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Geochemistry and provenance of the Lower Siwaliks from southwestern Kohat, western Himalayan Foreland Basin, NW Pakistan

K. ULLAH[1] M. ARIF[2,3*] M. TAHIR SHAH[4]

[1]**University of Peshawar, National Center of Excellence in Geology**
P.O. Box No. 734, University Campus, Peshawar 25120, Pakistan.

[2]**University of Peshawar, Department of Geology**
Peshawar 25120, Pakistan.

[3]**CIIT Department of Earth Sciences**
Abbottabad 22060, Pakistan.

[4]**University of Peshawar, National Center of Excellence in Geology**
Peshawar 25120, Pakistan.

*Corresponding author: E-mail: arif_pkpk@yahoo.com

ABSTRACT

Equivalent to the Lower Siwalik Group, the Late Miocene Chinji Formation in Pakistan consists of interbedded in-channel sandstone (SSt) and overbank mudstone (MSt) sequences. Twelve sandstone and sixteen mudstone samples from three different sections of the formation in southwestern Kohat, NW Pakistan were analyzed for major elements and selected trace elements. The Chinji sandstones are feldspathic and lithic arenites. They are mostly matrix-supported, moderately to well sorted, and contain angular to rounded framework grains. Authigenic carbonate makes up most of the matrix. The framework grains consist of abundant monocrystalline quartz, alkali feldspar, and lithic fragments with subordinate mica and trace to accessory amounts of heavy minerals including epidote, monazite, apatite, garnet, rutile, and brown hornblende. The lithic fragments consist of sedimentary, volcanic, and low-grade metamorphic rocks.The average concentration of Zr, Nb and Y, and the Ba/Sc and Ba/Co ratios in the studied samples are lower than the corresponding values for the upper continental crust (UCC) and Post-Archean Australian Shale (PAAS) indicating the presence of mafic phases in the source area(s). The high average Cr/Zr and Cr/V ratios of the investigated samples relative to UCC and PASS also support the presence of mafic lihtologies, possibly chromite and ultramafic rocks in the source region. The La/Sc and Th/Sc ratios of the Chingi samples are more like the UCC while the Th/Co and Cr/Th ratios suggest a major contribution from mafic rocks. The average percent differences of the Chinji samples from both the UCC and PAAS in terms of critical silicic to basic trace element ratios (Ba/Co, Ba/Sc, La/Co, La/Sc, Th/Co, Th/Sc, Zr/Cr, and Zr/Sc) suggest a mafic contribution of 23 to 47% (mudstone) and 56 to 69% (sandstone). The lower Th/U, Rb/Sr and Zr/Sc ratios in the studied samples than the corresponding values of the UCC and PAAS suggest negligible recycling for the sediments of the Chinji Formation. Petrographic point count data on the Chinji sandstone indicate sediment derivation from a dissected arc, suture belt, and recycled orogen corresponding to the Kohistan-Ladakh Arc, the Indus Suture Zone, and the Himalayan Tectonic units, respectively. The different source rocks identified on the basis of various petrographic and geochemical parameters occur as part of the mentioned tectonic domains.

KEYWORDS **Sandstone. Mudstone. Chinji Formation. Miocene. Western Himalayas. Pakistan.**

INTRODUCTION

The Lower Siwalik Group, called the Chinji Formation in Pakistan, is dominantly composed of interbedded, bright red, and brown-orange mudstone and ash-gray sandstone. The mudstone to sandstone ratio is 4:1 in the type section. The interbedded, in-channel and overbank mudstone sequences are 10–50 meters thick, and the major sand bodies are 5–10 meters thick (*e.g*. Willis, 1993; Willis and Behrensmeyer, 1994). In the Khaur area of Potwar Plateau, the Chinji Formation is divided into three facies: i) a thick sandstone (5 meters to tens of meters thick), ii) a thin sandstone (decimeters to a few meters thick), and iii) a laminated mudstone (decimeters to several meters thick) (Zaleha, 1997). In eastern Kohat, the channel type sandstone-bodies of the Chinji Formation are about 10m thick and extend laterally for many kilometers (Abbasi, 1998). Ages of the Kamlial-Chinji and Chinji-Nagri boundaries in Potwar are interpreted as 14.3Ma and 10.8Ma, respectively (Johnson *et al*., 1985) while to the west in the Surghar Range, the base and top of the Chinji Formation are believed to be 11.8Ma and 8Ma 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).

The Lower Siwalik Group of the Himalayan Foreland Basin is studied in different perspectives in different sub-basins of India (*e.g*. Raiverman, 2002; Kumar *et al*., 2003) and Potwar Plateau of Pakistan (*e.g*. Behrensmeyer and Tauxe, 1982; Johnson *et al*., 1985; Behrensmeyer, 1987; Quade *et al*., 1992; Willis, 1993; Willis and Behrensmeyer, 1994; Zaleha, 1997). The previously conducted studies on the Lower Siwaliks in Pakistan, *i.e*. the Chinji Formation (Abbasi and Friend, 1989; Abbasi, 1998), are confined to the eastern part of the Kohat plateau. However, details regarding petrographic characteristics of the Chinji Formation from southwestern Kohat have been published recently (Figs. 1, 2; Ullah *et al*., 2006). The present study focuses on the geochemical characterization and provenance determination of the Chinji Formation from southwestern Kohat Plateau with reference to the tectonic evolution of the Himalayan Ranges.

REGIONAL GEOLOGY OF THE WESTERN HIMALAYAS

The Western Himalaya in Pakistan consist of three tectonostratigraphic units. Located farthest north is the southern margin of the Eurasian crust including both the Hindu Kush and Karakoram and consisting of Paleozoic-Mesozoic succession intruded by a Jurassic to Cretaceous batholith and affected by both pre- and post-India-Eurasia collision metamorphic events (Searle, 1996; Hildebrand *et al.,* 2001; Fraser *et al.,* 2001). Sandwiched between the Eurasian crust along the Main Karakoram Thrust (MKT) to the north and the Indian crust along the Main Mantle Thrust (MMT) to the south, is the Cretaceous-Eocene intra-oceanic Kohistan Island Arc (KIA), which is intruded by the Kohistan batholith showing pre- and post-collisional stages of formation (Treloar *et al.,* 1989).

The formation of KIA initiated in the Early Cretaceous times (144 to 99Ma). The KIA collided with the Eurasian Plate at an age between 70 and 100Ma (Coward *et al*., 1986). Since then, it acted as an Andean-type margin until India-Eurasia/Kohistan collision between 65 and 50Ma along the Indus Tsangpo Suture Zone (ITSZ) (Maluski and Matte, 1984; Smith *et al*., 1994). Subsequent to collision, metamorphism of the subducting Indian crust took place in two main phases, diachronous from west to east (Staubli, 1989; Metcalfe, 1993). Phase 1 metamorphism (M_1) of the Greater Himalaya due to crustal thickening/thrust stacking circa 40Ma was followed by Phase 2 metamorphism (M_2) and production of leucogranite melts circa 20Ma associated with movement along the Main Central Thrust (MCT) and normal faulting. From circa 20Ma, faulting ceased and the KIA and Indian crust have only undergone simple uplift and erosion (Treloar *et al*., 1989; Burg *et al*., 1996).

For a better understanding, the Western Himalaya is divided from north to south into the following major lithotectonic zones (Fig. 1; Gansser, 1964):

i) The Trans-Himalayan zone predominantly consists of Upper Cretaceous to Eocene calc-alkaline plutons (LeFort, 1996). A granitic batholith occurs in its center, flanked in the south and north by a high-grade metamorphic belt and a sedimentary/ metasedimentary zone, respectively (Searle *et al*., 1996; Karim, 1998).

ii) The Main Karakoram Thrust contains blocks of greenstones, limestones, shales, conglomerates, quartzites, and serpentinites (Tahirkheli, 1982; Karim, 1998).

iii) The Kohistan-Ladakh island arc is bounded to the north and northwest by the Main Karakoram Thrust and to the south and southeast by the Indus Suture Zone (ISZ). The Kohistan terrain itself consists of i) the Jijal-Pattan Complex (mafic granulites and ultramafic rocks; Jan and Howie, 1980), ii) the Kamila Amphibolite (Jan, 1988), iii) the Chilas Complex (layered mafic, ultramafic rocks and quartz diorites; Jan *et al*., 1984; Treloar *et al*., 1996), iv) the Jaglot Group (slates, turbidites, and limestones as well as greenschist facies metabasalts, interbedded with volcanoclastic and schistose metasediments; Treloar *et al*., 1996) and v) Kohistan Batholith (gabbro, diorite, granodiorite, granite; Treloar *et al*., 1996).

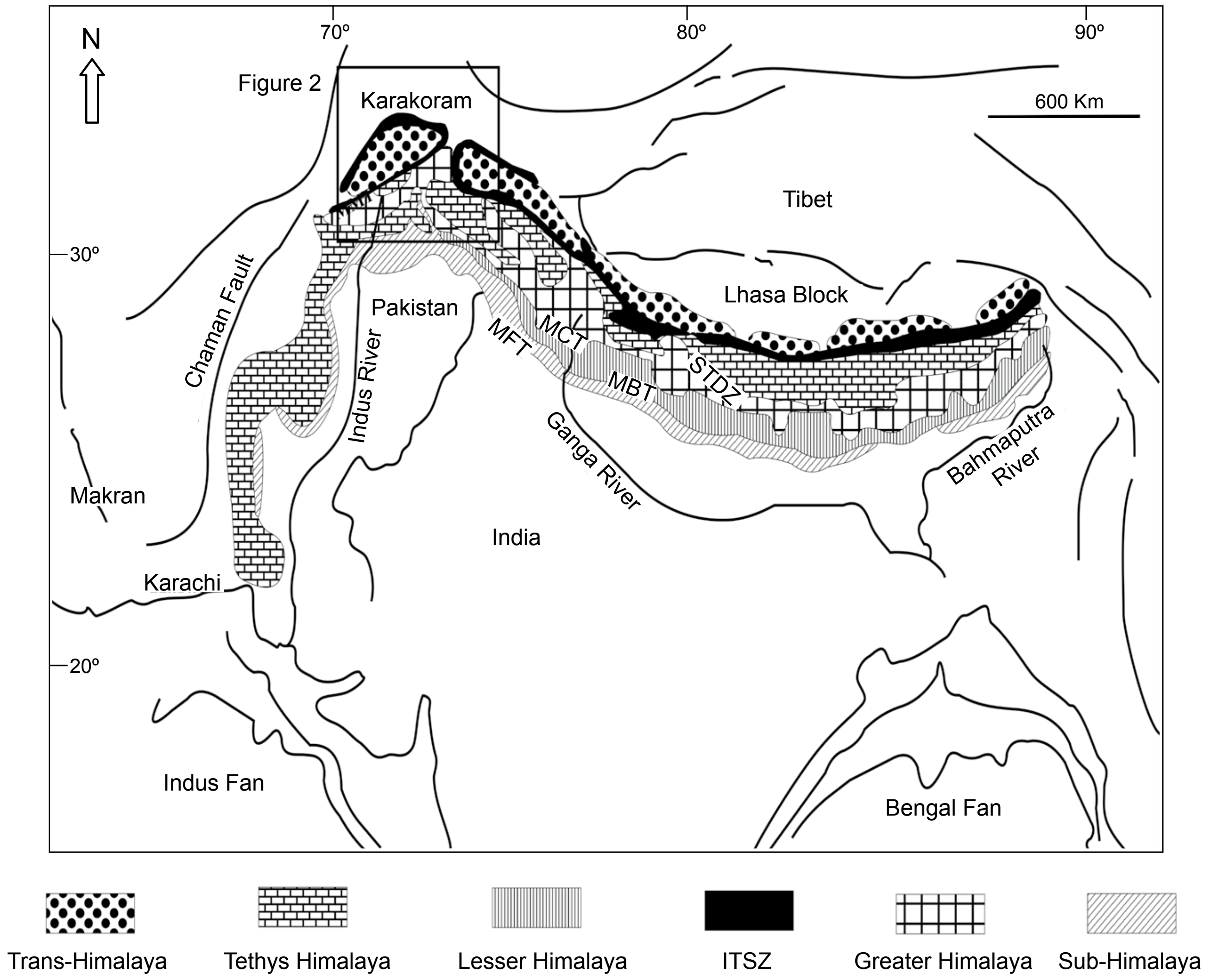

FIGURE 1. Location map of the Himalayan Range (after Critelli and Garzanti, 1994; Najman, 2006). ISZ: Indus Suture Zone, STDZ: South Tibetan Detachment Zone, MCT: Main Central Thrust, MBT: Main Boundary Thrust, MFT: Main Frontal Thrust.

iv) The Indus Suture Zone is composed of deep-water Indian continental rise sediments, Trans-Himalayan accretionary complexes, ophiolites and ophiolitic melanges, island arc volcanic rocks, and fore-arc basin sedimentary rocks (Tahirkheli *et al.*, 1979). Named after the Indus River, ISZ constitutes the westward extension of the roughly 2000km long Indus Tsangpo Suture zone (Gansser, 1964; Allègre *et al.*, 1984).

v) The Tibetan or Tethys Himalayan Zone preserves the Proterozoic to Eocene siliciclastic and carbonate sedimentary rocks that are interbedded with Paleozoic and Mesozoic volcanic rocks (Yin, 2006; and references therein).

vi) The Indian plate segments include the Greater Himalayan Crystalline Complex (GHC), the Lesser Himalayan Zone (LHZ), and the Sub-Himalaya. The GHC consists of the Indian continental crust and metamorphosed sedimentary rocks (ortho- and/ or para-gneisses, amphibolite, schists, and marble) of mainly Late Proterozoic–Cambrian age (Treloar and Searle, 1993; Parrish and Hodges, 1996). The GHC is subdivided into the following groups: i) the Nanga-Parbat Haramosh Massif (Coward, 1985; Butler and Prior, 1988; Chaudhry and Ghazanfar, 1990), ii) Kaghan group (Chaudhry and Ghazanfar, 1990), iii) Sharda group (Chaudhry and Ghazanfar, 1990), iv) Besham group (Treloar, 1989), v) Swat group (Kazmi *et al.*, 1984; Humayun, 1986; DiPietro *et al.*, 1993) and vi) Hazara group (Treloar, 1989). The GHC was thrust over the Late Palaeoproterozoic rocks (Valdiya and Bhatia, 1980) of the LHZ along the Main Central Thrust (MCT). The LHZ includes the nonfossiliferous low-grade metasedimentary rocks (LeFort, 1975) overlain by Permian to Cretaceous strata (the Gondwana Sequence) (Fig. 1; Gansser, 1964).

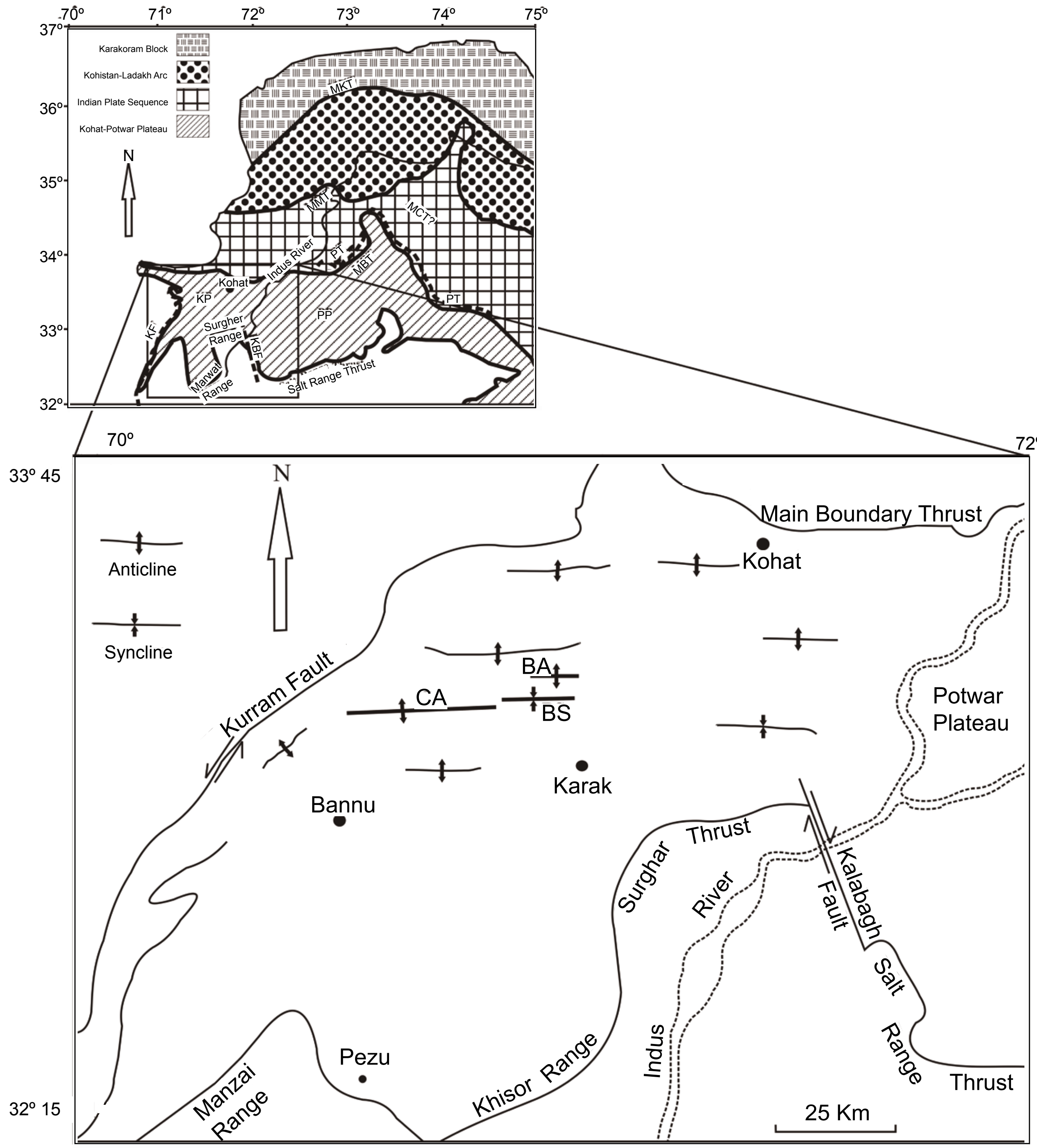

FIGURE 2. A) Regional tectonic map of northern Pakistan (modified after Kazmi and Rana, 1982): MKT: Main Karakoram Thrust, MMT: Main Mantle Thrust, PT: Panjal Thrust, MBT: Main Boundary Thrust, KP: Kohat Plateau, PP: Potwar Plateau, KF: Kurram Fault, KBF: Kalabagh Fault; B) Geological map of a part of the Kohat Plateau (after Meissner *et al.*, 1974 and Ahmad *et al.*, 2001).

SAMPLES, METHODS AND ANALYTICAL TECHNIQUES

Many representative samples were collected from three different sections of the Chinji Formation in southwestern Kohat, *i.e.* the Bahadar Khel anticline (latitude 33°09'79"N and longitude 70°57'64"E), Chashmai anticline (latitude 33°06'34"N and longitude 70°47'77"E) and Banda Assar syncline (latitude 33°07'52"N and longitude 70°55'88"E) where the total thickness of the formation is 140, 100 and 133 meters, respectively (Fig. 2b). Twelve sandstone and sixteen mudstone samples were selected for geochemical investigation. The petrography of these samples has already been published (Ullah *et al.*, 2006).

Whole-rock chemical analyses were carried out with X-Ray Fluorescence (XRF) and Atomic Absorption Spectrophotometers (AAS) under established standard conditions. Major elements were performed on fusion discs using the RIGAKU XRF-3370E spectrometer at the Geoscience Advance Research Laboratories, Islamabad. The Geological Survey of Japan standards were also run with every batch of ten samples. The results of analyses were then compared with the recommended values of USGS standard reference samples. The detection limits of XRF for major elements are as follows: SiO_2 (0.27%), TiO_2 (0.014%), Al_2O_3 (0.13%), Fe_2O_3 (0.08%), MnO (0.005%), MgO (0.03%), CaO (0.09%), Na_2O (0.02%), K_2O (0.03%) and P_2O_5 (0.03%). Furthermore, major elements were also analyzed using an AAS/UV spectrophotometer at the Geochemistry Laboratory of the National Center of Excellence in Geology, University of Peshawar (NCEGUP). Replicate analyses of the samples agree very well. The trace element analyses were performed on pressed powder pellets using Philips PW 1480 XRF at NCEGUP. The precision of the major elements is normally better than 6%, while precision of most of the trace elements is better than 5%. The exception is Yb whose precision is normally better than 7%. Total iron is reported as Fe_2O_3 (Cullers, 2000). Methods of chemical analysis, descriptions of sample sets, and estimates of analytical error are as given by Connor (1990).

PETROGRAPHY OF THE CHINJI SANDSTONE

The sandstone of the Chinji Formation is dominantly matrix supported and moderately to well sorted (Ullah *et al.*, 2006). The framework grains are angular to rounded and essentially consist of quartz, feldspar and lithics (rock fragments) with average modal abundances of 46, 30, 23 volume percent, respectively. The quartz is dominantly monocrystalline; alkali feldspar is much more abundant than plagioclase; and sedimentary rocks, including chert, dominate the lithic fragments. Chert, mudstone, lime mudstone, low-grade mica-schist, quartz-mica schist, and volcanic rocks also contribute to the total amount of lithic fragments in the Chinji sandstone. Variable amounts of mica including biotite, which is dominantly oxidized and/or highly deformed, also occur and may constitute as much as 9% of the framework grains. Heavy minerals in the Chinji sandstone include epidote, monazite, apatite, garnet, rutile and brown hornblende (suggesting high-grade metamorphism). The quartz grains contain inclusions of zircon, monazite, rutile, epidote and mica.

Authigenic carbonate occurs abundantly in all the studied samples and appears to have selectively replaced unstable framework components. Carbonate

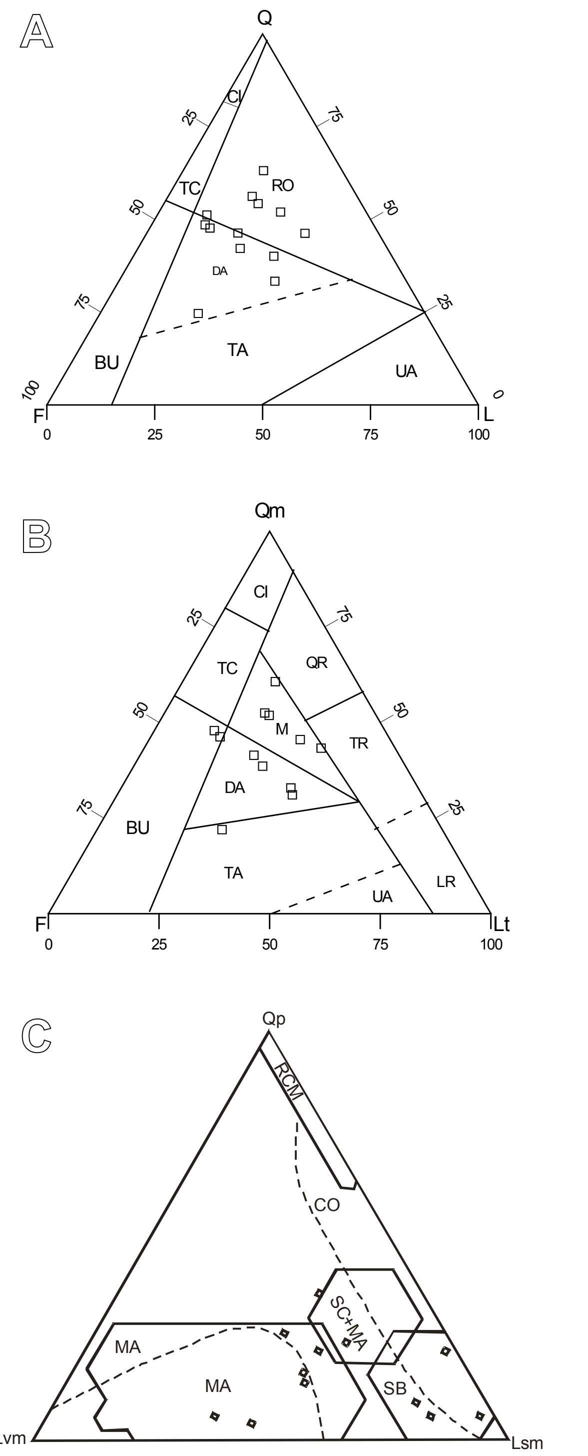

FIGURE 3. Provenance determination of the Chinji sandstone using the ternary discrimination diagrams of Dickinson and Suczek (1979) and Dickinson (1985): A) Q: quartz, F: Feldspars, L: Lithics, RO: Recycled Orogen, BU: Basement Uplift, TA: Transitional Arc, DA: Dissected Arc, UA: Undissected Arc, TC: Transitional Continental, CI: Continental Interior; B) Qm: Quartz monocrystalline, F: Feldspars, Lt: Lithics, QR: Quartzose Recycled, TR: Transitional Recycled, LR: Lithic Recycled; C) Qp: Quartz polycrystalline, Lvm: Lithics volcanics and metavolcanics, Lsm: Lithics sedimentary and metasedimentary, MA: Magmatic Arcs, SC+MA: Mixed Magmatic Arcs and Subduction Complexes, SB: Suture Belts, RCM: Rifted Continental Margin, CO: Collision Orogen. The dashed-line fields are from Dickinson and Suczek (1979).

TABLE 1. Whole-rock major and trace element composition of sandstone samples representing the Chinji Formation from the southwestern Kohat plateau, NW Pakistan. The middle alphabet in sample numbers indicates locality, C: Chashmai anticline, A: Banda Assar syncline and B: Bahadar Khel anticline. CIA: chemical index of alteration, CIW: chemical index of weathering, ICV: Index of chemical variability

Sample Nº	KCC-17	KCC-20	KAC-56	KAC-63	KBC-104	KBC-106	KBC-111	KBC-114	KBC-125	KBC-127
Major elements (wt % oxide)										
SiO_2	55.04	58.82	51.13	53.07	53.86	49.76	49.58	44.50	42.56	53.07
Al_2O_3	9.95	8.98	11.58	10.83	8.39	8.87	10.54	9.49	7.42	10.85
Fe_2O_3	3.37	4.64	4.84	4.33	4.26	4.42	4.29	4.19	3.25	3.75
MgO	1.69	2.30	2.66	3.71	2.92	2.22	2.29	2.70	1.72	2.35
CaO	11.75	9.50	12.24	12.26	11.55	16.36	13.59	19.43	23.65	9.74
Na_2O	1.46	1.76	1.77	1.65	1.02	0.98	1.76	1.89	1.57	1.70
K_2O	1.58	1.54	1.36	1.12	1.46	1.33	1.43	1.25	1.19	1.49
TiO_2	0.66	0.46	0.58	0.72	0.86	0.50	0.68	0.88	0.45	0.77
P_2O_5	0.09	0.10	0.09	0.10	0.09	0.13	0.09	0.09	0.08	0.10
MnO	0.21	0.12	0.12	0.11	0.11	0.17	0.19	0.19	0.14	0.11
LOI	14.33	11.80	13.38	12.53	15.47	15.28	15.44	15.28	17.89	15.92
Total	100.13	100.01	99.76	100.43	100.00	100.01	99.88	99.89	99.91	99.86
CIA	70.79	66.30	72.52	73.36	71.99	74.40	70.32	68.07	65.73	71.08
CIW	0.87	0.84	0.87	0.87	0.89	0.90	0.86	0.83	0.83	0.86
ICV	0.90	1.20	0.98	1.08	1.27	1.08	1.01	1.17	1.12	0.94
Trace elements (ppm)										
Sc	15	18	12	16	14	11	15	16	21	19
V	73	68	92	56	124	57	72	67	39	47
Cr	55	79	150	316	80	142	201	158	121	258
Co	35	32	39	37	24	33	38	34	42	29
Ni	22	40	35	60	78	43	37	24	87	29
Cu	15	10	13	9	50	10	13	11	6	8
Zn	30	40	40	37	98	39	37	34	26	31
Ga	7	8	8	9	16	8	8	8	6	6
Rb	58	52	55	52	126	54	62	52	44	52
Sr	201	285	191	223	143	233	213	262	201	257
Y	18	17	16	16	20	16	14	19	11	16
Zr	149	80	102	112	134	85	94	125	75	111
Nb	6	5	7	7	11	6	6	6	6	5
Ag	5	8	5	3	5	6	4	5	3	5
Cd	5	5	3	5	1	1	3	4	1	3
Sn	7	4	3	3	6	2	3	3	1	1
Sb	6	2	0	3	1	1	6	6	7	8
Cs	4	0	13	0	4	0	0	3	3	5
Ba	357	166	165	157	206	192	212	157	122	160
La	31	24	21	29	29	20	27	27	26	26
Ce	19	8	10	39	48	30	51	22	6	42
Nd	23	8	16	38	31	14	30	27	22	32
Sm	0	0	0	0	1	0	0	0	0	0
Yb	0	1	0	1	4	0	1	0	0	1
Hf	8	5	5	14	6	4	2	10	2	9
Ta	0	0	3	1	0	0	2	0	0	0
W	302	230	285	247	29	192	264	210	273	162
Pb	11	9	12	10	22	10	13	11	10	10
Th	8	5	7	6	13	5	7	6	5	6
U	3	4	4	4	4	3	3	3	3	4

also occurs along cracks and cleavages within some of the framework grains. The intra-granular filled fractures most probably developed by compaction during burial, while the unfilled ones formed during tectonic uplift (Abbasi and Friend, 1989; Ullah *et al.*, 2006). The incipient silica overgrowths on some quartz grains suggest pressure dissolution due to rock overburden (Pettijohn *et al.*, 1987; Ullah *et al.*, 2006).

TABLE 2. Comparison of important trace element ratios from the studied samples of the Chinji mudstone and sandstone with the corresponding data on Upper Continental Crust (UCC), Post-Archean Australian Shale (PAAS), Lower Continental Crust (LCC), Oceanic Crust (OC) and average Proterozoic sandstones, as well as sands derived from i) silicic rocks, ii) mafic rocks, iii) andesites, iv) granites, and v) ophiolites

	Chinji Sandstone						Reference Material		Chinji Mudstone					
					[a]% Difference with respect to								* % Difference with respect to	
Element/ Ratio	Min	Max	Mean	St. Dev	UCC	PAAS	UCC	PAAS	Min	Max	Mean	St. Dev	UCC	PAAS
Sc	11.00	21.00	15.70	3.06	42.73	-1.88	11.00	16.00	9.00	21.00	13.25	2.82	20.45	-17.19
V	39.00	124.00	69.50	24.22	15.83	-53.67	60.00	150.00	76.00	142.00	91.94	15.94	53.23	-38.71
Cr	55.00	316.00	156.00	82.59	345.71	41.82	35.00	110.00	56.00	215.00	107.06	42.35	205.89	-2.67
Co	24.00	42.00	34.30	5.21	243.00	49.13	10.00	23.00	16.00	24.00	19.81	2.54	98.13	-13.86
Ni	22.00	87.00	45.50	22.35	127.50	-17.27	20.00	55.00	43.00	136.00	78.38	28.44	291.88	42.50
Rb	44.00	126.00	60.70	23.41	-45.80	-62.06	112.00	160.00	70.00	125.00	97.69	17.19	-12.78	-38.95
Sr	143.00	285.00	220.90	40.92	-36.89	10.45	350.00	200.00	121.00	292.00	177.00	41.79	-49.43	-11.50
Y	11.00	20.00	16.30	2.54	-25.91	-39.63	22.00	27.00	16.00	23.00	20.38	2.22	-7.39	-24.54
Zr	75.00	149.00	106.70	24.24	-43.84	-49.19	190.00	210.00	99.00	195.00	144.75	29.31	-23.82	-31.07
Nb	5.00	11.00	6.50	1.72	-53.57	-65.79	14.00	19.00	9.00	13.00	11.25	1.18	-19.64	-40.79
Ba	122.00	357.00	189.40	64.58	-65.56	-70.86	550.00	650.00	24.00	233.00	194.81	51.02	-64.58	-70.03
La	20.00	31.00	26.00	3.50	-13.33	-31.58	30.00	38.00	2.00	42.00	32.25	9.44	7.50	-15.13
Th	5.00	13.00	6.80	2.39	-38.18	-54.67	11.00	15.00	8.00	15.00	11.06	2.08	0.57	-26.25
U	3.00	4.00	3.50	0.53	16.67	16.67	3.00	3.00	3.00	7.00	4.38	0.89	45.83	45.83
La/Sc	1.24	2.07	1.69	0.29	-37.86	-28.65	2.73	2.38	0.18	3.45	2.49	0.83	-8.87	4.65
La/Co	0.54	1.21	0.78	0.19	-74.02	-52.83	3.00	1.65	0.13	2.11	1.62	0.46	-46.05	-2.04
Th/Sc	0.24	0.93	0.45	0.20	-54.52	-51.49	1.00	0.94	0.52	1.27	0.87	0.23	-13.42	-7.65
Zr/Cr	0.35	2.71	0.93	0.73	-82.80	-51.08	5.43	1.91	0.72	2.38	1.48	0.43	-72.69	-22.35
Th/Co	0.12	0.54	0.21	0.12	-80.85	-67.70	1.10	0.65	0.42	0.78	0.57	0.12	-48.59	-13.28
Ba/Co	2.90	10.20	5.69	2.16	-89.66	-79.87	55.00	28.26	1.50	13.88	9.82	2.66	-82.14	-65.25
Ba/Sc	5.81	23.80	12.69	5.24	-74.61	-68.76	50.00	40.63	2.18	20.91	15.02	4.53	-69.96	-63.03
K/Rb	116.40	294.60	242.26	50.72	-19.49	4.76	300.89	231.25	157.70	260.60	221.76	25.05	-26.30	-4.10
Cr/Th	6.24	54.54	26.14	15.20	721.57	256.47	3.18	7.33	4.04	19.22	10.35	4.86	225.40	41.19
Cr/Sc	3.72	19.65	10.23	5.24	221.61	48.84	3.18	6.88	3.20	19.75	8.51	4.34	167.59	23.85
Zr/Sc	3.61	10.09	7.11	2.10	-58.87	-45.87	17.27	13.13	4.72	19.43	11.44	3.94	-33.74	-12.80
Th/U	1.25	3.25	1.96	0.62	-46.59	-60.83	3.67	5.00	1.60	3.75	2.59	0.60	-29.23	-48.10

[a]% Difference = 100 x (Chinji Sample Mean-Reference Material)/Reference Material

Plots of petrographic point count data on different discriminatory diagrams suggest three major tectonic orogens as source regions for the Chinji sandstone (Ullah *et al.*, 2006): i) recycled orogen, ii) magmatic arc orogen, and iii) suture belt (Fig. 3). The lithological composition of these and several other source orogens and mineralogical characteristics of the resulting sandstones are described in detail by Dickinson and Suczek (1979), Ingersoll *et al.* (1984), Boggs (1992) and Tucker (2001).

GEOCHEMISTRY OF THE CHINJI FORMATION

Trace element geochemistry can be employed to explain the heavy mineral content and determine the provenance of sandstone. For example, the REE and Th generally occur in minerals like zircon, monazite, allanite, apatite, and titanite (McLennan, 1989). Similarly, Zr and Hf may be concentrated in the coarser fraction of sediment due to zircon accumulation (Crichton and Condie, 1993). A moderate correlation of Zr with Yb, and Ti with Ta suggests some accumulation of zircon and titanite, respectively (Dupuis *et al.*, 2006).

The chemical compositions of the Chinji sandstone and mudstone and ratios between several pairs of major and trace elements are listed (Tables 1, I, II Electronic Appendix, available at www.geologica-acta.com) and compared with the relevant published data (Tables 2, 3). Although there is some overlap, the mean Zr content in the studied sandstone is distinctly lower than that in the associated mudstone (Tables 1, I, 2), which implies that sedimentary sorting has not played any significant role in controlling Zr concentration. A greater chemical and mineralogical homogeneity of mudrocks relative to the associated sandstones was also noticed by Critelli *et al.* (2008). In order to test the influence of grain size, the correlation of TiO_2, Cr, V and Zr were compared against Al_2O_3. The observed positive correlation demonstrates the affinity of these elements with clay minerals and associated phases, *e.g.* feldspars and they may thus have been concentrated during weathering processes.

The immobile nature and preferential concentration in felsic rocks during crystallization make Zr, Nb, and Y potential provenance indicators (Taylor and McLennan, 1985). Despite exhibiting some overalp in overall ranges, the average contents of Zr, Nb and Y in the studied samples of the Chinji mudstone are markedly higher than the corresponding values in the associated sandstone (Tables 1, I). However, almost all these contents are lower than the

TABLE 3. Summary of the whole-rock trace element composition and ratios in sandstone and mudstone of the Chinji Formation from southwestern Kohat, NW Pakistan and comparison with corresponding data on the Upper Continental Crust (UCC) and Post-Archean Austalian Shale (PAAS) (Taylor and McLennan, 1985)

Ratio	La/Sc	Th/Sc	Co/Th	Cr/Th
Chinji Mudstone	1.35-3.41 (2.4)	0.51-1.16 (0.9)	1.11-3.23 (1.8)	4.04-19.22 (10)
Chinji Sandstone	1.03-3.04 (1.7)	0.20-0.91 (0.5)	3.57-11.11 (5.5)	6.24-75.40 (25.3)
UCC[a]	2.70	0.71	0.9	3.3
PAAS[a]	2.40	0.91	1.58	7.53
LCC[a]	0.30	0.03	33	222
OC[a]	0.10	0.58	214	1227
Average Proterozoic Sandstone[c]	4.21	1.75	-	5.71
Silicic Source[b]	2.50-16.30	0.84-20.50	0.22-1.5	0.40-15.00
Mafic Source[b]	0.43-0.86	0.05-0.22	7.10-8.30	22-500
Andesites[c]	0.90	0.22	4.65	9.77
Granites[c]	80	3.57	0.17	0.44
Ophiolites[c]	0.25	0.02	70	410

[a]Taylor and McLennan (1985)

[b]Amstrong-Altrin et al. (2004)

[c]Condie (1993)

corresponding values in both the UCC and PAAS (Table 2) indicating the presence of mafic phases in the source area(s) for the Chinji sediments.

The contents of Co, Sc, Ba and trace element ratios like Ba/Sc and Ba/Co also are used to distinguish among sediments derived from amphibolites, tonalities, and other acidic rocks (Cullers, 1994; Mongelli *et al.*, 1996). The average Ba/Co and Ba/Sc ratios in the Chinji Formation from the study area are significantly lower than the UCC and PAAS (Tables II, 2). Accordingly, the Chinji sediments are characterized by very low Ba and relatively high Co and Sc contents thereby supporting the presence of basic rocks in their source region.

Since the contents of elements like Cr and Zr are controlled by the abundance of chromite and zircon, respectively, the ratio between them may be a good indicator of relative influxes from mafic versus felsic sources (Wronkiewicz and Condie, 1989). The higher average Cr/Zr ratios in the studied mudstone and sandstone than both the UCC and PAAS point to a mafic source for the Chinji Formation (Tables I, 2). Similarly, the high to very high Cr/V ratios in almost all the investigated Chinji samples relative to both the UCC and PAAS (Tables I, 2) reflect the presence of some chromite and ultramafic components (Bock *et al*., 1998) in the source area. Such lithologies are particularly characteristic of ophiolites.

There is a marked difference between felsic and basic rocks in trace element ratios like La/Sc, Th/Sc, Th/Co, and Cr/Th (Table 3; Fig. 4). Hence, such ratios may be used to determine the average provenance composition (Wronkiewicz and Condie, 1990; Cox *et al*., 1995; Cullers, 1995). The La/Sc and Th/Sc ratios from the studied sandstones and mudstones are similar to that of the PAAS, but the Cr/Th and Co/Th ratios are higher than both the UCC and PAAS. Being the result of high Cr, Co and low Th concentrations, the high Cr/Th and Co/Th ratios suggest utmost contribution from a mafic source (Tables II, 2, 3). On the other hand, the Th/Co versus La/Sc ratios demonstrates a dominantly silicic provenance for the Chinji Formation (Fig. 4) (Cullers, 2002). Although the lithophile elements, K and Rb, are believed to be relatively mobile during metamorphism, their absolute values, like the Th/Sc ratios, suggest acidic-intermediate igneous precursors (Shaw, 1968). Whereas a few mudstones and most sandstones of the Chinji Formation have their K/Rb ratios higher than that of the PAAS, the K/Rb ratios of all the Chinji samples are lower than the UCC (Tables II and 2). Furthermore, the average K/Rb ratio of the Chinji mudstone is lower than both the UCC and PAAS.

Sedimentary recycling in oxidizing conditions results in a distinct fractionation of Th and U during rock weathering. U^{+4} is readily oxidized to U^{+6}, which forms the highly soluble species, the uranyl ion, that can be removed from the system, whereas, Th retains its oxidation state and remains relatively insoluble (McLennan and Taylor, 1980). As a consequence, the Th/U ratios may increase due to successive cycles of weathering and redeposition and thus may serve as a potential marker of these processes. The overall ranges of the Th and U contents in the Chinji samples show a little overlap with the corresponding values for the UCC and PAAS. However, the average Th/U ratios of the Chinji sandstone and mudstone are lower than both the UCC and PAAS (Tables II, 2) thereby suggesting negligible recycling for the studied deposits.

The degree of sedimentary recycling in clastic sedimentary rocks can be determined from their Rb/Sr ratios (McLennan *et al*., 1993). Whereas the average Rb/Sr ratio in the studied sandstone closely matches the UCC value, the average Rb/Sr ratios of the Chinji mudstone and sandstone both are lower than the corresponding values for both the UCC and PAAS (Tables 1, I), thereby suggesting minimal sedimentary recycling of the Chinji Formation. The Zr/Sc ratios can also be used as a measure of the degree of sedimentary recycling. Relative to Sc, the Zr concentration is expected to enhance since the degree of recycling is likely to increase the amount of the stable mineral zircon in sedimentary deposits (Nesbitt and Young, 1982). The average Zr/Sc values in the Chinji mudstones and sandstones are lower than the corresponding values for UCC and PAAS (Tables II, 2) indicating that a recycled sedimentary source was a minor component (Roddaz *et al*., 2005). Furthemore, somewhat non-uniform elemental distribution in the studied mudstone samples relative to PAAS also records insignificant recycling processes to the Chinji sediments (*cf.* Perri *et al*., 2013).

DISCUSSION

The Chinji sandstone is composed of both feldspathic and lithic arenites. The relative proportion of different types of quartz grains indicates a low-grade through high-grade metamorphic rock provenance (Ullah *et al*., 2006). Source areas with such lithological characteristics occur primarily in orogenic belts located along suture zones and magmatic arcs (Dickinson and Suczek, 1979; Dickinson, 1985). As pointed out in the section on petrography, three major tectonic orogens are identified as potential source areas for the Chinji Formation based on petrographic data on sandstone (Ullah *et al*., 2006). These include i) recycled orogens, *e.g*. the Himalayan Tectonic Units, ii) magmatic arc orogen, *e.g*. the Kohistan-Ladakh Arc and iii) suture belt, *e.g*. the Indus Suture Zone.

Sediment influx from Himalayan Tectonic Units

In the early Miocene, the foreland basin received sediments from the Tethyan Himalayan cover sequence and metamorphic clasts from the ultra-high pressure gneiss terrains in the western Himalaya. That is why the Siwalik sandstones from the Potwar Plateau (NW Pakistan) contain metamorhphic (phyllite, fine-grained schist lithics, and coarse-grained gneiss) and sedimentary detritus that was derived from the High and/or Lesser Himalaya (Critelli and Ingersoll, 1994). The high-grade GHC became a source of sediments after 11 to 5Ma when it became exposed to erosion so high-grade metamorphic clasts started appearing in the Siwalik Group of the Himalayan Foreland Basin (DeCelles *et al*., 1998; Sakai *et al*., 1999; White *et al*., 2001). Two different ages are proposed for the exposure of the GHC. Whereas the apatite fission track dating supports an age later than 10 to 4Ma, the widespread early Miocene leucogranites indicate exposure of the GHC at ~21 to 17Ma (*e.g*. Scaillet *et al*., 1990, 1995; Dézes *et al*., 1999; Guillot *et al*., 1999; Murphy and Harrison, 1999; Searle *et al*., 1999;).

The change in the heavy mineral assemblage, according to Cerveny *et al*. (1989) and Willis (1993) is clear evidence for an influx from the blue-schist to amphibolite grade rocks of the Kohistan arc terrain. However, zircon fission track ages younger than 12Ma have not yet been obtained from this terrain, and are reported only from the bedrock of northern Pakistan in the region of the Nanga Parbat-Haramosh Massif (Ruiz and Diane, 2006).

According to the steady-state evolutionary model for Himalayas, there is a gradual shift of the deformational front from the hinterland towards south. However, the MCT and MBT are believed to be contemporaneous features that are still active (Seeber *et al*., 1981; Seeber and Armbruster, 1981). This view is supported by several other geological and geomorphological features, *e.g*. knick points in river profiles across the MCT and uplifted terraces in the Higher Himalaya, that indicate ongoing tectonic activity along the MCT (Valdiya, 1980; Seeber and Gornitz, 1983) and MBT (Nakata, 1989; Valdiya, 1992; Malik and Nakata, 2003).

Most of the Himalayan orogen was exhumed at a rate between 0.1 and 1.0mm/a (Einsele, 1992), but the average uplift rate for the High Himalayas has been ~1.5mm/a for the last 20Ma (Burg *et al*., 1987). There is a clear correlation between high exhumation rates and local structural development, which suggests that the rate and magnitude of deformation have played an important role in deciding where and how fast Himalayan exhumation, occurs (Yin, 2006). Theories proposed for differential denudation in the MCT hanging wall from east to west along the Himalayas include i) an eastward increase in the magnitude of slip along the MCT due to counter-clockwise rotation of India with respect to Asia during Indo-Eurasian collision (Guillot *et al*., 1999), ii) an eastward change in the dip angle of the subducted Indian continent (Guillot *et*

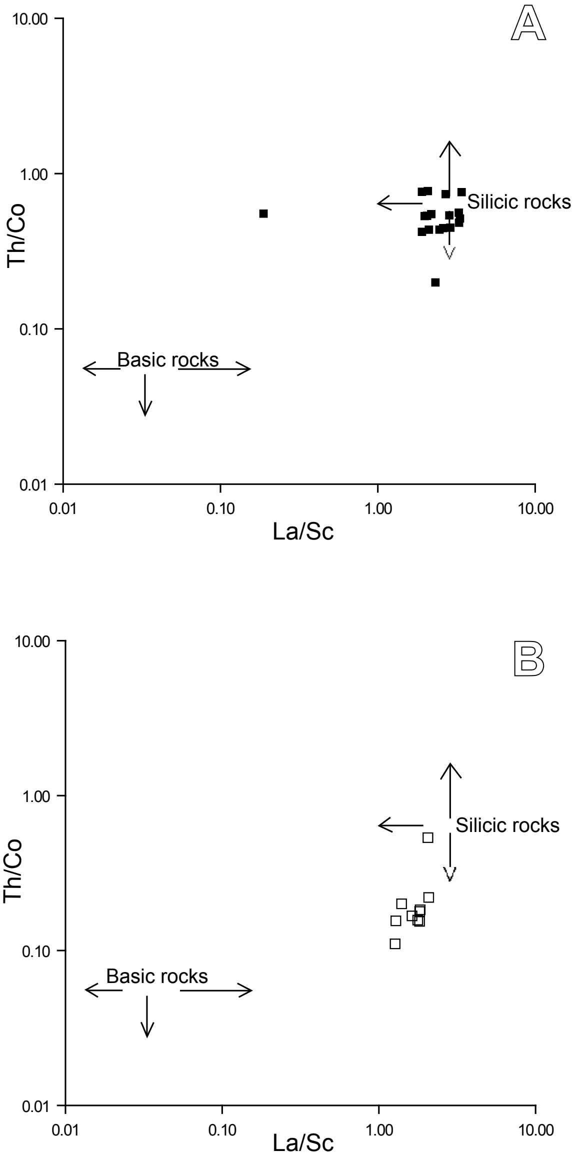

FIGURE 4. The Th/Co versus La/Sc relation in the studied samples of A) mudstone and B) sandstone from Chinji Formation. The fields for silicic and basic rocks are as defined by Cullers (2002).

al., 1999) and iii) an eastward increase in the magnitude of exhumation in response to regional variation of climatic conditions (Finlayson *et al.*, 2002).

The $^{40}Ar/^{39}Ar$ biotite ages decrease systematically from >40Ma around the margin to ≤5Ma in the core of the Nanga Parbat syntaxis. This indicates differential exhumation, heat advection or a combination of both during the development of the syntaxis (Zeitler *et al.*, 2001). Assuming 350°C, 1 and 5m.y., and 30°C/km as the closure temperature of biotite, duration of exhumation and a constant geothermal gradient, respectively, the core of the Nanga Parbat syntaxis has experienced exhumation at a rate of 7.0±4.5mm/a. The exhumation rate in the core of the western Himalayan syntaxis has been high since the latest Miocene time (Zeitler, 1985; Treloar *et al.*, 1989a; George *et al.*, 1995; Winslow *et al.*, 1994, 1995; Schneider *et al.*, 1999), although exhumation rate around the edge of the Nanga Parbat syntaxis is 0.30±0.20mm/a (Yin, 2006) and the average exhumation rate calculated for the Early and Middle Miocene times is 0.67mm/a (Zeitler *et al.*, 1989; Treloar *et al.*, 2000).

Sediment influx from the Kohistan-Ladakh Arc

A comparison of the average ratios of the Th/U, Rb/Sr and Zr/Sc of the Chinji Formation with the corresponding average values for UCC and PAAS suggests that there was little sedimentary recycling for these sediments (Tables I, 2; McLennan *et al.*, 1993; see Roddaz *et al.*, 2005). The data published by Najman *et al.* (2003a, b) show major arc erosion at 18Ma, which is inconsistent with the previously held belief that this occurred at 11Ma. The latter interpretation is based on the increased fluvial discharge to the foreland basin and the first appearance of arc-derived hornblende in the basin sediments (Cerveny *et al.*, 1989). However, the late appearance of hornblende may also be due either to i) a gradual erosion through deeper levels of the arc cover or ii) diversion to the region of a river that was already carrying hornblende.

Similarly, there is a sharp contrast in composition of the Modern Indus sands upstream and downstream of Tarbela Lake. The Indus sand composition from Tarbela Lake indicates a strong influx of sediments from an active continental margin, *i.e.* 81±2% followed by 19±2% from Himalayan tectonic units (Garzanti *et al.*, 2005), whereas, the total Indus budget downstream of Tarbela Lake suggests a bulk bedload contribution of 47±2% from active margin units and 53±2% from Himalayan passive margin units (Garzanti *et al.*, 2005). This major difference is due to the fact that tributaries which join the Indus River before it enters Tarbela flow across the Karakorum, the Ladakh Arc, South Tibet and the Kohistan Arc with minimal input from the tributaries draining the Himalayan passive margin, whereas downstream Tarbela, the Indus River, is joined by major rivers draining the Himalayan passive margin. 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 plutonic, metamorphic, and sedimentary/ metasedimentary grains which represent lithologies of the Karakoram and Hindu Kush ranges in the region (Garzanti *et al.*, 2005). The Kohistan-Ladakh arc and Nanga Parbat-Haramosh Massif supply high-grade quartzo-feldspathic sands, and the Ladakh batholith sheds pure arkosic detritus (Garzanti *et al.*, 2005). Heavy minerals in these sands are dominated by blue-green to subordinately green and brown hornblende, garnet, and epidote (Garzanti *et al.*, 2005).

Sediment influx from Suture Belt, *i.e.* the Indus Suture Zone

A study of the history of the Himalaya erosion and deposition shows that the Paleogene Himalayan Foreland Basin received sediments mainly from southern Tibet, the Indus Suture Zone, and the supracrustal sections of the ultra-high pressure gneiss terrains in the western Himalaya. The Siwalik Group rocks from eastern Kohat and Potwar predominantly plot in the recycled orogen, which suggest major influx from medium to high grade metamorphic rocks, with only a subordinate contribution from sedimentary, arc, and ophiolite lithologies (Abbasi and Friend, 1989; Critelli and Ingersoll, 1994; Garzanti *et al*., 1996; Pivnik and Wells, 1996).

The suspended sediment load of the Indus River shows distinct negative anomalies for Nb and positive anomalies for Ni relative to PAAS, which are similar to the trace element signatures of the mafic and ultramafic magmatic rocks of the Indus and Shyok suture zones (Honegger *et al*., 1982, 1989; Rai, 1987; Sharma, 1991; Ahmad *et al*., 1996). The formation and emplacement of the Kohistan-Ladakh magmatic arc is believed to have taken place in response to the northward movement of the Indian Plate, subduction of the neotethys and India-Eurasian collision along the Indus and Shyok suture zones (Thakur, 1992). The plagioclase/total feldspar ratios for the Arabian Sea sand (mean=0.66) also indicate its derivation from collision orogenic belts (Suczek and Ingersoll, 1985). Lithic populations of the Arabian Sea sand (metasedimentary and sedimentary), micas (predominantly muscovite and biotite), and amphiboles suggest a source area composed of uplifted basement terrains of granitic to granodioritic composition with extensive metasedimentary and sedimentary terrains (Suczek and Ingersoll, 1985).

SOURCE AREA LITHOLOGIES OF THE CHINJI FORMATION

The presence of an appreciable amount of feldspars in the Chinji Formation indicates either high relief or arctic climate at the source area (Prothero and Schwab, 2003). The higher proportion of alkali feldspar than plagioclase shows an abundance of granite and acidic gneisses in the source area. Alternatively, this feature might also be due to the higher chemical stability of alkali feldspar than plagioclase during weathering and transportation (Tucker, 2001). However, the presence of microcline also favors the presence of granitic and pegmatitic sources in the hinterland areas.

The greater abundance (ranging up to 9% of the total framework grains) and mostly bent character of mica flakes in the Chinji sandstones suggests sediment derivation from deformed metamorphic assemblages (see also Michaelsen and Henderson, 2000). The presence of metamorphic lithic fragments and grains of epidote and garnet indicate a similar provenance. 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 ultrabasic-basic source rocks (Dubey and Chatterjee, 1997).

The heavy mineral assemblage of the Chinji Formation in the Potwar area mainly includes amphibole, chlorite, tourmaline, garnet, epidote, magnetite, and pyrite, indicating a granodiorite source rock for the sediments. Here, the formation contains 20–300ppm Cr, 20–200ppm Ni, 50–400ppm V indicating basic source rocks. The range of Zr concentrations (50–500ppm) suggest that some of the material was also derived from acidic to intermediate rocks, while the presence of alkali feldspar indicates acidic igneous source rocks (Alam *et al*., 2003).

Samples from the studied sequence contain low amounts of Zr, Nb, and Y, and low average Ba/Co and Ba/Sc ratios compared to the UCC and PAAS indicating the presence of mafic phases in the source area(s) for their constituent sediments (Tables I, 2). Similarly, the high Cr/Zr and Cr/V ratios relative to UCC and PAAS indicate mafic and ultramafic source rocks for the Chinji Formation of the southwestern Kohat plateau (Tables II, 2, 3).

On the other hand, the Th/Sc and La/Sc ratios suggest a provenance similar to PAAS for the Chinji Formation. As the average source of the PAAS is presumed to be granitic, the studied sediments are most probably derived from a source area with felsic composition (Table II). Similarly, the Th/Co versus La/Sc relation indicates a dominantly silicic provenance, but the Cr/Th ratios suggests a major contribution from mafic rocks (Tables II, 2, 3; Fig. 4) (see Cullers, 2002).

The source lithologies for the studied sandstones occur in northern Pakistan. For example, the Kohistan batholiths, consisting of unmetamorphosed/metamorphosed granite-diorites as well as pegmatites and aplites could be the major sources of the plutonic provenance (Jan *et al*., 1981). The Jijal-Pattan complex is exposed along the Indus River to the north of ISZ and mostly consists of garnet granulites and ultramafic rocks (Jan, 1985). The Kamila amphibolite to the north of the ISZ chiefly consists of amphibolite with subordinate amounts of ultramafics, gabbro, diorite, tonalite, and granite (Jan, 1988). The 2500km long and discontinuous ISZ in northern Pakistan is characterized by the occurrence of a variety of *mélanges* containing talc carbonate schist, serpentinite, chromitite, 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 of the Besham Group and Nanga Parbat syntaxis (Tahirkheli, 1982), granite and granitic gneisses of the Mansehra and Swat areas, pelitic, psammitic, and calcareous schists as well as marbles of the Besham, Hazara and Swat areas (Treloar *et al.*, 1989b).

CONCLUSIONS

The recycled orogen sediments are assumed to have been derived from the Himalayan tectonic units, the magmatic arc orogen sediments from the Kohistan-Ladakh arc, and the suture belt sediments from the Indus Suture Zone.

The greater chemical stability of alkali feldspar than plagioclase accounts for the higher modal abundance of the former in sandstone. However, this feature may also reflect a dominance of granite and acidic gneisses in the source area. Furthermore, the abundance of feldspar in the studied formation indicates either high relief and/ or arctic climate at the source area.

The presence of mica and other heavy minerals of metamorphic origin, *e.g.* epidote, garnet and brown hornblende indicates that the source area contained metamorphic rocks.

The Th/U ratio of the Chinji Formation (MSt=2.6, SSt=2) is lower than those of the UCC (3.7) and PAAS (5), which suggest that these are first cycle sediments. The lower Zr/Sc ratios of mudstone (11.3) and sandstone (7.1) than the corresponding UCC (17.27) and PAAS (13.12) values suggest a minor contribution from recycled sedimentary sources.

Lower values of Zr, Nb, and Y in sandstone and mudstone than the PAAS indicate the consistent presence of mafic phases in the source area.

The average Ba/Sc, Ba/Co and Cr/Zr ratios favor the presence of some basic/ultrabasic rocks in the source area, however, the La/Sc and Th/Co ratios propose a provenance similar to UCC/PAAS/felsic rocks.

The average percent differences of the Chinji sandstone from both the PAAS and UCC in terms of petrogenetically important trace element ratios (Ba/Co, Ba/Sc, La/Co, La/Sc, Th/Co, Th/Sc, Zr/Cr, and Zr/Sc) suggest a mafic contribution of 56 to 69%. However, the average percent differences between the Chinji mudstone and both the PAAS and UCC in terms of the same parameters indicate 23 to 47% mafic provenance. The percent differences between the Chinji samples and the PAAS are consistently lower than that between the former and the UCC.

Generally, TiO_2, Zr, Rb and V all show a significant positive correlation with Al_2O_3 indicating affinity of these components with clay minerals and associated phases.

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