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Petrography of Sandstones from the Kamlial and Chinji Formations, Southwestern Kohat Plateau, NW Pakistan: Implications for Source Lithology and Paleoclimate

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Abstract

The Kamlial and Chinji formations of the southwestern Kohat plateau (Himalayan Foreland basin) dominantly consist of sandstones and shales deposited in a terrestrial foreland basin that developed in response to the Himalayan orogenic movements. Detailed petrographic studies of representative samples from three different sections reveal that both the Kamlial and Chinji sandstones contain abundant quartz with subordinate feldspars, variable proportions of lithic grains, accessory amounts of micas and traces of a number of heavy minerals. The feldspar content mostly ranges from 18 to 30% and 24 to 28% in the Kamlial and Chinji sandstones, respectively. The abundance of lithic grains shows a wide range of variation (11 to 35%). Although the lithics are mainly sedimentary, but fragments of volcanic and low-grade metamorphic rocks also occur in appreciable amounts. Micas, including both muscovite and biotite, are generally less than 10 % of the total detrital grains. The observed heavy minerals include epidote, monazite, apatite, garnet, zircon, rutile and brown hornblende. The crystals of zircon, monazite, rutile, epidote and mica also occur as tiny inclusions in quartz grains.

On the basis of modal composition, the Kamlial and Chinji sandstones fall into the groups of feldspathic and lithic arenites. The former mostly originates by the weathering of feldspar-rich crystalline rocks whereas the latter is believed to be derived from rugged high-relief source areas. The presence of appreciable amount of feldspars in all the studied sandstone samples favors either high relief or arctic climate at the source area. The overall variation in the relative abundance of different types of quartz grains (monocrystalline including both non-undulatory and undulatory types and polycrystalline containing 2-3 and >3 subgrains) in the Kamlial sandstone indicates derivation from medium-high grade metamorphic rocks with subsidiary contribution from low grade metamorphic rocks. In comparison, the same parameter shows almost equal contribution from medium-high grade and low-grade metamorphic rock provenance for the Chinji sandstone. Similarly, the consistent presence of mica, epidote, and garnet also indicates a source region composed of metamorphic rocks. On the other hand, the average contents of different types of quartz grains from the Kamlial and Chinji Formations show granitic and/or gneissic source. The greater abundance of alkali feldspar than plagioclase further supports this conclusion. Similarly, the higher amount of non-undulatory monocrystalline quartz than the undulatory one suggests the presence of plutonic and volcanic rocks in the source area or, alternatively, a long distance/amount of transport of the detritus. Furthermore, the inter-sectional variation in modal composition and types of quartz grains in both the Kamlial and Chinji sandstones suggest a strong spatial control on their deposition.

1. Introduction

Petrography and heavy mineral suites of sandstone provide information about the nature of source rocks, the uplift history and evolution of orogenic belts. However, at the same time, weathering conditions in the source area also play an important role in controlling sediments composition (Critelli et al., 1997). In areas of intense tectonic activity, source-rock type determines sediment composition more than do climate and relief (Dickinson, 1970). Where tectonism is negligible, climate and relief are more important in determining the final composition of clastic sediments (Basu, 1976).

This paper presents the results of petrographic studies of sandstones of the Kamlial and Chinji formations of the southwestern Kohat Plateau for determination of their source rocks and paleoclimatic conditions. Samples representing these two formations were collected from three sections: the Banda Aisore syncline, the Bahadar Khel anticline and the Chashmai anticline (Fig. 1). The tectonically disturbed nature of the region and lack of continuous sedimentary sections make it impossible to identify the stratigraphic position of a sample more accurately than an assignment to its formation. Thin sections of the collected sandstone samples were studied in detail and the petrographic data used for classifying the rocks based on their modal composition following the scheme designed by Okada (1971), Basu et al. (1975) and modified by Tortosa et al. (1991).

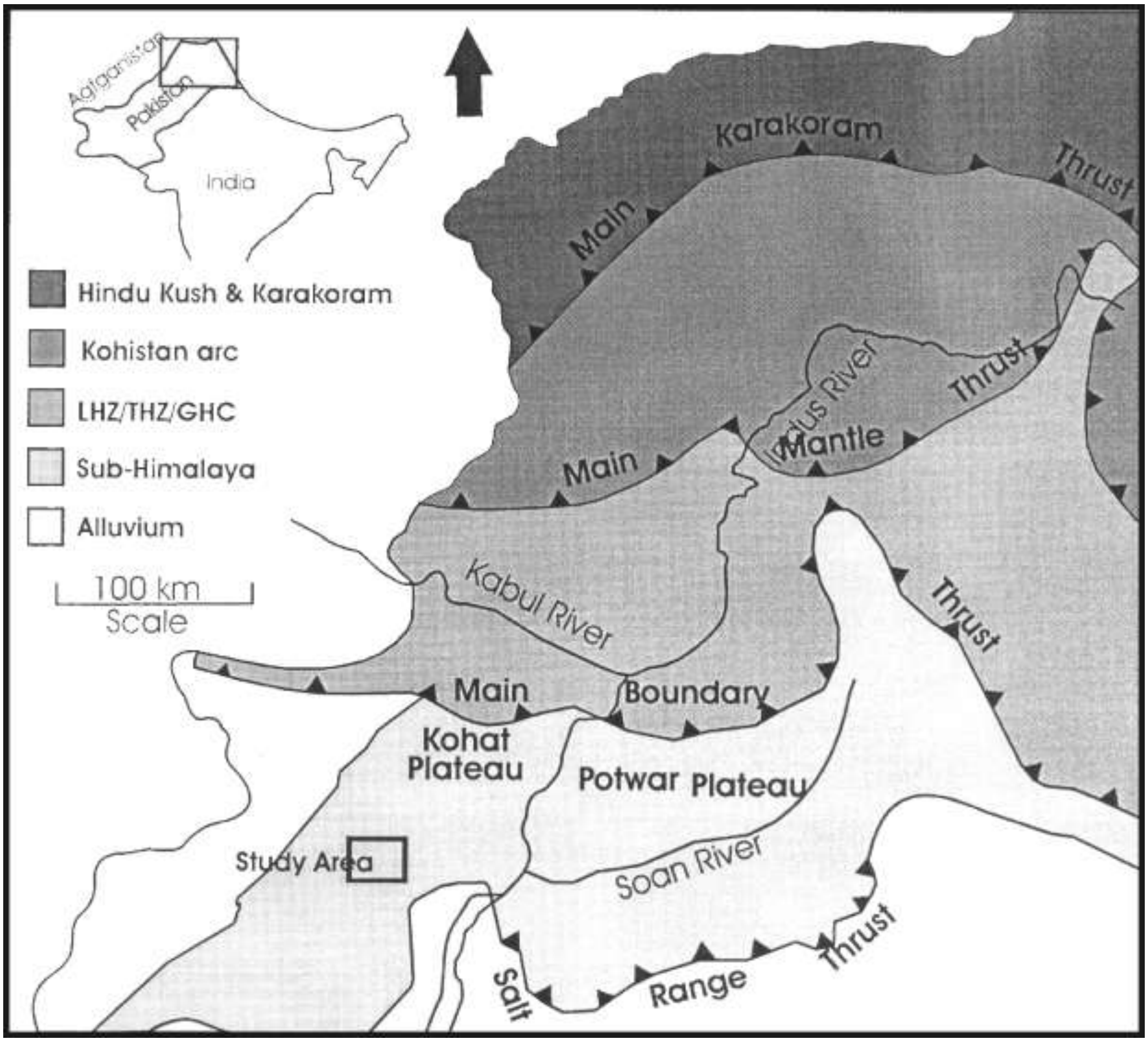


Fig. 1. Location of the study area with reference to regional tectonic framework. The Indus river in the east separate Kohat from the Potowar Plateau and the MBT marks its northern extremity.

2. Regional Geology and Tectonics

The Himalaya consists of six lithotectonic zones (Gansser, 1964). From north to south, these belts and their representative rock types include the following:

(i) The Trans-Himalayan zone consists of the upper Cretaceous to Eocene calc-alkaline plutons, interpreted as the Andean-type northern margin of the Tethys (Le Fort, 1996).

(ii) The Indus suture zone, i.e., the zone of collision between the India and Eurasia, is composed of deep-water Indian continental rise sediments, the Trans-Himalayan accretionary complexes, ophiolites and ophiolitic melanges, island arc volcanics, and forearc basin sedimentary rocks (Searle, 1983; Robertson and Degnan, 1993).

(iii) The Tibetan or the Tethys Himalayan Zone (THZ) consists of the Proterozoic to Eocene siliciclastic and carbonate sedimentary rocks interbedded with Paleozoic and Mesozoic volcanic rocks (Yin, 2006; and references therein).

(iv) The Greater Himalayan Crystalline Complex (GHC) is composed of the Indian continental crust and sedimentary rocks of mainly the late Proterozoic–Cambrian age (Parrish and Hodges, 1996), now regionally metamorphosed and intruded by leucogranite crustal melts in the uppermost part (e.g., Treloar and Searle, 1993) (Fig. 1).

Although the GHC is generally considered to be composed of high grade rocks, it consists of low grade to essentially unmetamorphosed sedimentary strata, and thus becomes indistinguishable from the THZ in northern Pakistan (Pogue et al., 1999). The high grade GHC rocks generally form a continuous belt along the east-trending axis of the Himalayan range, but they also occur as isolated patches surrounded by the low grade Tethyan Himalayan strata such as in the Nanga Parbat massif of northern Pakistan (DiPietro and Pogue, 2004). Although a high grade equivalent of the GHC does not occur in northern Pakistan (Yeats and Lawrence, 1984), high grade rocks belonging to the Lesser Himalayas are reported from within and adjacent to the Nanga Parbat syntaxis (DiPietro and Isachsen, 2001). The GHC is thrusted over the unmetamorphosed or low grade late Palaeoproterozoic rocks of the Lesser Himalayan Zone (LHZ) along the Main Central Thrust (MCT) (Valdiya and Bhatia, 1980).

(v) The Lesser Himalayan Zone (LHZ) includes the nonfossiliferous low-grade metasedimentary rocks (Heim and Gansser, 1939) that are overlain by Permian to Cretaceous strata (the Gondwana Sequence) (Gansser, 1964). This zone completely lacks the Ordovician to Carboniferous strata that occur in the THZ (Yin, 2006).

(vi) The Sub-Himalayas contain molasse sediments in Pakistan that are best preserved in the fold-thrust belts of the Potwar-Kohat plateau, Trans Indus ranges, and Sulaiman and Kirthar belts, and have mostly unconformable contacts with the underlying Eocene carbonate rocks (Thakur, 1992). The MBT is defined as the thrust placing the LHZ over Tertiary sedimentary strata (Heim and Gansser, 1939) (Fig. 1).

3. Local geology of the Kohat Plateau

Located between 32°-34° N and 70°-74° E, the ~ 10,000 km^2 Kohat Plateau constitutes the westernmost deformed part of the Himalayan Foreland basin. It consists of anticlinal hills that resulted from the ongoing collision between the Indian and Eurasian plates and contains some of the best exposed Cenozoic sedimentary rocks (Pivnik and Wells, 1996). The Kohat Plateau is bounded by the MBT in the north, Surghar Range Thrust/ Salt Range Thrust in the south, Kalabagh Fault (and Indus River) in the east and Kurram Fault in the west (Khan et al., 1986; Jaume and Lillie, 1988). The first comprehensive geological map of the Kohat Plateau was published by the United States Geological Survey (Meissner et al., 1974).

The Kamlial and Chinji formations are part of the Miocene molasse sequence of the Kohat Plateau. The Kamlial Formation is the upper part of the Rawalpindi Group, while the Chinji Formation constitutes the Lower Siwaliks (Meissner et al., 1974). Both the formations are composed of sandstones, shales and conglomerates, that are believed to have been deposited in a terrestrial foreland basin in response to the Himalayan orogenic movements during the collision (Meissner et al., 1974; Johnson et al., 1985).

3.1. Kamlial Formation

The name “Kamlial Formation” was used for the rocks exposed near the Kamlial village (Late. 33° 15′ N; Long. 72° 30′ E.) in the Attock district. These rocks were previously named “Kamlial Stage” by Pinfold (1918). The name “Kamlial Formation” was proposed by Lewis (1937) and later accepted by the Stratigraphic Committee of Pakistan (1964).

The Kamlial Formation in eastern Kohat is comprised of dark-gray to greenish-gray sandstone (about 75%) exhibiting spheroidal weathering, interbedded with dark-red to maroon color siltstone (about 20%) and subordinate intraformational conglomerates (about 5%). The sandstone is fine to medium grained, cross-bedded, channelized and intercalated with lenses of intraformational conglomerates or thin layers of clay flakes (Abbasi, 1991). The Kamlial sandstone is characterized by the presence of high amounts of detrital green minerals such as chlorite, greenish biotite and minor amount of glauconite (Abbasi and Friend, 1989). Tourmaline and garnet are its common heavy mineral constituents (Abbasi and Khan, 1990).

The lower contact of the Kamlial Formation with the Murree Formation is transitional, but in the Kohat plateau, it unconformably overlies the Kohat Formation. Its upper contact with the Chinji Formation is, however, conformable. The age of the Kamlial Formation is middle to late Miocene (Fatmi, 1973; Meissner et al., 1974). It is also assigned an age from 18.3 to 14.3 Ma on the basis of magnetic stratigraphic studies (Johnson et al., 1982).

3.2. Chinji Formation

The terms “Chinji Zone” of Pilgrim (1913) and “Chinji Stage” of Pascoe (1963) for stratigraphic units consisting of interbedded sandstone, silty clay and siltstone were later on reformed as “Chinji Formation”. The type section is exposed near the Chinji village (Late. 32° 41′ N., Long. 72° 22′ E.).

The Chinji Formation in the Potwar plateau is dominantly composed of bright red and brown orange siltstone interbedded with ash-gray sandstone (siltstone to sandstone ratio = 4:1 in the type section). The interbedded in-channel and overbank siltstone sequences are 10-50 meter thick. Major sand bodies are multistoreyed with individual storeys generally 5-10 meter thick that are complexly stacked both vertically and laterally (Willis and Behrensmeyer, 1994).

From the Kohat plateau, the Chinji Formation is described with reference to four units (Meissner et al., 1974). The bottom unit consists of interbedded sandstone, silty clay and siltstone followed by a unit predominantly composed of sandstone containing subordinate beds of siltstone and silty clay. The next unit is also composed of sandstone, siltstone and silty clay and the topmost unit is mostly silty clay and claystone containing yellowish-gray, medium to coarse-grained sandstone at the base.

Based on magnetic stratigraphic studies in Potwar, 14.3 Ma and 10.8 Ma are interpreted to be the ages of the lower and upper contacts of the Chinji Formation, respectively (Johnson et al., 1985). To the west in the Surghar range, these contacts are believed to be 11.8 Ma and 8 Ma old, respectively (Khan and Opdyke, 1993). On the basis of different fauna, the age of the formation is considered to be late Miocene (Sarmatian) (Fatmi, 1973).

4. Petrographic methods and grain counting

Chips of thin sections were cut from twenty two sandstone samples and impregnated with casting resin, thinner, and then heated to enable setting of the friable material. Further impregnation with petropoxy was required to make the thin section preparation possible (Garzantia et al., 2005). The framework constituents of these thin sections were counted randomly with grid spacing adjusted such that to allow 300 counts, without counting a grain more than once (Rumelhart and Ingersoll, 1997). The Gazzi-Dickinson method of point counting was used (Ingersoll et al., 1984), and crystals larger than 0.0625 mm within lithic fragments were counted as monocrystalline grains. In all cases, the effects of diagenesis were "mentally removed" so that the original detrital composition could be accurately determined (Rumelhart and Ingersoll, 1997).

The major categories of grains identified during the point counting include nonundulatory monocrystalline quartz (Q_{nu}), undulatory monocrystalline quartz (Q_u), polycrystalline quartz with 2-3 subgrains (Qp_{2-3}), polycrystalline quartz with >3 subgrains ($Qp_{>3}$), plagioclase (P), potash-feldspar (K), sedimentary lithic (Ls), carbonate lithic (Lc), volcanic lithic (Lv), metamorphic lithic (Lm) and chert. Heavy minerals, mica and miscellaneous grains were also included in this record (Ingersoll and Suczek, 1979).

The relative percentage of the four types of quartz were plotted on the provenance-discrimination diagram of Basu et al. (1975). Girty et al. (1988) have also recommend this diagram for the discrimination of quartz grains derived from plutonic and metasedimentary rocks. However, Tortosa et al. (1991) suggest that the diagram must be used with caution if plutonic and middle-upper grade metamorphic rocks occur in the source area.

5. Results

5.1. Kamlial Formation (n = 10)

Sandstone of the Kamlial Formation is mostly matrix (dominantly carbonate) supported. The sandstone is mainly well to moderately sorted, with sand particles generally subangular to subrounded. Quartz (Q), chiefly monocrystalline, is the dominant detrital constituent of the Kamlial sandstone. The abundance of quartz generally increases upsection from < 60% in the lower and middle parts to ≥ 60% in the upper part of the formation. The average quartz and feldspar (F) contents are, respectively, 50.9 and 25.3% (Qt/F=2.0) in the Banda Aisor syncline, 60 and 23.6% (Qt/F=2.5) in the Chashmai anticline, and 54 and 22.9% (Qt/F=2.4) in the Bahadar Khel anticline. The average abundance of feldspar is approximately similar in all the three sections. Although the overall range of feldspar is 9 to 33%, it mostly falls between 18 to 30%. Lithic grains show a much wider range of variation from 11 to 35%.

The nonundulatory type of monocrystalline quartz (Q_{nu}) is more dominant than the undulatory one (Q_u) in the Chashmai anticline and Banda Aisor syncline, but Q_u is more at the Bahadar Khel anticline. The detrital feldspar component of the Kamlial Formation is dominated by alkali feldspar. The average P/F ratios are 0.39, 0.32 and 0.26 in the Banda Aisor syncline, Chashmai anticline and Bahadar Khel anticline, respectively. Some of the feldspar grains are kaolinized or sericitized (Fig. 2a). Grains of microcline and perthitic alkali feldspar as well as fresh plagioclase also occur in a couple of thin sections (Fig. 2b).

Lithic fragments are mainly sedimentary (Ls) (argillite, shale and chert) (Fig. 2c). However, volcanic (Lv) and low-grade metamorphic (Lm) (slate and schist) lithics also occur in appreciable amounts (Figs. 2d, e, f). The average contents of lithic fragments are: Lm=23%, Lv=37%, Ls=40% in the Banda Aisor syncline, Lm=24%, Lv=13%, Ls=63% in the Chashmai anticline and Lm=23%, Lv=22%, Ls=55% in the Bahadar Khel anticline.

Metamorphic lithics are dominantly of quartz-mica schist and slate in all the three sections (Figs. 2d, e, f). Other metamorphic lithics include mica-schist, phyllite and quartzite (Figs. 2e, f). Mica-schist is consistently present throughout the Banda Aisore syncline and Bahadar Khel anticline. Sedimentary lithics include mudstone, lime mudstone and siltstone.

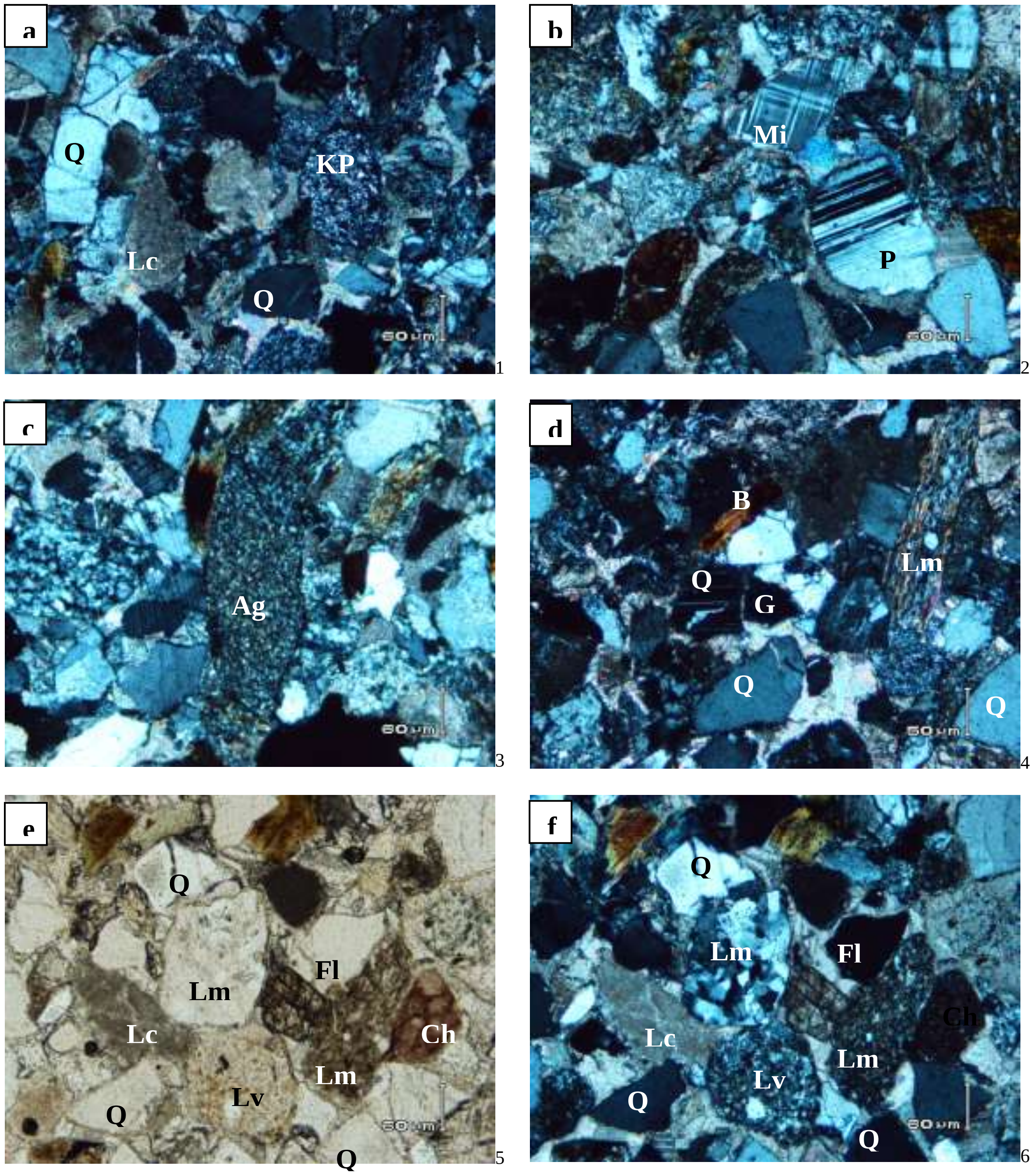
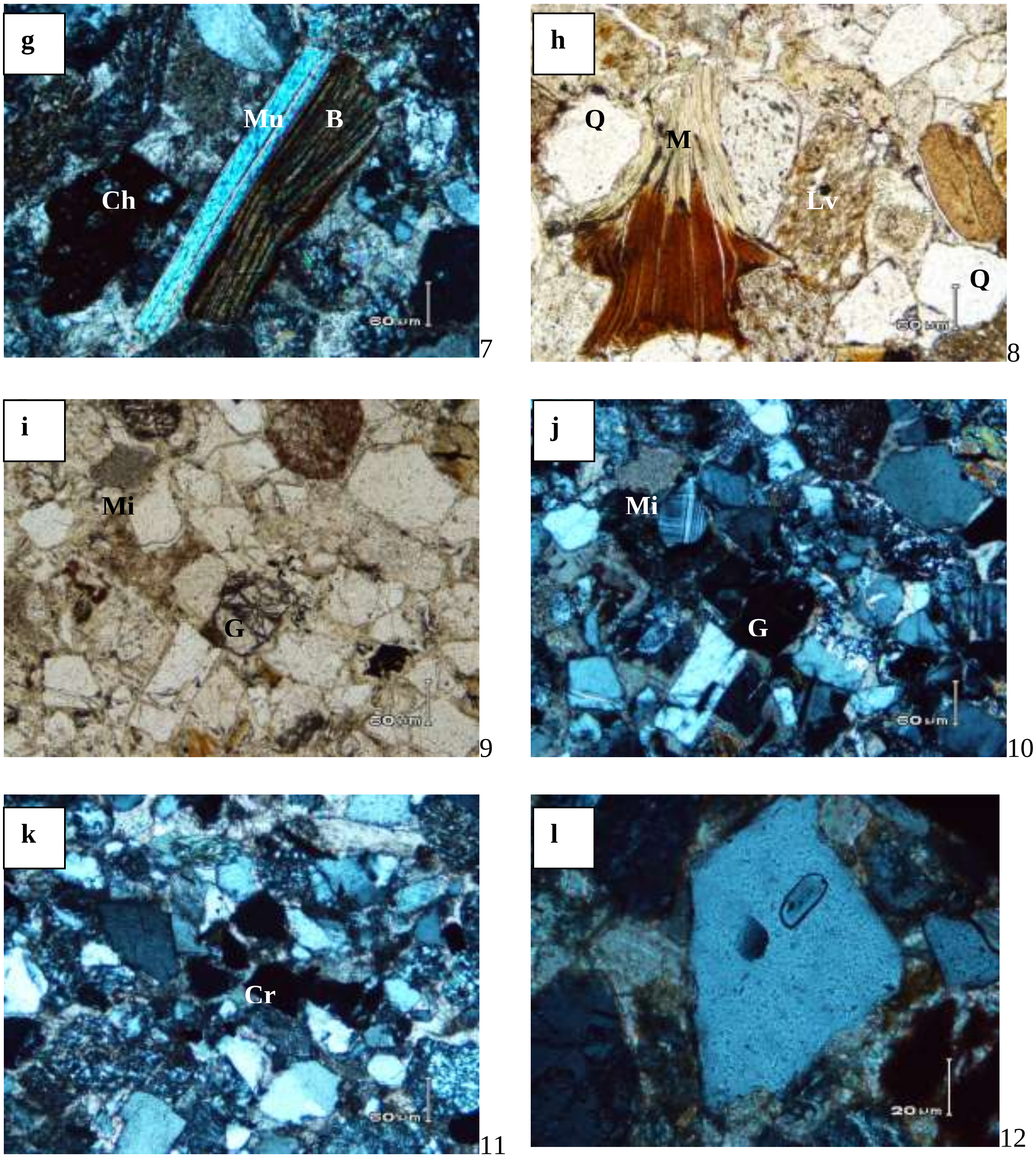


Fig. 2. Photomicrographs of the Kamlial and Chinji sandstones: a. Kaolinized plagioclase (KP), carbonate lithic (Lc) (micritic) and quartz (Q). Fractures in quartz grain (left) are filled with carbonate. b. Fresh plagioclase (P) and microcline (Mi) displaying the characteristic albite polysynthetic and cross-hatched twinning, respectively. c. Argillite (Ag). A lithic clast composed of fine grained material. d. Quartz (Q), garnet (G), metamorphic lithic (Lm) and biotite (B). Quartz grains are subangular to subrounded, garnet is isotropic, biotite is oxidized, and the metamorphic lithic is of quartz-mica schist. e, f. Quartz (Q), volcanic lithic (Lv), metamorphic lithic (Lm), carbonate lithic (Lc), chert (Ch) and fluorite (Fl). Subangular quartz grain having a fracture filled with carbonate. A number of lithic grains can be identified. Metamorphic lithic grains shown in the photomicrograph are of quartzite and quartz-mica schist. Chert (Ch) derived from sedimentary sources can be mistaken for very finely crystalline volcanic rock fragments or clay clasts if not carefully examined. (Continued)



g. This photomicrograph contain biotite (B), muscovite (M) and chert (Ch). **h.** Mica (M), quartz (Q) and volcanic lithic (Lv) can easily be identified. **i & j.** Garnet (G) and microcline (Mi). Garnet has high relief and is isotropic. Microcline with typical grid twinning. **k.** Chromite (Cr) is in the center of the photomicrograph. **l.** Quartz containing tiny inclusions of zircon/monazite.

Of the total frameworks in the Kamlial Formation, mica (Figs. 2g, h) ranges from 3 to 6% at the Chashmai anticline, 2.6 to 7% at the Banda Aisore syncline, and 1.3 to 15% at the Bahadar Khel anticline. The maximum amounts of mica (i.e., 7% and 15%) occur in the upper part of the formation at the Banda Aisore syncline and Bahadar Khel anticline, respectively. Biotite prevails in all the three sections and is dominantly oxidized. Some of the mica flakes are highly deformed.

Trace amounts of a number of heavy minerals also occur in the Kamlial Formation. These include epidote, garnet, monazite, ilmenite, rutile, apatite, chromite and fluorite (Figs. 2d, e, f i, j, k). In addition to discrete grains, zircon, monazite and muscovite also occur as inclusions in different grains of quartz. As pointed out earlier, carbonate is the dominant constituent of the matrix. Besides, carbonate also occurs as fracture-fills and/or replacing relatively unstable framework grains along cracks and cleavages in several of the studied thin sections. Fractures in grains of quartz are divisible into two: (1) filled with calcite and (2) those without any calcite filling. The former probably developed by compaction during burial and the latter during tectonic uplift (Abbasi and Friend, 1989). A few quartz grains have incipient silica overgrowths. The quartz overgrowths may be the result of pressure dissolution, when the grains are buried under the pressure of the overlying rocks (Pettijohn et al., 1987).

5.2. Chinji Formation (n = 12)

The dominantly matrix supported sandstone of the Chinji Formation is moderately to well sorted and its framework grains are angular to rounded. The matrix is dominantly carbonate. The average framework composition of the sandstone is Q=44, F=24, L=32 (Q/F=1.9) at the Banda Aisor syncline, Q=59, F=27, L=12 (Q/F=2.2) at the Chashmai anticline, and Q=54, F=28, L=18 (Q/F=2.0) at the Bahadar Khel anticline, respectively. Monocrystalline quartz (Qm) dominates in all the three sections of the Chinji Formation with average Qm/Qp ratio of 25.8 at the Banda Aisor syncline, 18.5 at the Chashmai anticline and 15.3 at the Bahadar Khel anticline. Q_{nu} is dominant at the Chashmai anticline, but is suppressed by Q_u at the Banda Aisor syncline and Bahadar Khel anticline. Alkali feldspar is the dominant feldspar in the Chinji Formation, increasing upsection relative to plagioclase in the Chashmai anticline, but decreasing upsection at the Banda Aisor syncline. However, the ratio of plagioclase to alkali feldspar does not display any meaningful trend in the samples from the Bahadar Khel anticline. The occurrence of microcline is also relatively more common in the Chinji sandstone than in the Kamlial sandstone (Figs. 2b, i, j). Lithic fragments range from 12 to 32% in the Chinji sandstone and are dominated by sedimentary lithics including chert (Fig. 2c). The lithic fragment composition of the formation at the Chashmai anticline is dominated by Ls (averaging 81%) followed by Lm (averaging 16%) (Figs. 2d, e, f). The occurrence of Lv (Figs. 2e, f) is confined to the upper part of the formation only and constitutes 10% of the lithic grains. Lm decreases upsection at the Chashmai anticline. At the Banda Aisor syncline, the formation is dominated by Lv (averaging 48%), followed by Ls (averaging 36%), and Lm (averaging 16%). Lv shows an upsection increase from 43 to 53% whereas Lm shows upsection decrease from 19 to 13%. The average content of lithic fragments at the Bahadar Khel anticline is: Ls=52%, Lv=27% and Lm=29%. Metamorphic clasts are dominantly low-grade mica-schist, quartz-mica schist (Figs. 2d, e, f) and slate while the sedimentary clasts include mudstone and lime mudstone.

Of the total frameworks in the Chinji Formation, mica (Figs. 2g, h) ranges from 3 to 9% at the Chashmai anticline, 0 to 3% at the Banda Aisore syncline and 1 to 9% at the Bahadar Khel anticline. The dominantly oxidized and/or highly deformed flakes of biotite occur in almost all the three sections.

Heavy minerals of the Chinji Formation include epidote, monazite, apatite, garnet, rutile and brown hornblende (high-grade metamorphic hornblende) (Figs. 2d, e, f, i, j, k). The quartz grains contain inclusions of zircon, monazite, rutile, epidote and mica. Authigenic carbonate is abundant in all the samples and appears to have selectively replaced unstable framework components. Besides, carbonate also occurs as fracture-fills in some framework grains along cracks and cleavages. These carboanet-filled fractures in quartz grains are probably developed by compaction during burial, and unfilled fractures are developed during tectonic uplift (Abbasi and Friend, 1989). The incipient silica overgrowths in some quartz grains also suggest pressure dissolution under the pressure of the overlying rocks (Pettijohn et al., 1987).

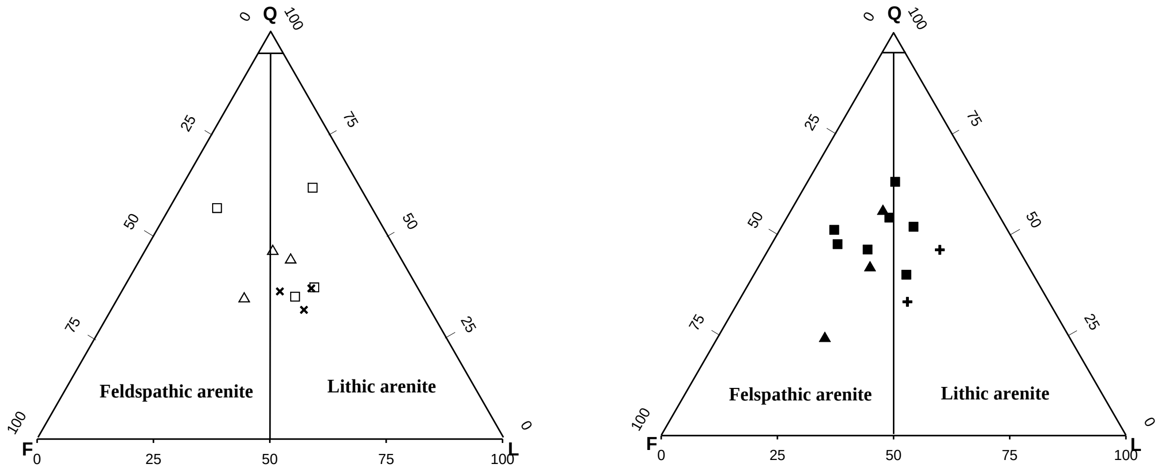
6. Discussion

Mineralogically, the sandstones of the Kamlial and Chinji formations of the studied sections belong to both feldspathic and lithic arenites (Figs. 3A, B) (Okada, 1971; Folk, 1974). However, sandstone of the Kamlial and Chinji formations from the Banda Aisore syncline is totally lithic arenite while that of the Chinji Formation from the Chashmai anticline is exclusively feldspathic arenite (Figs. 3A, B).

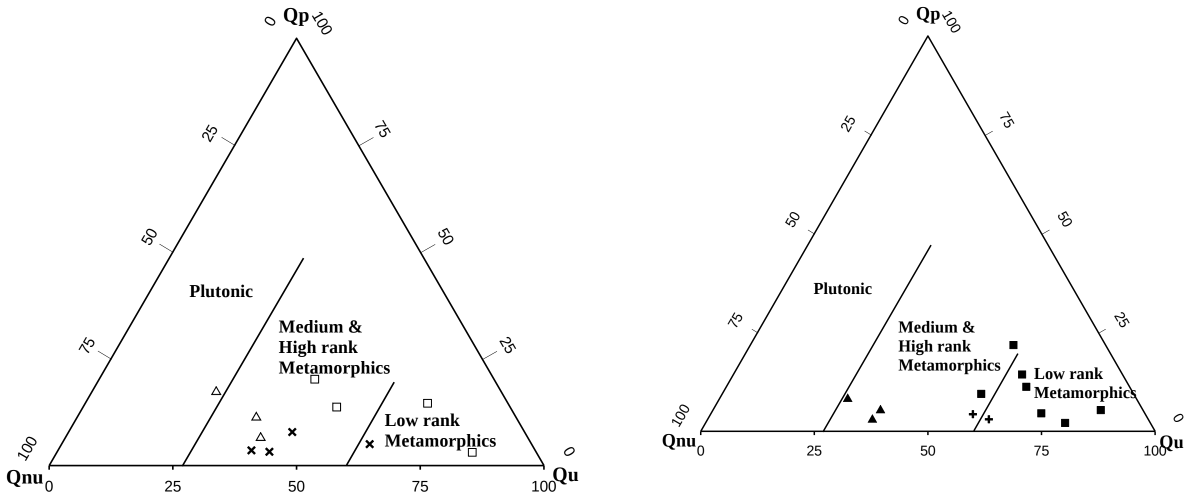
Feldspathic arenites are assumed to be first-cycled deposits that mainly originate by the weathering of feldspar-rich igneous and metamorphic rocks. The formation of feldspathic arenites implies preservation of large quantities of feldspars during the process of weathering. This may happen due either to (1) very cold or very arid climatic conditions that inhibit the chemical weathering processes, or (2) warmer, more humid climates where rapid uplifts allow faster erosion of feldspars before they can be decomposed (Boggs, 1992). The findings by Dickinson and Suczek (1979) also support the latter possibility for the origin of feldspathic arenites.

The higher proportion of unstable lithics and the moderately higher feldspar content of lithic arenites suggest their derivation from rugged high-relief source areas. This is because the detritus is stripped off rapidly from such elevated areas before the weathering processes could destroy the unstable clasts. Furthermore, lithic arenites mostly contain fine-grained lithic clasts presumably derived from source regions dominated by volcanic rocks, schists, phyllites, slates, fine-grained sandstones, shales and limestone. Source areas with such lithological characteristics occur primarily in orogenic belts located along suture zones and magmatic arcs (Dickinson and Suczek, 1979; Dickinson, 1985).

The relative proportion of different types of quartz grains in the Kamlial sandstone are mostly derived from medium- and high-grade metamorphic rocks, with only subsidiary contribution from low-grade metamorphics (Fig. 4A) whereas those from the overlying Chinji Formation indicate both medium-high grade and low-grade metamorphic rock provenance (Fig. 4B). Only one sample of the Kamlial Formation from the Chshmai section falls along the boundary line between metamorphic and plutonic provenances thereby indicating the possibility of an igneous origin for some of the quartz grains (Fig. 4A).



Figs. 3A and B. A. Mineralogical characterization of the Kamlial and Chinji sandstone (fields after Okada, 1971). Q, Quartz; F, Feldspar; L, Lithics. Unfilled square, triangle and cross for Bahadar Khel, Chashmai and Aisor Banda sections, respectively of Kamlial sandstone. B. Mineralogical characterization of the Chinji sandstone. Filled square, triangle and "+" sign for Bahadar Khel, Chashmai and Aisor Banda sections, respectively.



Figs. 4A and B. A. Ternary plot of detrital quartz types of the Kamlial sandstone (after Basu et al., 1975). Qp, Quartz polycrystalline; Qnu, Quartz nonundulatory (monocrystalline); Quartz undulatory (monocrystalline). Unfilled square, triangle and cross for Bahadar Khel, Chashmai and Aisor Banda sections, respectively. B. Ternary plot of detrital quartz types of the Chinji sandstone (after Basu et al., 1975). Filled square, triangle and "+" sign for Bahadar Khel, Chashmai and Aisor Banda sections, respectively.

It is noteworthy that the types of quartz grains from the Chashmai anticline indicate their derivation exclusively form medium- and high-grade metamorphic rocks, that of the Banda Aisore syncline from medium- and high-grade as well as low-grade sources, while the Bahadar Khel anticline shows dominance of low grade metamorphic rocks in their source areas (Figs. 4A, B). The low content of polycrystalline quartz in the Kamlial and Chinji formations possibly indicates a long distance of transportation (Dabbagh and Rogers, 1983). The dominance of $Qp_{2\text{-}3}$ over $Qp_{>3}$ in the Kamlial and Chinji formations indicates an origin from metamorphic source rocks (Blatt et al., 1980; Asiedu et al., 2000).

The abundance of monocrystalline quartz in all the studied sections of the Kamlial and Chinji formations indicates that the presence of granitic and volcanic rocks in the source areas cannot be ruled out (Young, 1976). The abundance of Q_{nu} over the Q_u in the Kamlial Formation at the Chashmai anticline and the Banda Aisor syncline suggests plutonic and volcanic source rocks (Basu, 1985), while the abundance of Q_u over the Q_{nu} in the Bahadar Khel anticline shows a metamorphic and/or tectonically deformed source area. Q_{nu} dominates over the Q_u in the Chinji Formation at the Chashmai anticline. The reverse is true in case of the other two studied sections of the Chinji Formation.

The average contents of different quartz types from the Kamlial Formation are: Q_{nu}=53, Q_u=42, $Qp_{2\text{-}3}$=4 and $Qp_{>3}$=1 at the Banda Aisor syncline, Q_{nu}=25, Q_u=62, $Qp_{2\text{-}3}$=9 and $Qp_{>3}$=4 at the Bahadar Khel anticline, and Q_{nu}=55, Q_u=33, $Qp_{2\text{-}3}$=7 and $Qp_{>3}$=5 at the Chashmai anticline. The average contents of different quartz types in the Chinji Formation are: Q_{nu}=36, Q_u=60, $Qp_{2\text{-}3}$=3 and $Qp_{>3}$=1 at the Banda Aisor syncline, Q_{nu}=21, Q_u=68, $Qp_{2\text{-}3}$=9 and $Qp_{>3}$=2 at the Bahadar Khel anticline, and Q_{nu}=61, Q_u=33, $Qp_{2\text{-}3}$=5 and $Qp_{>3}$=1 at the Chashmai anticline. All this data is indicative of a granitic and/or gneissic source (Tortosa et al., 1991).

The presence of an appreciable amount of feldspar in the Kamlial and Chinji formations indicates either high relief or arctic climate at the source area (Prothero et al., 2003). The higher proportion of alkali feldspar than plagioclase shows dominance of granite and acidic gneisses in the source area. However, this feature might also be due to the higher chemical stability of alkali feldspar than plagioclase during transportation (Tucker, 1992). The presence of microcline also favors granitic and pegmatitic sources.

The abundance of mica rarely exceeds 10 % of the total framework grains in the Kamlial and Chinji sandstones. The flakes of micas are mostly bent thereby suggesting their derivation from metamorphic or deformed assemblages (Michaelsen and Henderson, 2000). A similar provenance is indicated by the presence of lithic grains of metamorphic origin, grains of epidote and garnet. The occurrence of monazite, apatite and rutile, on the other hand, suggests both metamorphic and igneous (plutonic) source rocks (Morton et al., 1992). Chromite may have been derived from unmetamorphosed/metamorphosed basic to ultrabasic source rocks (e.g., Dubey and Chatterjee, 1997).

All the suggested varieties of source lithologies for the studied sandstones occur in northern Pakistan. For example, the sedimentary/metasedimentary lithologies occur as a part of the Hindu Kush-Karakoram range (Gaetani et al., 1990). Similarly, the ~ 100 km wide Tethyan sequence consists of Cambrian to Eocene unmetamorphosed or weakly metamorphosed rocks and extends along the entire length of the Himalayas (Gansser, 1964). The Indus Suture Zone (ISZ) in northern Pakistan is characterized by the occurrence of a variety of mélanges containing talc carbonate schist, greenstone, greenschist, metagabbro and metasediments (Kazmi et al., 1984).

South of the ISZ, the Indian continental margin is composed of late Precambrian to early Paleozoic gneisses, ortho- and paragneisses of the Besham group and Nanga Parbat syntaxis (Tahirkheli, 1982), granite and granitic gneisses of the Mansehra and Swat, pelitic, psammitic and calcareous schists as well as marbles of the Besham, Hazara and Swat areas (Treloar, 1989). Similarly, slates and quartzites are the dominant lithologies of lower Hazara and Attock-Cherat ranges (Calkins et al., 1975; Hussain et al., 1989). The Karakoram and Kohistan batholiths, consisting of unmetamorphosed/metamorphosed granite-diorites as well as pegmatites and aplites in the north, could be the major sources of plutonic provenance in the north (Jan et al., 1981). The Jijal-Pattan complex is exposed along the Indus River to the north of MMT and dominantly consists of garnet granulites and ultamafic rocks (Jan, 1985). The Kamila amphibolite to the north of MMT chiefly consists of amphibolite with subordinate amounts of ultramafics, gabbro, diorite, tonalite and granite (Jan, 1988).

The uplift rates of the Himalayan orogenic belt increased substantially during the Miocene times (Zeitler, 1985) that rapidly exposed deepseated metamorphic and igneous rocks for denudation. Subsequently, the Himalayan drainage system analogous to the present day river systems of Indus, Ganges and Brahmaputra (Abid et al., 1983) started flowing axially into their respective basins depositing thick detrital sediments. The type of sediments carried by these drainage systems is primarily controlled by the lithologies exposed in their catchment areas. For example, the present day Indus River in northern

Pakistan contains sediments consisting of plutoniclastic, metamorphiclastic and sedimentary/metasedimentary grains which represent the lithologies of the Karakorum and Hindukush ranges in the region (Garzanti et al., 2005). The Kohistan-Laddakh arc and Nanga Parbat Haramosh Massif supply high-grade quartzofeldspathic sands whereas the Ladakh batholith sheds pure arkosic detritus (Garzanti et al., 2005). Heavy minerals in all these sands are dominated by blue-green to subordinately green and brown hornblende, garnet and epidote (Garzanti et al., 2005). The Soan, Kurram and Tochi rivers carry lithic sands with abundant sedimentary and low-grade metasedimentary components (limestone, shale/slate, sandstone/ metasandstone, chert). Heavy minerals, including epidote, garnet, red to coffee-brown chrome spinel, and staurolite, are largely recycled from terrigenous units (Garzanti et al., 2005).

The composition of the Indus sands from the Tarbela lake suggest a dominant supply of Indus bedload from the active-margin (81±2% i.e., 60±6% from Karakorum; 6±4% from the Ladakh arc and South Tibet; 14±4% from the Kohistan arc), followed by the Himalayan units (19±2% i.e., Nanga Parbat 13±3%; Tethys and Greater Himalaya 6±3%) (Garzanti et al., 2005). At the Salt Range front, the detrital modes of Indus sands reflect extensive recycling of older Indus sediments (54±3%) with subordinate contributions from the Kabul (33±2%), Soan (11±2%), and Kurram, Tochi, Gomal rivers (3±2%) (Garzanti et al., 2005).

Furthermore, lithofacies of the Chinji and Nagri formations are thought to represent deposits of either the paleo-Indus river or a similar axial fluvial system (Johnson et al., 1982). The multistoried channel type sandstone-bodies of the Chinji Formation in southeastern Kohat suggest a consistent flow direction to the SSE (Abbasi, 1998). The sedimentary structures of the overlying Nagri Formation suggest a dominant paleoflow direction to the SSW (Abbasi, 1998). The river system that entered the Kohat area, changed from sandy to silty during the deposition of Kamlial and Chinji formations, respectively (Abbasi, 1998).

There are broad similarities between channel geometries, discharges and sedimentary characters of Siwalik rivers and modern Indus river system including emergence from mountain belt, generally parallel flow to the basin axis, slopes range from 0.000085 to 0.00018, and bankfull discharges in the order of 102-103m3s-1 (Mackey and Bridge, 1995).

7. Conclusions

- Mineralogically, the sandstones of the Kamlial and Chinji formations of the southwestern Koaht Plateau are feldspathic and lithic arenites.
- The quartz grains of the Kamlial sandstone are mainly derived from medium- and high-grade metamorphic rocks, with subsidiary contribution from low grade metamorphics, whereas the overlying Chinji Formation indicates subequal contribution from medium-high grade and low-grade metamorphic rock provenances. The relative dominance of polycrystalline quartz grains composed of 2-3 crystals (Qp_{2-3}) also proposes an origin from metamorphic source rocks. Similarly, the presence of mica and other heavy minerals indicate that the source area was composed of metamorphic rocks. However, the relatively greater abundance of monocrystalline quartz in the Kamlial and Chinji formations indicates that the presence of granitic and volcanic rocks in the source areas cannot be ruled out, or else the quartz grains have traveled a longer distance of transportation.
- Section to section within formation differences in the modal composition of sandstone and types of quartz grains are also noteworthy. The spatial and temporal increase in relative abundance of undulatory and non-undulatory monocrystalline quartz suggests plutonic/volcanic and metamorphic/tectonically deformed source areas, respectively.
- Although the alkali feldspar is chemically more stable than plagioclase, its high proportion indicates dominance of granite and acidic gneisses in the source area. Similarly, the average contents of different quartz types from the Kamlial and Chinji formations are suggestive of a granitic and/or gneissic source. Furthermore, appreciable amount of feldspar in the Kamlial and Chinji formations indicates either high relief of the source area or arctic climate.

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