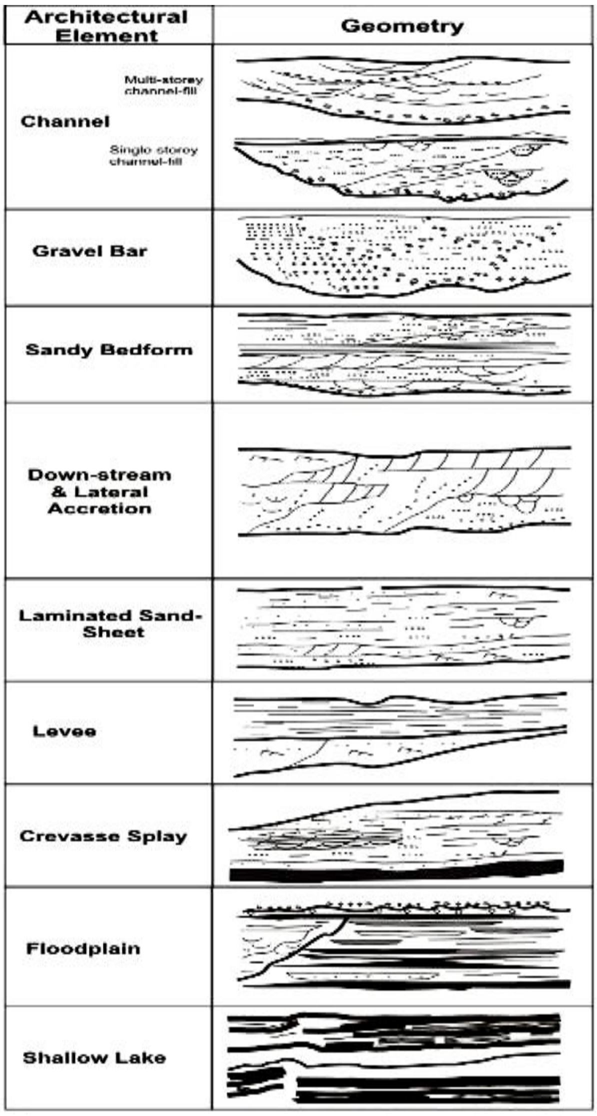


Fig. 3. Summary of the main architectural elements encountered in the Warchha Sandstone.

5. Petrographic analysis

Sandstone constitutes 45% of the Warchha Sandstone. The texture (grain size, sorting, and grain morphology) is very heterogeneous, varying from coarse-grained sandstone in the channel deposits, to very fine-grained sandstone interbedded with claystone in the floodplain deposits. Textural properties recorded within the Warchha Sandstone generally exhibit a loose-to-normal packing with tangential, concavo-convex and sutured contacts between the grains. Major detrital framework components of the sandstones – especially quartz, feldspar and rock fragments – have been recalculated as 100% for QFL diagrams, allowing these to occupy one of the three poles. Plots in the QFL diagrams proposed by Pettijohn [6] and Folk [7] show that 95% of the sandstones are arkoses and arkosic-arenites, and 5% of the sandstones are sub-arkoses (Fig. 5). The average modal composition of sub-arkoses is Q70% F22% L8% and that of arkoses and arkosic-arenites was Q60% F30% L10%. The overall average composition is Q57% F34% L9%.

6. Clay mineralogy

Claystone, shale, mudstone and siltstone, constitute 45% of the measured thickness of the Warchha Sandstone. Of these types, mudstone constitutes 50%, claystone 30% and siltstone 20% of the fine-grained clastics. XRD and SEM studies indicate that kaolinite is the dominant clay mineral, with illite, smectite, chlorite and mixed layers of illite/smectite also occurring in varying amounts and in several forms (Fig. 6).

7. Provenance

Provenance discriminations are based on the schemes of Dickinson et al. [8] and consider the hierarchy of different depositional environments for provenance interpretation defined by Ingersoll et al. [9]. Plots on QFL and QmFLt triangular diagrams indicate that the Warchha Sandstone was likely derived mostly from cratonic interiors and transitional continental blocks (Fig. 7; [10]). The plotted samples were concentrated along the Q-F/Qm-F lines within the stable cratonic, continental transitional and recycled orogenic areas in the continental block provenances (Fig. 7; [9, 10]).

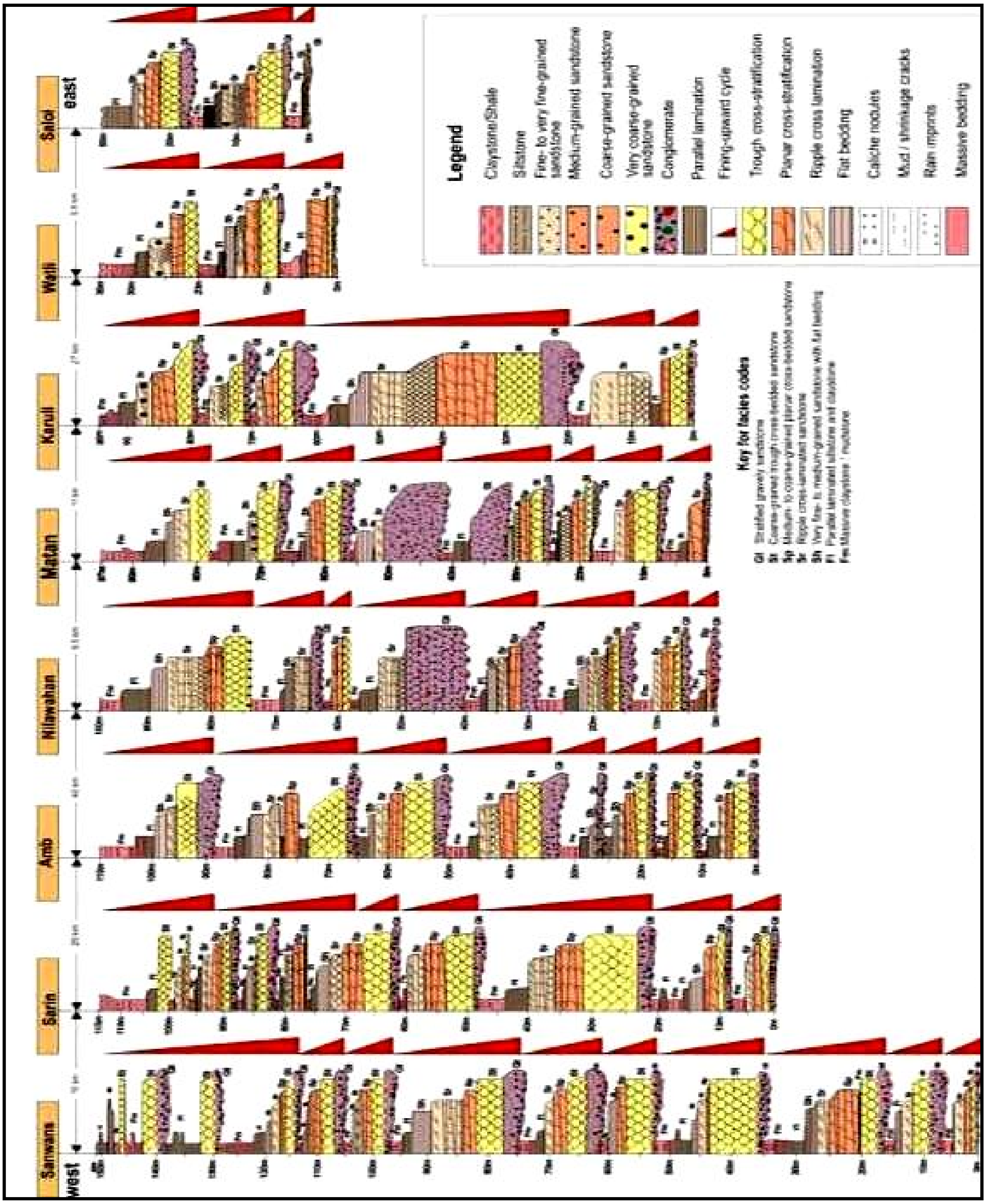


Fig. 4. Fluvial fining-upward cycles in the Warchha Sandstone from eight localities in the Salt Range.

Several other petrographic and sedimentologic characteristics were additionally used to determine the distribution of the source areas and type of source terrane of the Warchha Sandstone. Palaeocurrent directions indicate transport to the north and northwest, suggesting a source area to the south and southeast. The clast and sandstone composition does not suggest any change in the source area over time. Based on the detrital grain composition of the sandstones, the quartz grains in the Warchha Sandstone were likely to have been derived from the erosion and recycling of crystalline igneous or metamorphic rocks [11]. Detrital quartz grains showing evidence of plastic deformation (Figs. 8a-d), as demonstrated in thin section by grains possessing an undulatory extinction, are common in the Warchha Sandstone and indicate substantial tectonic uplift of crystalline basement rocks in the source region. Monocrystalline grains of detrital quartz of medium- to coarse-grain size (Figs. 8a-b) were likely derived from granites [10,11and12], whereas the fine-grained monocrystalline grains are most likely the product of breakage and chipping of larger quartz grains derived from an igneous provenance. By contrast, polycrystalline elongated and stretched quartz grains are most likely to have been derived from a metamorphic source [13], such as granite-gneiss or schist (Figs. 8c-d). Additionally, the rounded to well-rounded nature of some quartz grains is indicative of a sedimentary source [12]. Detrital K-feldspar grains were mainly derived from either acidic igneous rocks [14] or from granite and gneisses [12], whereas plagioclase feldspar grains were mainly derived from low-grade mica-schist. The detrital feldspar grains therefore likely indicate both an igneous and a metamorphic source. Detrital micas were most likely derived from low-grade metamorphic rocks like quartzite, schist, and gneiss, or from plutonic igneous rocks of granitic composition [13]. The presence of minor amounts of sedimentary rock fragments, including shale, siltstone, sandstone, limestone, dolomite, chert fragments and altered feldspar grains, indicates an additional sedimentary provenance.

8. Source rocks

The mineralogical data and Qm, F,Lt diagram (Figs. 5 and 7) indicate that a granitic or gneissic terrane ultimately contributed much of the straight extinction quartz and the K-feldspar in the Warchha Sandstone. The phyllite, schist and slate clasts are derived from low-grade metamorphic rocks.

Additionally, sub-rounded to rounded clasts of sedimentary rocks were possibly derived from the reworking of mature sedimentary rocks of Cambrian or Precambrian age. Heterogeneous weathering of feldspar grains is indicative of active tectonism, moderate relief, rapid erosion and hot climatic conditions, all of which indicate that the most probable geographic locations of the source areas was: 1) the Aravalli System, 2) the Malani Range, 3) an unrecognized but more local source of sedimentary rocks.

9. Depositional setting

The sedimentary facies within the Warchha succession represents the successive occurrence of different depositional sub-environments within the fluvial system at a given point (Fig. 9). The grouped cross-stratified sandstones are substratum sediments deposited in the canalized zones as transverse bars, point bars and channel lags (facies Gt, St and Sp). Ripple cross-laminated sandstones represent predominantly levee–type sediments (facies Sr). Horizontally bedded and solitary sets of cross-stratified finer-grained sandstones were deposited by overbank sheet floods, red claystone with siltstone and fine-grained sandstone lenses represent floodplain sediments (facies Sh, Fl and Fm). The arrangement of facies into fining-upward cycles characterised by a distinct set of architectural elements, all supports the hypothesis that the Warchha Sandstone accumulated in a high-sinuosity, meandering fluvial environment [13].

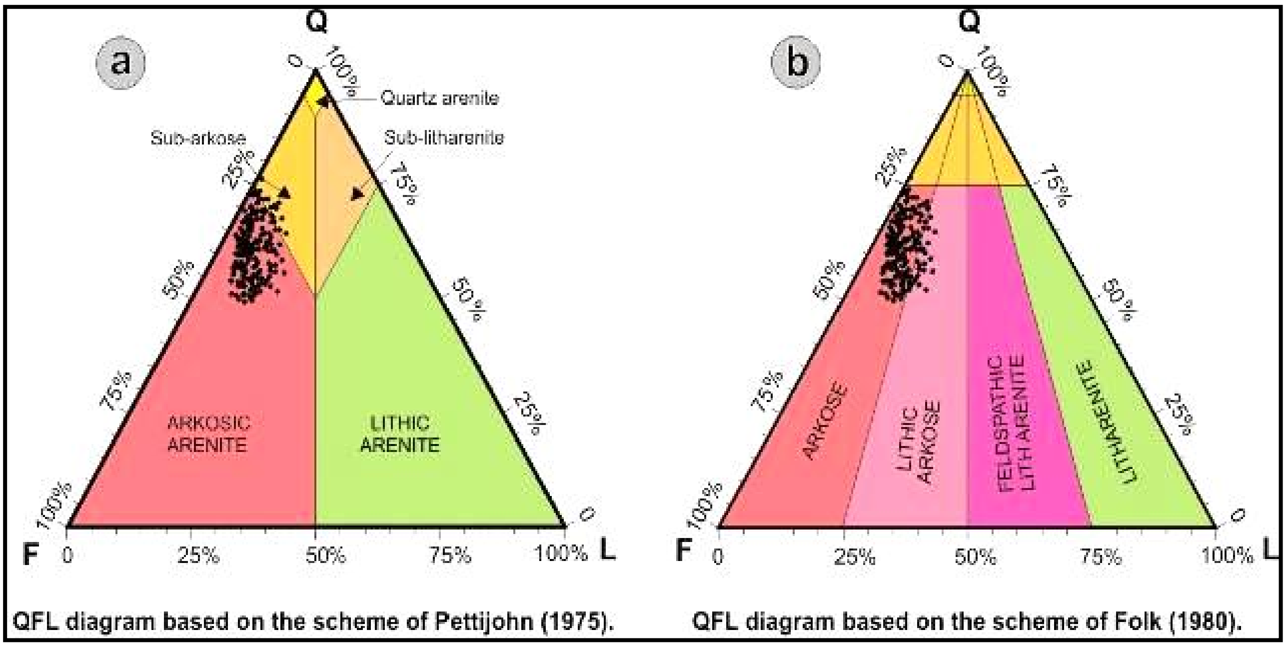


Fig. 5. Interpretation of the sandstone composition from the petrography of eight sections of the Warchha Sandstone based on schemes proposed by a) Pettijohn (1975) and b) Folk (1980). Standard plots: Quartz, Feldspar, Lithic grains (Q,F,L), showing arkosic to subarkosic nature of the sandstone.

Furthermore, the high proportion of overbank sediments testifies to the growth of appreciable alluvial floodplain relief which likely arose through the restriction of movement of channel belts by clay-plugged former channels, a common feature in systems characterised by channels of high sinuosity [13, 15, 16]. As is common in many high-sinuosity fluvial successions, the sedimentary characteristics of individual fining-upward cycles in the Warchha Sandstone are remarkably uniform [16], each recording the initiation, infill and final abandonment of a channel element.

Each cycle within the succession records the cutting and migration of an erosively-based fluvial channel that was subsequently in-filled by lateral migration of point bar deposits on inner bends (facies Gt, St and Sp) and its eventual abandonment and plugging with slack water deposits (facies Sh and Sr), before becoming overlain by unconfined floodplain overbank deposits (facies Fl and Fm) (Fig. 9).

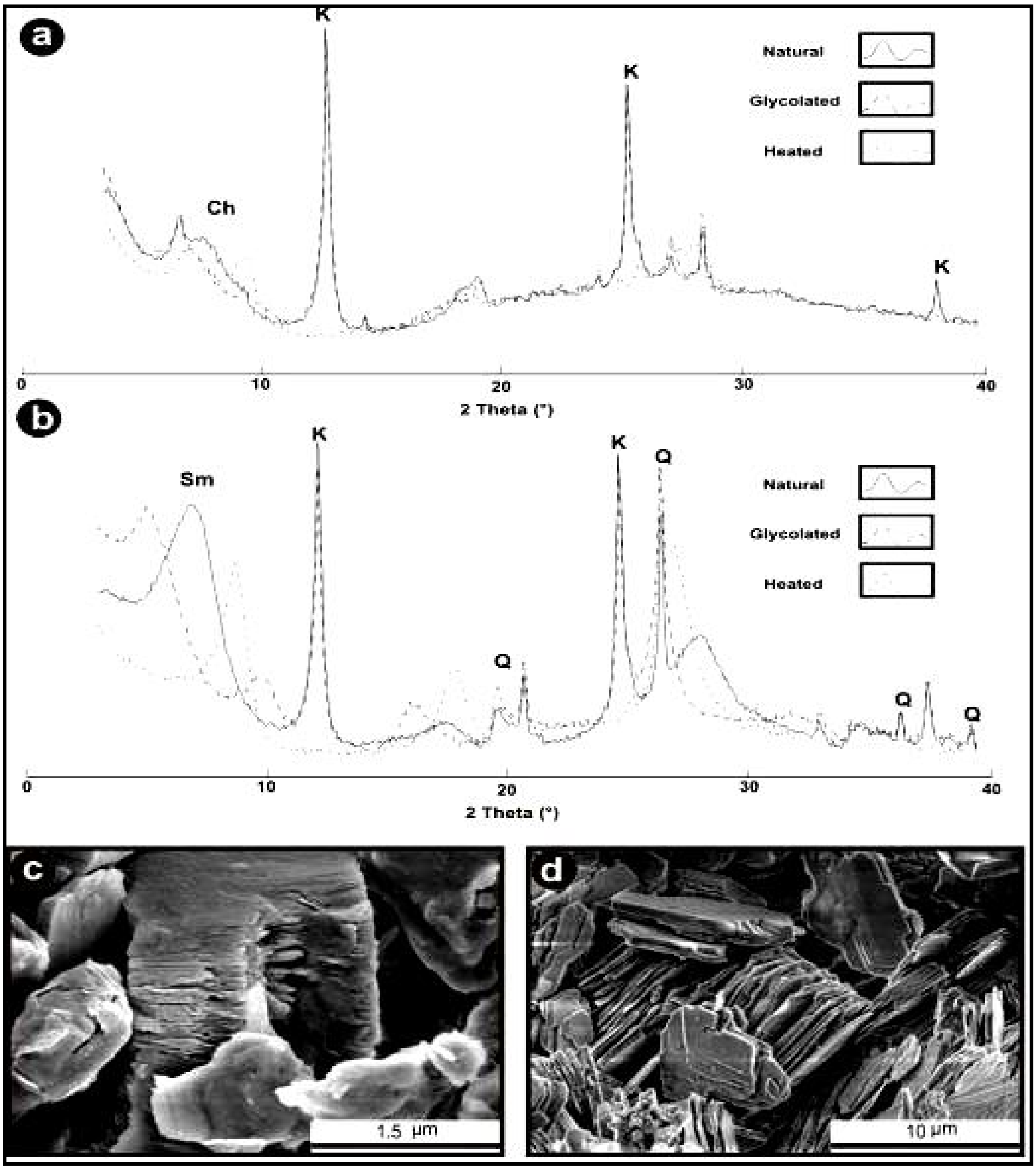


Fig. 6. a) XRD analysis of the Warchha Sandstone, Salt Range, Pakistan. a) Kaolinite (K) and chlorite (Ch). b) Kaolinite (K), smectite, montmorillonite (Sm) and quartz (Q). c, d) Scanning electron micrographs of kaolinite in the Warchha Sandstone. Stacked plates of kaolinite showing face-to-face arrangement and pseudo- hexagonal (books) outline of individual plates.

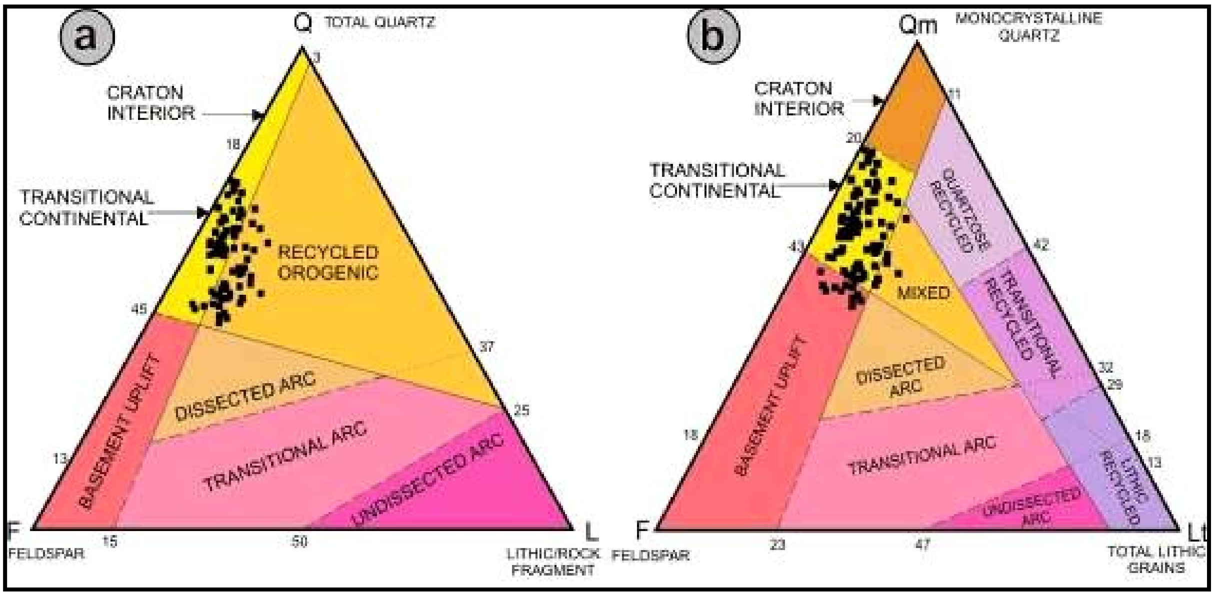


Fig. 7. Interpretation of provenance from the Warchha Sandstone in the Salt Range, Pakistan based on schemes proposed by Dickinson et al. (1983). a) Quartz, Feldspar, Lithic fragments (Q,F,L). b) Monocrystalline Quartz, feldspar, total lithic grains (Qm, F, Lt).

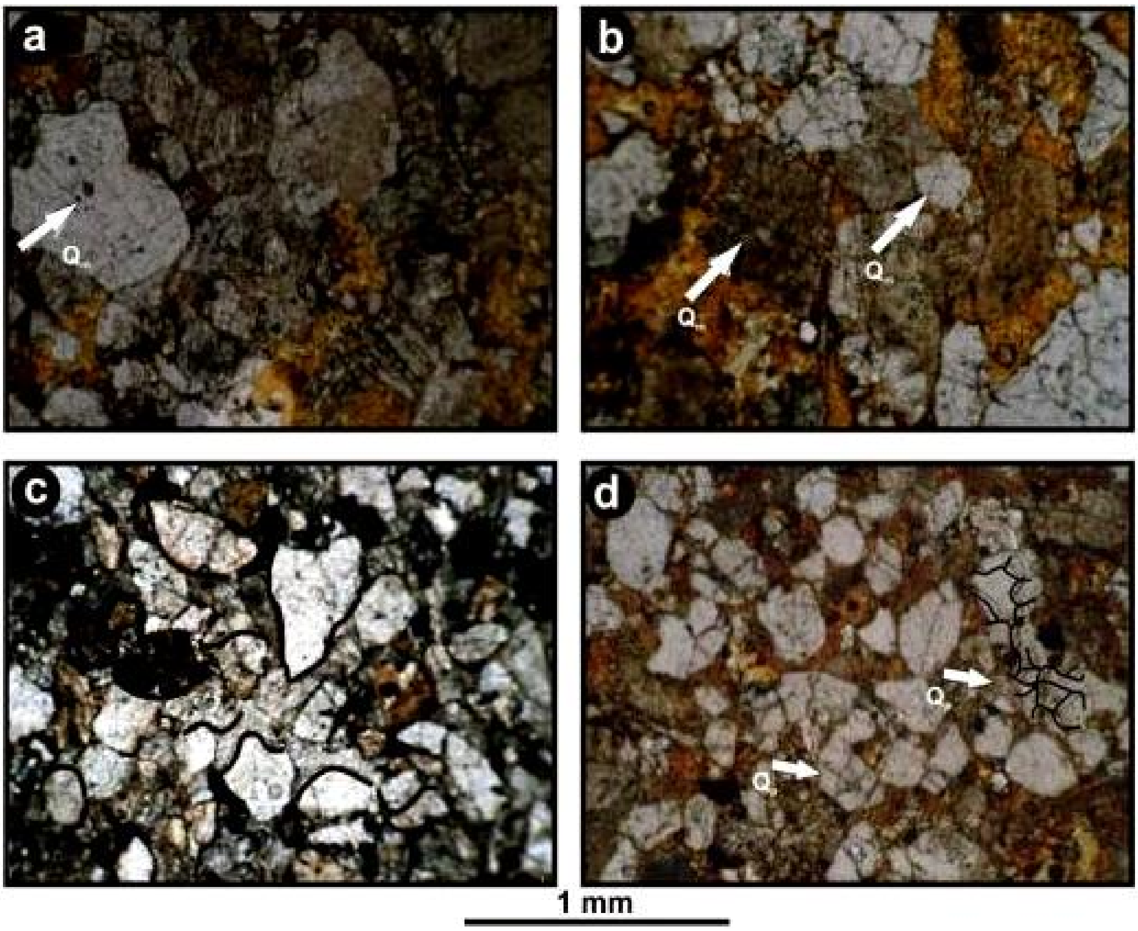


Fig. 8.Thin section photomicrographs of detrital grains in the Warchha Sandstone indicating their source rock. a) Monocrystalline quartz grains of igneous origin. b) Quartz grains of plutonic origin having microlites showing typical granitic source. c) Coarse – grained, poorly sorted sandstone with angular to sub-angular quartz grains with convex-concave contacts. Feldspar is dominantly plagioclase. d) Polycrystalline, stretched, elongated quartz grains of metamorphic origin having sutured contacts. e) Deformed rock fragments of metamorphic origin.

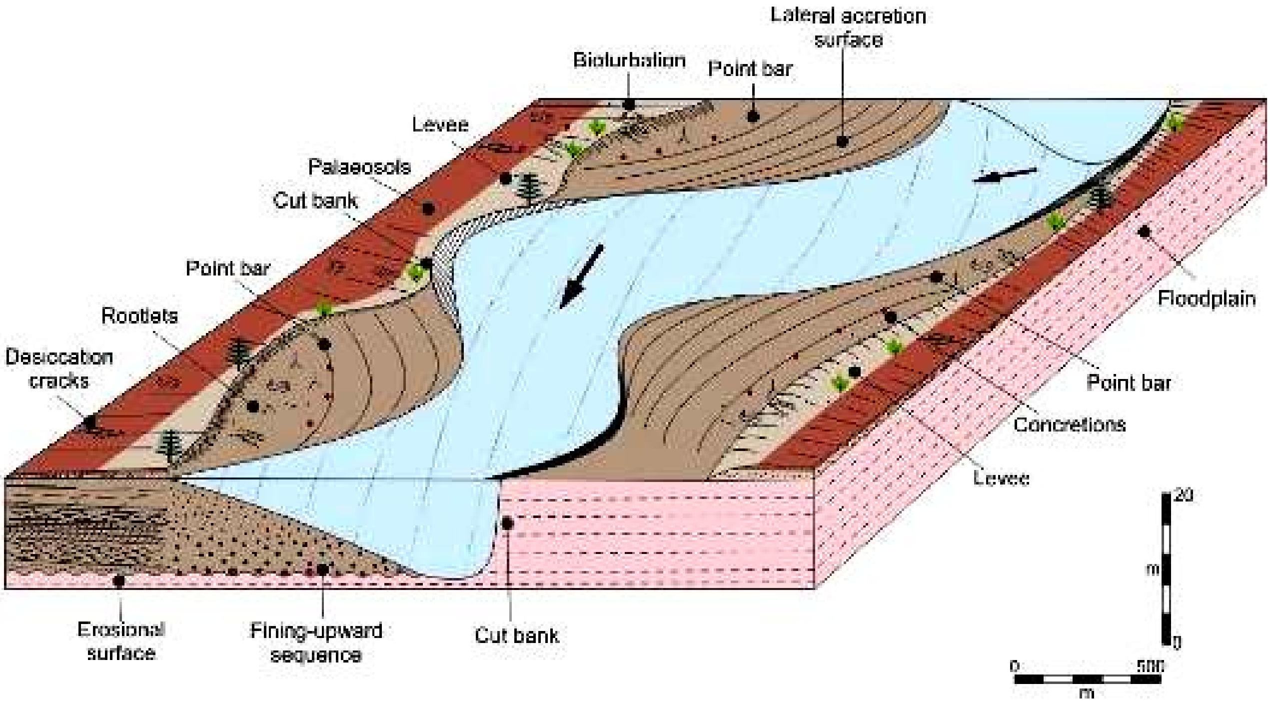


Fig. 9. Generalized deposional model for the Warchha Sandstone. Vertical sequence of meandering sand body produced by a high-sinuosity channel. The sequences are laterally continuos. fining-upward successions that form lateral accretion units, some of which can be traced laterally over 1 km.

Conclusions

1. The Warchha Sandstone is fluvial in origin and was deposited by a high-sinuosity, laterally accreting, meandering fluvial system, deposits of which are arranged into a series of 3 to 10 fining-upward cycles.
2. The succession is characterised by seven distinctive lithofacies types (Gt, St, Sp, Sr, Sh, Fl and Fm), each of which occur in a predictable order within the individual fining-upward cycles.
3. Successive cycles indicate palaeoflow directions which repeatedly switched from northeasterly to northwesterly, probably as a result of the lateral migration of successive meander loops in different directions. The overall regional flow direction for the fluvial succession was from south to north down a low gradient palaeo-slope.
4. Petrographically, the sandstone is mainly arkose to sub-arkose and the overall grain size is dominated by sand and clay in equal proportion.
5. On the basis of clast-type analysis, together with palaeocurrent and petrographic interpretations, the provenance of the Warchha Sandstone is considered to be the Aravalli Range to the southeast and the Malani Range to the south of the Salt Range, both of which lie on the stable Indian Craton.

References

[1] Wardlaw, B.R., Pogue, K.R., 1995, The Permian of Pakistan. In: Scholle P.A., Peryt, T.M., Ulmerscholle, D.S. (Eds.), the Permian of Northern Pangea, 2. Sedimentary Basins and Economical Resources, Springer Verlag, New York, p.215-224

[2] Miall, A.D., 1985, "Architectural-element analysis: A new method of facies analysis applied to fluvial deposits." Earth Science Reviews, v.22, p.261-308

[3] Miall, A.D., 1996, The geology of fluvial deposits: Sedimentary facies, Basin analysis, and Petroleum geology. Springer-Verlag, New York,

[4] Atchley, S.C., et al., 2004, "Eustatic control on alluvial sequence stratigraphy: a possible example from the Cretaceous-Tertiary transition of the Tornillo Basin, Big Bend National Park, West Texas, USA." J. Sediment. Res., v.74, p.391-404

[5] Cleveland, D. M., et al., 2007, "Continental sequence stratigraphy of the Upper Triassic (Norian-Rhaetian) Chinle Strata, Northern New Mexico, USA: Allocyclic and Autocyclic origins of palaeosol bearing alluvial successions." J. Sediment. Res., v.77**,** p.909-924

[6] Pettijohn, F.J., 1975, Sedimentary Rocks 3rd edition. Springer-Verlag, New York

[7] Folk, R.L., 1980, Petrology of Sedimentary Rocks. Hemphills, Austin, Texas

[8] Dickinson, W.R., et al., 1983, "Provenance of North American Phanerzoic sandstone in relation to tectonic setting." Geol. Soc. Am. Bull., v.94, p.222-235

[9] Ingersoll, R.V., Kretchmer, A.G., and Valles, P.K., 1993, The effect of sampling scale on actualistic sandstone petrofacies: Sedimentology, v. 40, p. 937–953.

[10] Dickinson, W.R., 1985, Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Dordrecht-Boston-

Lancaster. D. Reidel Publ. Co. p.333-361.

[11] Dutta, P.K., 2007, First- cycle sandstone composition and colour of associated fine-grained rocks as an aid to resolve Gondwana stratigraphy in peninsular India. In: Arribas, J., Critelli, S., Johnson, M.J. (Eds.), Sedimentary provenance and petrogenesis: perspectives from petrography and geochemistry. Geol. Soc. Am. Spec. Paper, 420, p.241-252

[12] Basu, A. et al., 1975, "Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation." J. Sediment. Petrol., v.45, p.873-882

[13] Ghazi, S., 2009, Sedimentology and stratigraphic evolution of the Early Permian Warchha Sandstone, Salt Range, Pakistan, PhD thesis, Univ. of the Leeds, England,

[14] Ghosh, S. K., Kumar, R., 2000, "Petrology of Neogene Siwalik Sandstone of the Himalayan foreland basin, Garhwal Himalaya: Implication for source area tectonics and climate." J. Geol. Soc. India, v.55, p.1-15.

[15] Ghazi, S., Mountney, N.P., 2009, "Facies and architectural element analysis of a meandering fluvial succession: The Permian Warchha Sandstone, Salt Range, Pakistan." Sediment. Geol., v.221, p.99-12.

[16] Ghazi, S., Mountney, N.P., 2011,"Petrography and provenance of the Early Permian Fluvial Warchha Sandstone, Salt Range , Pakistan." Sediment. Geol., v. 233, p. 88-110.