SANDSTONE PETROLOGY AND PROVENANCE OF THE SIWALIK GROUP (NORTHWESTERN PAKISTAN AND WESTERN-SOUTHEASTERN NEPAL)

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ABSTRACT: The Siwalik Group consists of a Neogene sedimentary succession 5-8 km thick, deposited as the Himalayan foreland basin developed following collision between the Indian and Eurasian continents. It consists of fluvial deposits composed of shale, siltstone, and sandstone in the lower part and thick sandstone and conglomerate in the upper part.

This paper presents new petrologic data on the sandstone composition of two coeval petrofacies of Siwalik Group in two areas: the Potwar Plateau of northwestern Pakistan, and the Surai Khola and Bakiya Khola localities of western and southeastern Nepal. In both regions, detrital modes reflect a collisional-orogen provenance. Petrologic parameters indicate derivation from mid-crustal rocks and overlying sedimentary strata ascribed to different tectonostratigraphic units of the High Himalaya and Tibetan zone.

The Siwalik sandstones of the Potwar Plateau (NW Pakistan) are composed of low- to medium-grade metamorphic and sedimentary detritus, and subordinately, of ophiolitic and volcanic detritus. Abundant metamorphic detritus consists of phyllite, fine-grained schist lithics, and coarse-grained gneiss derived from the High and/or Lesser Himalaya. Sedimentary detritus is represented by abundant limestone, radiolarian chert, siltstone, shale, very fine-grained quartzarenite, and other sandstone grains. The siliciclastic grains probably were eroded from older terrigenous sequences, belonging to the Tethys Himalayan and Lesser Himalayan zones, uplifted during the India-Eurasia collision. Ophiolitic, volcanic lithic grains and radiolarian chert reflect a provenance from the Indus suture and Trans-Himalayan belt.

The sandstones of western and southeastern Nepal (Surai Khola and Bakiya Khola sections) have higher quartz and lower feldspar contents than those of northwestern Pakistan and contain sedimentaclastic (western Nepal) and metamorphiclastic sandstones (southeastern Nepal).

Comparison of the data presented here with previous work on pre- and post-Siwalik sandstones of the Himalaya Range and of the remnant-ocean basins along both sides of the Indian Peninsula (also derived from the Himalayan suture belt) suggests abundant quartzolithic detritus from the Eocene to the present. Varying proportions of lithic populations in time are related to rapid uplift of the Himalayas and intense unroofing of sedimentary, metasedimentary and deeper terranes.

INTRODUCTION

Following continental collision between India and Asia (at about 54 Ma; Molnar and Tapponnier 1975; Tapponnier et al. 1986; Dewey et al. 1989; Harrison et al. 1992), the Himalayan chain experienced intense uplift and erosion; enormous quantities of terrigenous detritus accumulated in ancient and recent terrestrial foreland basins (Murrees, Siwaliks, and Indo-Gangetic Plain; Gansser 1964). The Murree Supergroup and Chulung La Formation since the Early Eocene (Garzanti et al. 1987; Critelli and Garzanti 1994), and the Siwalik Group, in the mid-Miocene to Pliocene, are the main fluvial strata in foreland basins developed along the flexed Indian margin (Fig. 1). From about 21 to 17 Ma, an important transition occurred in the development of southern Tibet and the Himalayas (Harrison et al. 1992, 1993). This time interval corresponds with the end of deposition of the upper Murree Supergroup, movement of the Main Central Thrust, and the onset of huge sediment accumulation in remnant-ocean basins along both sides of the Indian Peninsula (e.g., Curray and Moore 1974; Graham et al. 1975; Moore 1979; Critelli et al. 1990). During and following this main tectonic uplift, the Siwalik Group was deposited between 18.3 and 4.9 Ma (Cerveny et al. 1988; Johnson et al. 1988; Harrison et al. 1993).

The Siwalik Group has received significant attention in terms of stratigraphy and structural geology (e.g., Burbank et al. 1986; Johnson G.D. et al. 1986; Baker et al. 1988; Burbank and Raynolds 1988; Burbank et al. 1988; Burbank and Beck 1989, 1991), magnetostratigraphy (e.g., Opdyke et al. 1982; Johnson N.M. et al. 1982, 1985, 1988; Appel et al. 1991), sedimentology (e.g., Tandon 1976; Parkash et al. 1980; Behrensmeyer and Tauxe 1982; Mulder and Burbank 1993), composition (e.g., Krynine 1937; Chaudhri 1971, 1972; Sinha and Sastri 1973; Abid et al. 1983), and geochemical and geochronological analysis of detrital grains, such as zircon, K-feldspar, and muscovite (e.g., Cerveny et al. 1988; Harrison et al. 1993).

The aim of this paper is to provide quantitative petrographic information on the Siwalik Group sandstones in northwestern Pakistan (Potwar Plateau) and in western and southeastern Nepal (Surai Khola and Bakiya Khola) and compare these new data with previous analyses of pre- and post-Siwalik sand and sandstone (e.g., Ingersoll and Suczek 1979; Moore 1979; Suczek and Ingersoll 1985; Critelli et al. 1990; Critelli and Garzanti 1991, 1994).

GEOLOGIC AND STRATIGRAPHIC SETTING

The Siwalik Group crops out along a continuous belt, 2500 km long, from northwestern Pakistan to northeastern India (Fig. 1); it consists of 5–8 km of essentially fluvial sediments. The Siwalik Group is composed of fluvial cycles, which represent migrations of major trunk rivers (i.e., the ancestral Indus and Ganges and their affluents) in both northwestern Pakistan and Nepal. It constitutes the greater part of the sedimentary fill of the foreland basin developed in front of the Himalayas (Gansser 1964; Parkash et al. 1980; Burbank et al. 1986; Johnson G.D. et al. 1986). The age of the Siwalik Group (18.3–4.9 Ma) has been established by magnetic-polarity stratigraphy, and fission-track and isotopic dating techniques (e.g., Johnson G.D. et al. 1982; Johnson N.M. et al. 1982, 1985, 1988; Cerveny et al. 1988; Harrison et al. 1993).

Many sedimentologic studies have described the sedimentary successions of the Siwalik Group at various localities (e.g., Sinha and Sastri 1973; Tandon 1976; Parkash et al. 1980; Behrensmeyer and Tauxe 1982; Brookfield and Andrews-Speed 1984; Johnson N.M. et al. 1982, 1985, 1988; Cerveny et al. 1988; Corvinus 1988; Burbank and Beck 1989; Mulder and Burbank 1993). Burbank and Beck (1989) and Mulder and Burbank (1993) suggested two distinct phases of sedimentation in the Potwar Plateau. The older phase is characterized by white sandstones deposited by a very large, east-flowing large fluvial system at about 7.5 Ma. The younger phase is characterized by brown sandstone, siltstone, mudstone, and conglomerate, including also volcaniclastic ash layers; this phase represents deposition by smaller fluvial systems from about 6 to 4.5 Ma.

In the Potwar Plateau (Fig. 2), paleocurrent analysis documents an overall paleoflow direction toward the southeast; also, an axial drainage system oriented subparallel to the Himalayan Range has been inferred to have transported sediment toward the southwest (Burbank and Beck 1991). The sandstones are typically 10–50 m thick, multistoried, and traceable over many kilometers. These strata are interpreted by Burbank and Beck (1991)

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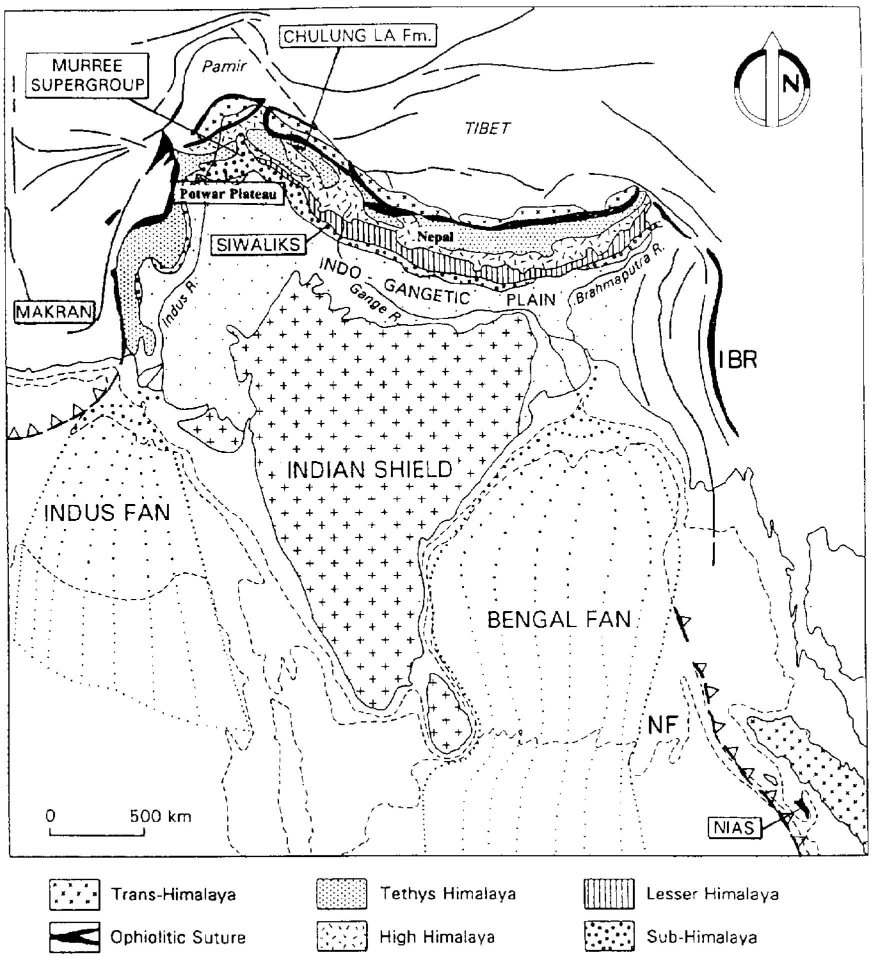

FIG. 1.—Tectonic map of the Himalayan Range, Indian shield and surrounding areas, showing the Potwar Plateau and Nepal. IBR = Indo-Burman Range; NF = Nicobar Fan. Modified from Critelli and Garzanti (1994).

and Mulder and Burbank (1993) to represent deposits generated by a large river system, probably the ancestral Indus River.

In Nepal (Fig. 2), the Siwalik Group is well exposed along the Surai Khola (western Nepal) and Bakiya Khola (southeastern Nepal). Corvinus (1988) and Appel et al. (1991) studied a 5500-m-thick deformed stratigraphic section of the Siwalik Group along the Surai Khola locality; the section is an upward-coarsening sequence consisting of mudstone interbedded with thin sandstone in the lower part and thick sandstone interbedded with conglomerate in the upper part. This Siwalik section has been divided into six lithologic units by Corvinus (1988), with a progressive increase of sandstone and conglomerate up-section. The Bakiya Khola section of the Siwalik Group, 2600 m thick, has been described by Harrison et al. (1993). This section, consisting predominantly of siltstone and sandstone, thickens and coarsens upward; the upper 1000 m consists of thicker sandstone and conglomerate.

SANDSTONE PETROGRAPHY

Many compositional studies have considered both the framework composition of Siwalik sandstone and the accessory-mineral assemblages (e.g., Krynine 1937; Chaudhri 1971, 1972; Tandon 1976; Parkash et al. 1980; Abid et al. 1983); also, conglomerate composition has been studied in the context of syntectonic deposition (e.g., Burbank et al. 1988; Mulder and Burbank 1993). Detailed studies of individual detrital grains in these areas have included fission-track studies on detrital zircon (e.g., Burbank and Tahirkheli 1985; Cerveny et al. 1988), and isotopic studies on K-feldspar and muscovite (e.g., Harrison et al. 1993).

Siwalik Group sandstone was collected in three study areas (Fig. 2), including stratigraphic sections to which our data are directly compared: (1) in northwestern Pakistan, with data of Burbank et al. (1988) and Mulder and Burbank (1988) on conglomerate, (2) in western Nepal, and (3) in southeastern Nepal; in the latter two areas, we utilized the same samples used for isotopic studies by Harrison et al. (1993) (Fig. 1). In these areas, the Siwalik Group is constrained by detailed magnetostratigraphic studies.

Eighty-six unaltered medium to coarse sandstone samples were selected for thin-section analysis; 66 are representative of the Siwalik at the Potwar Plateau (northwestern Pakistan), 10 of the Bakiya Khola (southeastern Nepal), and 10 of the Surai Khola (western Nepal). Five modern sand samples from fluvial systems cutting through the Main Central and Main Boundary Thrust zones (Fig. 2) were also studied.

Our samples from the Potwar Plateau have magnetostratigraphic age ranges from 10.5 to 4.9 Ma (Burbank and Beck 1991; Mulder and Burbank 1993); the samples from Bakiya Khola and Surai Khola have magnetostratigraphic depositional ages (Harrison et al. 1993) ranging from 10.8 and 4.9 Ma. To analyze detrital-mode evolution from the Eocene to the present, the 91 sandstone/sand samples are also compared with pre-Siwalik (Murree Supergroup; Critelli and Garzanti 1994) and syn- and post-Siwalik deposits (Indus and Bengal Fans; Ingersoll and Suczek 1979; Suczek and Ingersoll 1985). Five hundred points were counted for each thin section, etched, and stained for plagioclase and potassium feldspar, according to

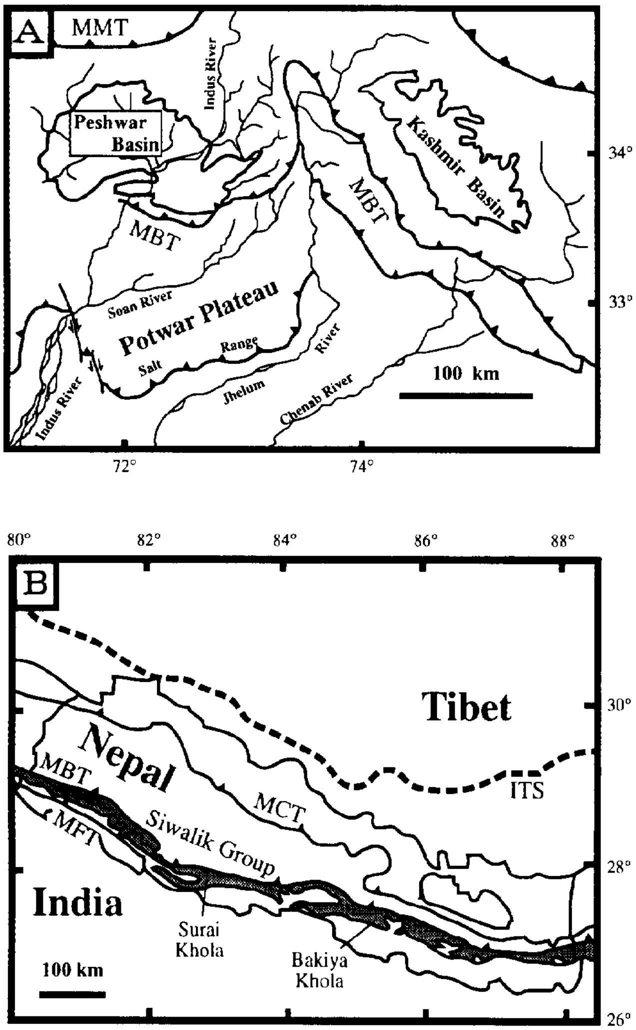

FIG. 2.—Detailed maps of the major tectonic features of A) the Potwar Plateau (after Mulder and Burbank 1993) and B) Nepal (after Harrison et al. 1993). ITS = Indus Tsangpo Suture; MMT = Main Mantle Thrust; MCT = Main Central Thrust; MBT = Main Boundary Thrust; MFT = Main Frontal Thrust.

TABLE 1.—*Categories used for sandstone/sand modal point-count and assigned framework grains in recalculated plots. NCE, CE, NCI, CI are those of Zuffa (1985, 1987). RF = rock fragment*

	Recalculated Parameters				
Petrographic Classes	QmFLt	QtFL	QmPK	QpLvm-Lsm	Lm-LvLs
NCE					
Quartz (single crystal)	Qm	Qt	Qm		
Fine-grained polycrystalline quartz with tectonic fabric	Lt	Qt		Qp	
Polycrystalline quartz without planar fabric	Lt	Qt	Qm	Qp	
Quartz in plutonic RF	Qm	Qt	Qm		
Quartz in metamorphic RF	Qm	Qt	Qm		
Quartz in granitic and/or gneissic RF	Qm	Qt	Qm		
Quartz in sandstone RF	Qm	Qt	Qm		
K-feldspar (single crystal)	F	F	K		
K-feldspar in plutonic RF	F	F	K		
K-feldspar in metamorphic RF	F	F	K		
K-feldspar in granitic and/or gneissic RF	F	F	K		
Plagioclase (single crystal)	F	F	P		
Plagioclase in plutonic RF	F	F	P		
Plagioclase in metamorphic RF	F	F	P		
Plagioclase in granitic and/or gneissic RF	F	F	P		
Plagioclase in sandstone RF	F	F	P		
Micas and Chlorites (single crystal)					
Micas and Chlorites in plutonic RF					
Micas and Chlorites in metamorphic RF					
Micas and Cllorites in granitic and/or gneissic RF					
Monocrystalline dense mineral					
Dense minerals in metamorphic RF					
Dense minerals in plutonic and or gneissic RF					
Opaque minerals					
Phyllite	Lt	L		Lsm	Lm
Fine-grained shcist	Lt	L		Lsm	Lm
Slate	Lt	L		Lsm	Lm
Volcanic with vitric texture	Lt	L		Lvm	Lv
Vocalnic with felsitic texture	Lt	L		Lvm	Lv
Volcanic with microlitic texture	Lt	L		Lvm	Lv
Volcanic with lathwork texture	Lt	L		Lvm	Lv
Metavolcanic	Lt	L		Lvm	Lm
Serpentinite	Lt	L		Lvm	Lm
Serpentineschist	Lt	L		Lvm	Lm
Chert (including arillaceous and radiolarian chert)	Lt	Qt		Qp	Ls
Shale	Lt	L		Lsm	Ls
Siltstone and very-fine grained sandstone	Lt	L		Lsm	Ls
CE					
Dolostone	Lt	L		Lsm	Ls
Fossiliferous and unfossiliferous Limestone	Lt	L		Lsm	Ls
NCI					
Argillaceous and/or siltitic rip-up clast					
CI					
Carbonate concretion (caliche)					
Alterites and undetermined grains					
Carbonate cement (spars and microspars calcite)					
Other cements					
Authigenic Quartz					
Siliciclastic matrix					

the Gazzi-Dickinson method (Ingersoll et al. 1984) (Table 1). Point-count results are tabulated and recalculated in Tables 2 and 3.

All of the samples have quartzolithic composition, but there are two petrofacies with distinctive character, a more feldspathic one for the Siwalik sandstones of the Potwar Plateau and a more quartzose one for the Nepal area (Fig. 3).

Siwaliks of the Potwar Plateau

Sandstones of the Potwar Plateau are quartzolithic ($Q_{48}F_{18}L_{34}$). Quartz grains are represented by monocrystalline and fine-grained polycrystalline types; plagioclase is common (average P/F = 0.68) and K-feldspar is present in all samples. Aphanitic lithic grains ($Lm_{62}Lv_{7}Ls_{31}$) include abundant metasedimentary (phyllite and fine-grained schist) (Fig. 4A), and sedimentary grains (limestone, dolostone, radiolarian chert, argillaceous chert, siltstone, shale, very fine quartzarenite, and other sandstone) (Fig. 4B, C, D). Ophiolitic lithics (serpentinite, serpentine schist, and metavolcanic) are present in some samples (Fig. 4E). Volcanic lithics (Fig. 4D) are subordinate (Lv/L = 0.07). Coarse-grained rock fragments (distributed in Qm, K, P, M, according to the Gazzi-Dickinson method) are largely derived from medium- to high-grade metamorphic rocks. Accessory minerals range from 1% to 4% of the total, and include zircon, tourmaline, titanite, opaques, amphibole (glaucophane, hornblende), garnet, sillimanite, epidote, apatite, kyanite, and staurolite. Hornblende content increases up-section. Glaucophane is present in older sandstones, where it is associated with chrome spinels and abundant ophiolitic and metavolcanic detritus. The KDS samples (Kas Dovac locality) include a more quartzose ($Q_{69}F_{7}L_{24}$) variant (relative to the mean of the other samples, $Q_{46}F_{19}L_{35}$). The more quartzose samples have both abundant polycrystalline quartz and inherited overgrowths, suggesting second-cycle monocrystalline quartz

TABLE 2.—*Recalculated modal point-count data for the Siwalik Group of the northwest Pakistan (Potwar Plateau)**

	QmF Lt %			QtFL %			QmP K %			Qp LvmLsm %			LmLvLs %				
Sample No.	Qm	F	Lt	Qt	F	L	Qm	P	K	Qp	Lvm	Lsm	Lm	Lv	Ls	P/F	Lv/L
GCBC9	36	20	44	42	20	38	65	19	16	12	13	75	65	7	28	0.55	0.07
KKBC9	37	14	49	45	14	41	73	16	11	16	10	74	66	2	32	0.60	0.02
HKBC9	40	20	40	44	20	36	67	18	15	10	17	73	73	5	22	0.54	0.05
JKBC9	45	15	40	50	15	35	75	15	10	13	9	78	62	1	37	0.59	0.01
RKBC9	39	16	45	46	16	38	71	20	9	14	16	70	60	7	33	0.69	0.07
KDBC9	42	15	43	47	15	38	74	16	10	13	18	69	66	8	26	0.62	0.08
UKBC9	33	18	49	39	18	43	64	25	11	12	21	67	73	12	15	0.70	0.12
GCTC9	38	14	48	44	14	42	73	14	13	14	18	68	61	14	25	0.53	0.14
MH286	37	20	43	42	20	38	65	20	15	10	14	76	73	4	23	0.57	0.04
MH433	35	16	49	43	16	41	68	21	11	15	11	74	60	7	33	0.66	0.07
HKTC9	45	15	40	51	15	34	75	17	8	16	11	73	59	7	34	0.69	0.07
RKTC9	46	22	32	51	22	27	69	19	12	17	6	77	68	3	29	0.61	0.03
KKTC9	42	17	41	46	17	37	70	21	9	10	10	80	74	5	21	0.70	0.05
UKTC9	36	20	44	43	20	37	65	22	13	14	5	81	78	2	20	0.63	0.02
SKTC9	45	17	38	50	17	33	73	18	9	14	12	74	63	5	32	0.67	0.05
JKTC9	41	16	43	49	16	35	71	17	12	19	8	73	67	6	27	0.58	0.06
CGKS-040m	31	15	54	38	15	47	68	20	12	12	21	67	70	11	19	0.63	0.11
CGKS-132m	37	10	53	49	10	41	78	13	9	23	11	66	74	4	22	0.59	0.04
CGKS-143m	34	18	48	39	18	43	65	21	14	11	8	81	64	5	31	0.60	0.05
CGKS-366m	34	19	47	44	19	37	64	26	10	21	11	68	67	6	27	0.71	0.06
CGKS-525m	33	20	47	41	20	39	63	20	17	17	14	69	76	5	19	0.54	0.05
CGKS-619m	47	22	31	53	22	25	67	18	15	18	7	75	61	7	32	0.55	0.07
CGKS-920m	35	17	48	42	17	41	68	21	11	15	11	74	70	4	26	0.66	0.04
JKS-010m	50	10	40	57	10	33	84	14	2	17	11	72	54	7	39	0.89	0.07
JKS-038m	49	15	36	56	15	29	76	20	4	19	2	79	89	2	9	0.85	0.02
JKS-215m	49	21	30	54	21	25	69	17	14	16	4	80	72	3	25	0.55	0.03
JKS-290m	35	18	47	41	18	41	65	28	7	13	11	76	56	6	38	0.81	0.06
JKS-380m	26	18	56	35	18	47	60	24	16	16	18	66	61	12	27	0.60	0.12
JKS-430m	44	21	35	49	21	30	67	25	8	14	8	78	79	6	15	0.76	0.06
JKS-490m	27	18	55	36	18	46	60	22	18	17	22	61	59	14	27	0.55	0.14
JKS-520m	34	25	41	41	25	34	57	29	14	17	9	74	73	8	19	0.67	0.08
JKS-562m	51	14	35	59	14	27	78	18	4	21	6	73	90	4	6	0.80	0.04
JKS-590m	34	21	45	39	21	40	62	26	12	11	17	72	70	6	24	0.69	0.06
JKS-637m	34	24	42	45	24	31	59	26	15	25	8	67	83	5	12	0.64	0.05
KKS-BC9	40	12	48	50	12	38	77	15	8	20	12	68	60	8	32	0.64	0.08
KKS-000m	35	24	41	42	24	34	59	25	16	17	9	74	60	10	30	0.60	0.10
KKS-110m	41	22	37	48	22	30	66	19	15	19	11	70	65	6	29	0.56	0.06
KKS-148m	43	8	49	53	8	39	84	9	7	19	10	71	57	4	39	0.57	0.04
KKS-227m	37	20	43	46	20	34	64	23	13	18	19	63	51	8	41	0.64	0.08
KKS-314m	33	20	47	42	20	38	63	28	9	19	10	71	60	8	32	0.75	0.08
KK2-390m	41	24	35	46	24	30	63	27	10	13	5	82	45	2	53	0.73	0.02
KKS-485m	37	14	49	43	14	43	72	18	10	12	10	78	48	4	48	0.64	0.04
KKS-603m	44	25	31	50	25	25	63	21	16	17	5	78	85	4	11	0.56	0.04
MHS-1-045m	33	21	46	40	21	39	61	26	13	16	21	63	67	15	18	0.67	0.15
MHS-2-150m	31	20	49	39	20	41	61	31	8	16	18	66	50	10	40	0.80	0.10
MHS-5-547m	31	23	46	41	23	36	58	31	11	21	18	61	59	8	33	0.73	0.08
MHS-6-679m	42	21	37	48	21	31	66	27	7	17	13	70	59	2	39	0.80	0.02
UKS-011m	35	17	48	43	17	40	67	25	8	18	17	65	63	8	29	0.76	0.08
UKS-150m	37	26	37	44	26	30	59	30	11	20	20	60	71	7	22	0.74	0.07
USK-240m	42	20	38	48	20	32	67	25	8	15	9	76	57	4	39	0.76	0.04
UKS-286m	41	28	31	46	28	26	59	27	14	17	8	75	62	6	32	0.65	0.06
UKS-369m	31	26	43	42	26	32	55	31	14	25	19	56	69	13	18	0.69	0.13
UKS-503m	38	24	38	45	24	31	61	30	9	19	15	66	54	8	38	0.76	0.08
UKS-616m	39	23	38	46	23	31	63	22	15	20	14	66	63	9	28	0.59	0.09
UKS-715m	41	20	39	50	20	30	68	26	6	22	8	70	54	4	42	0.80	0.04
KDS-(−100m)	33	22	45	41	22	37	59	34	7	17	11	72	63	8	29	0.83	0.08
KDS-000m	32	31	37	40	31	29	50	32	18	20	14	66	64	14	22	0.64	0.14
KDS-099m	63	6	31	76	6	18	91	7	2	42	9	49	63	8	29	0.82	0.02
KDS-216m	49	6	45	65	6	29	89	9	2	36	5	59	38	5	57	0.79	0.05
KDS-306m	56	9	35	68	9	23	87	10	3	34	6	60	48	4	48	0.74	0.04
KDS-310m	43	20	37	49	20	31	68	19	13	17	7	76	68	5	27	0.59	0.05
KDS-394m	58	7	35	71	7	22	88	11	1	36	6	58	45	8	47	0.96	0.08
KDS-501m	39	22	39	45	22	33	64	27	9	16	17	67	50	13	37	0.75	0.13
KDS-600m	41	22	37	48	22	30	64	20	16	18	8	74	70	2	28	0.56	0.02
KDS-709m	58	7	35	70	7	23	89	8	3	36	10	54	49	6	45	0.75	0.06
KDS-765m	47	8	45	63	8	29	85	11	4	34	3	63	44	3	53	0.71	0.03
x̄	40	18	42	48	18	34	69	21	10	18	12	70	62	7	31	0.68	0.07
SD	±10	±6	±6	±8	±6	±6	±9	±6	±4	±7	±5	±7	±12	±3	±11	±0.10	±0.03

* See Table 1 for explanation of symbols.

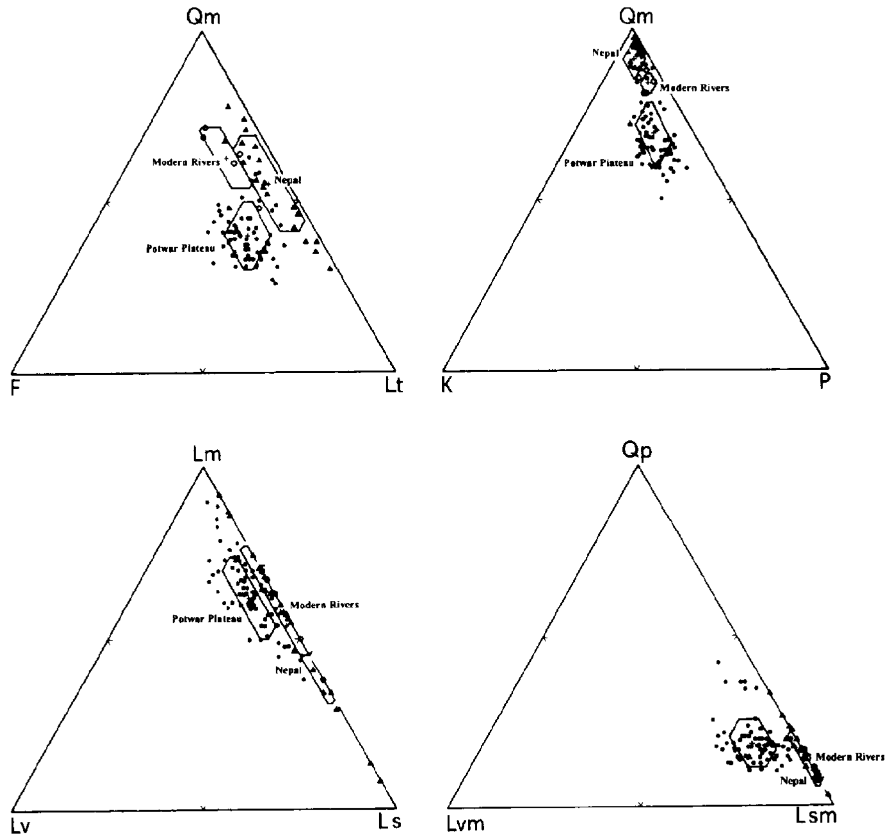

FIG. 3.—QFL, QmKP, QpLvmLsm, and LmLvLs diagrams for the Siwalik Group, of the northwestern Pakistan (Potwar Plateau), western and southeastern Nepal (Surai Khola and Bakia Khola), and modern river sands of the Nepal area. Polygons are one standard deviation on either side of the mean (see Table 1 for explanation of symbols).

(well rounded grains with preserved overgrowth; Sanderson 1984) derived from siliciclastic sedimentary rocks (Fig. 4F).

Interstitial components include detrital siliciclastic matrix and locally abundant authigenic carbonate cement as pore filling, patchy calcite, and poikilotopic cement. Fe-oxide and phyllosilicate cements are subordinate.

Siwaliks of Nepal

Sandstones from Bakiya Khola and Surai Khola are very similar in composition; Bakiya Khola has average modes $Q_{59}F_6L_{35}$ and $Lm_{61}Lv_1Ls_{38}$, whereas Surai Khola has $Q_{57}F_4L_{39}$ and $Lm_{47}Lv_1Ls_{52}$. The only significant difference is that the Bakiya Khola sandstones are mixed metamorphiclastic-sedimentaclastic sandstones; Surai Khola are sedimentaclastic sandstones higher in sedimentary lithics. Siltstone, shale, very fine sandstone, extrabasinal carbonate, and metasedimentary grains (phyllite and fine-grained schist) are common. Monocrystalline quartz is abundant; feldspar is minor. Intrabasinal carbonate (not included in QFL or LmLvLs recalculation), such as caliche grains (Fig. 4G), are particularly common. Interstitial components include detrital siliciclastic matrix and abundant poikilotopic calcite. $^{40}Ar/^{39}Ar$ dating of K-feldspar (Harrison et al. 1993) of the Bakiya Khola sandstones indicate that uplift was typically only 3 m.y. older than deposition (t_{dep} = 8.25–2.2 Ma). Pedogenic carbonates are present in the Bakiya Khola section, and isotopic values indicate changing $^{13}C_{PDB}$ between 11–7 Ma and 7–2 Ma (Harrison et al. 1993); this suggests a change from dominantly C3 plants (i.e., trees) to dominantly C4 plants (i.e., grasses) related to intensification of the Asian monsoon brought about by uplift and erosion of the Gangdese belt.

Modern Sand of Nepal

Comparison between Siwalik sandstone and modern sand of similar sedimentary and tectonic setting, and derived from similar source rocks, is important for solving many questions regarding the accuracy of provenance information based on analysis of ancient sandstone (e.g., Ingersoll 1990). Modern sands were collected along the Napayani River (MR1), Napayani Khola (MR2), Seti Khola at Pokhara (MR3), Madi River at Damouh (MR4), and Kali Kandaki at Ramdi (MR5). Modern sands also have quartzolithic composition (Fig. 3), and are very similar to the Bakiya Khola and Surai Khola sandstones. Monocrystalline quartz is abundant and feldspar content is low ($Q_{65}F_{12}L_{23}$; P/F ranges from 0.61 to 0.89). Lithic grains include abundant extrabasinal carbonate and metasedimentary varieties. Coarse-grained rock fragments include mica schist, gneiss (Fig. 4H), and plutonic rocks (distributed during modal analysis into Qm, F, and M petrographic classes; Table 1). These sands have a great abundance of accessory minerals (5.0–10.2% of total rock), represented by sillimanite, garnet, amphibole, tourmaline, titanite, staurolite, cordierite, kyanite, opaques and epidote.

COMPARISON WITH RELATED SANDSTONE AND SAND

Since Paleocene/Eocene time, collision between India and Asia has induced uplift of the Himalayan suture belt, producing an immense volume of detrital sediments that have been deposited in adjacent foreland basins or in deltas and submarine fans along the continental margins at both sides of the Indian Peninsula (i.e., Makran Coast, Nias Island, Indus Fan, and Bengal/Nicobar Fan) (Fig. 1). Upon initial collision and uplift

TABLE 3.—*Recalculated modal point-count data for the Siwalik Group of the Bakia Khola (BAK) and Surai Khola (SS) (Nepal) and modern river sands (MR)**

	QmF Lt%			QtFL %			QmP K %			Qp Lvm Lsm %			LmLvLs %				
Sample No.	Qm	F	Lt	Qt	F	L	Qm	P	K	Qp	Lvm	Lsm	Lm	Lv	Ls	P/F	Lv/L
BAK 6	71	3	26	72	3	25	95	4	1	6	0	94	86	0	14	0.91	0.00
BAK 26	66	3	31	70	3	27	95	3	2	11	2	87	41	1	58	0.64	0.01
BAK 50a	55	6	39	58	6	36	91	4	5	8	0	92	57	0	43	0.44	0.00
BAK 85	61	9	30	68	9	23	87	9	4	23	0	77	87	0	13	0.69	0.00
BAK 91	35	3	62	47	3	50	93	5	2	19	3	78	47	3	50	0.73	0.03
BAK 112	48	19	33	50	19	31	72	13	15	7	1	92	64	2	34	0.47	0.02
BAK 136	38	1	61	48	1	51	96	3	1	16	1	83	34	0	66	0.83	0.00
BAK 149	30	2	68	39	2	59	93	6	1	14	0	86	55	0	45	0.80	0.00
BAK 182	68	10	22	73	10	17	87	6	7	26	0	74	92	0	8	0.49	0.00
BAK 191	52	7	41	61	7	32	88	7	5	22	0	78	56	0	44	0.56	0.00
SS 3	48	2	50	50	2	48	95	3	2	3	0	97	13	0	87	0.66	0.00
SS 4	74	2	24	79	2	19	97	2	1	19	0	81	60	0	40	0.78	0.00
SS 5	67	6	27	70	6	24	92	7	1	10	0	90	63	0	37	0.86	0.00
SS 6	56	8	36	62	8	30	87	10	3	17	2	81	34	2	64	0.77	0.02
SS 7	42	5	53	46	5	49	88	7	5	8	1	91	58	1	41	0.61	0.01
SS 8	38	4	58	41	4	55	91	5	4	6	1	93	29	1	70	0.53	0.01
SS 10	62	4	34	66	4	30	94	2	4	14	2	84	64	2	34	0.38	0.02
SS 11	54	7	39	57	7	36	89	5	6	8	1	91	74	0	26	0.48	0.00
SS 12	78	4	18	84	4	12	95	4	1	33	0	67	68	0	32	0.75	0.00
SS 15	46	2	52	48	2	50	96	3	1	4	0	96	8	0	92	0.75	0.00
$\bar{x}$	55	5	40	59	5	36	91	5	4	13	1	86	54	1	45	0.66	0.01
SD	±14	±4	±15	±13	±4	±14	±6	±3	±3	±8	±1	±8	±23	±1	±23	±0.15	±0.01
Modern Rivers																	
MR 1	61	11	28	63	11	26	85	9	6	7	0	93	50	0	50	0.61	0.00
MR 2	69	15	16	70	15	15	82	12	6	6	0	94	70	0	30	0.68	0.00
MR 3	64	8	28	66	8	26	88	10	2	7	0	93	38	0	62	0.81	0.00
MR 4	72	13	15	75	13	12	84	14	2	16	0	84	67	0	33	0.89	0.00
MR 5	48	11	41	53	11	36	81	13	6	13	0	87	63	0	37	0.67	0.00
$\bar{x}$	63	12	25	65	12	23	84	12	4	10	0	90	58	0	42	0.73	0.00
SD	±9	±3	±11	±8	±3	±10	±3	±2	±2	±4	±0	±4	±13	±0	±13	±0.11	±0.00

* See Table 1 for explanation of symbols.

of the Himalayan margin in the Early Eocene, synorogenic sediment began to fill the evolving foreland region (Critelli and Garzanti 1994). Piggyback and foreland basins have been filled by terrestrial sediments of the Chulung La Formation and Murree Supergroup, respectively (Fig. 5). Sandstones from the Murree Supergroup have quartzolithic composition ($Q_{68}F_5L_{27}$) with abundant metasedimentary, volcanic, and sedimentary lithics (Critelli and Garzanti 1994); sandstones from the Chulung La Formation have lithofeldspathic composition ($Q_{24}F_{26}L_{50}$), with abundant volcanic detritus. Both of them also have ophiolitic detritus.

During Oligo-Miocene time, sediment derived from the Himalyan belt was probably also transported west and east, respectively, into Makran and offshore Sumatra (Nias Island) subduction zones (e.g., Moore 1979; Velbel 1985; Critelli et al. 1990; Critelli 1993) (Fig. 5). Trench-fill (Panjgur Unit) and trench-slope (Makran Group) sandstones have quartzolithic composition ($Q_{56}F_{10}L_{34}$) with metasedimentary, sedimentary, ophiolitic, and volcanic detritus. It is likely that transport of Himalayan detritus through the ancestral Indus River filled the Makran trench (Critelli et al. 1990).

Trench-fill (Oyo Complex) and trench-slope (Nias slope) sandstones of Nias Island are quartzolithic ($Q_{70}F_{11}L_{19}$), and the detritus is mostly of metasedimentary and volcanic origin. Apart from volcanic detritus of Nias and Makran, derived from the nearby volcanic arcs, nonvolcanic detritus has close relationships with the Himalayan source terranes.

During the Neogene, a large amount of sediment was trapped in terrestrial foreland basin developed at the front of the Himalaya suture belt, forming the Siwalik Group. Rise of the Himalayas and Tibet at this time is indicated by Siwalik sandstone composition, by isotopic data on the high Himalaya crystalline rocks (Hodges et al. 1992),and by isotopic and fission-track data on the Siwalik Group (Burbank and Tahirkheli 1985; Cerveny et al. 1988; Harrison et al. 1993) and Bengal fan (Copeland and Harrison 1990; Amano and Taira 1992). However, most sediment has been transported by the Indus and Ganges/Brahmaputra river systems to their respective deltas, with much of the fluvial sediment bypassing the deltas and transported by turbidity currents to the Indus and Bengal/Nicobar fans (Graham et al. 1975).

The Indus Fan ($Q_{43}F_{30}L_{27}$) and Bengal Fan ($Q_{57}F_{28}L_{15}$) (Ingersoll and Suczek 1979; Suczek and Ingersoll 1985) (Fig. 5) are more feldspathic than the Siwalik and pre-Siwalik sandstones. Isotopic data on the Bengal fan (Copeland and Harrison 1990; Amano and Taira 1992) confirm rapid uplift and unroofing of the tectonic units of the High Himalayan crystalline rocks. Also, modern rivers draining the High Himalaya (north of Main Central Thrust) and Lesser Himalaya (north of Main Boundary Thrust) are more quartzose ($Q_{65}F_{12}L_{23}$) on the east side of the Indian Peninsula, and differences in feldspar content may be related to uplift of crustal blocks in the Himalaya zone (Copeland and Harrison 1990; Amano and Taira 1992) or also to the influence of uplifted granitoid rocks of the Indian

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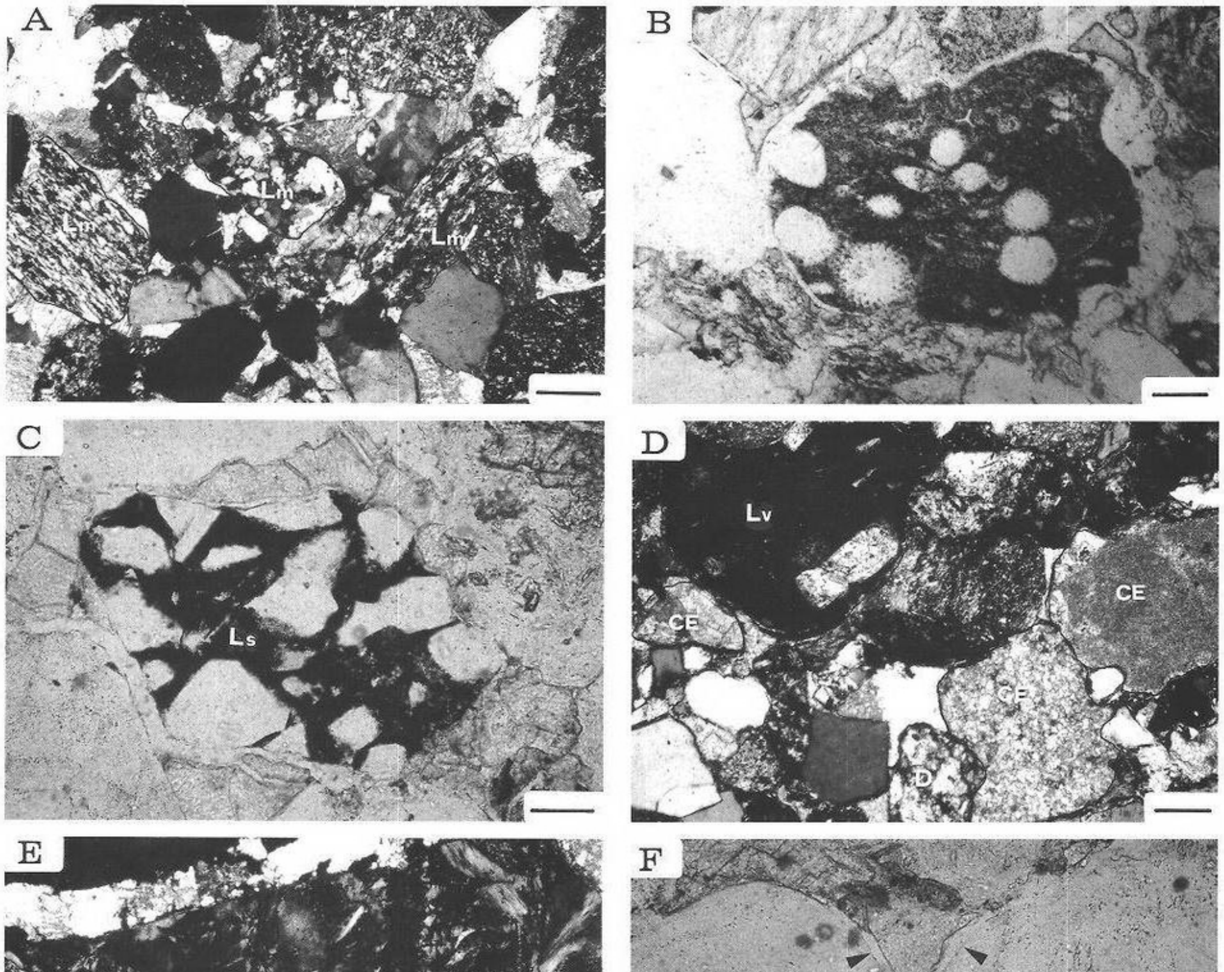
FIG. 4.—Photomicrographs of main framework grains from the Siwalik Group and modern river sand: **A)** metasedimentary lithic grains (phyllite and fine-grained mica schist); **B)** radiolarian chert; **C)** sedimentary lithic grain (Ls, siltstone); **D)** volcanic lithic with microlitic texture (Lv), dense mineral (D), and extrabasinal carbonate grains (CE); **E)** serpentinite grain; **F)** well-rounded quartz grains with inherited overgrowths, testifying a second-cycle quartz; **G)** oversized caliche grain; **H)** coarse-grained amphibole schist rock fragment (Modern river sand). **A, D, E, G, H** = crossed polars; **B, C, F** = plane-polarized light. Scale bar represents 0.2 mm for all photographs.


A
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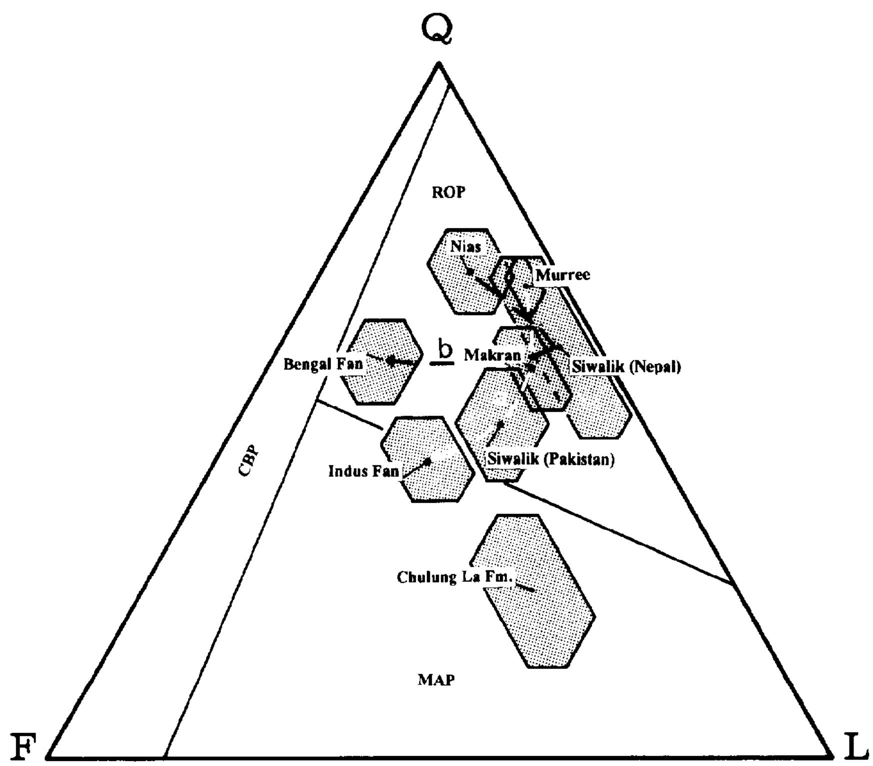

FIG. 5.—QFL triangular plot superposed on provenance fields (Dickinson 1985; ROP = recycled-orogen provenance; MAP = magmatic-arc provenance; CBO = continental-block provenance), showing detrital-mode evolution from Eocene–Modern sandstones/sands of the Himalayan Range and surrounding areas. Sandstone/sand data include: (1) foreland sandstones of the Eocene to Miocene Murree Supergroup and Chulung La Formation (data from Critelli and Garzanti 1994); (2) foreland sandstone of the middle Miocene–Pliocene Siwalik Group; (3) remnant-ocean sandstone of the Oligocene–Pliocene Makran Group (data from Critelli et al. 1990), and Nias Island (data from Moore 1979); and (4) remnant-ocean sand of the modern Bengal and Indus Fans (data from Ingersoll and Suczek 1979, and Suczek and Ingersoll 1985). The two trends (shown by white, a, and black, b, lines) suggest progressive compositional shift from quartzolithic to quartzofeldspathic sandstones/sands from the Eocene to the present for western (i.e., line a; Murree, Makran, Pakistan-Siwalik, and Indus Fan) and eastern (i.e., line b; Nias, Nepal Siwalik, and Bengal Fan) sides of the Indian Peninsula.

shield. These compositions are similar to sand composition of the Ganges delta (e.g., Mallik 1976) and of deep-sea sands of the Indian ocean (e.g., Jipa and Kidd 1974; Mallik 1978).

DISCUSSION AND CONCLUSIONS

After collision of the Indian block with the southern active margin of Asia, a large amount of siliciclastic sediment accumulated within foreland and remnant-ocean basins developed from Eocene to the present in front of the collision zone and at both sides of the Indian block. Terrestrial sedimentation is active within basins developed along the collision zone. From the Eocene through the Neogene, an immense quantity of quartzolithic sandstones (Murree Supergroup, Critelli and Garzanti 1994; and Siwalik Group) were deposited in these basins and in subduction zones west (Makran; Critelli et al. 1990) and east (Nias Island, Moore 1979) of the Indian block.

Portions of the Siwalik strata were deposited by large rivers (i.e., the ancestral Indus and Ganges) draining the uplifted Himalayan belt during the late Neogene (Parkash et al. 1980; Burbank and Beck 1991; Mulder and Burbank 1993); the entire succession represents the sedimentary fill of the foreland basin related to the Neogene collision between India and Asia. The Siwalik Group is probably the largest quartzolithic petrosome in the world derived from a collisional-orogen provenance (Fig. 5; e.g., Dickinson and Suczek 1979; Dickinson 1985). Main petrographic parameters are consistent with this origin, but subtle differences in composition are evident between Pakistan and Nepal.

Composition of lithic grains indicates that detritus was derived from a suture belt including mainly low- to medium-grade metamorphic, sedimentary, and subordinately volcanic and ophiolitic rocks.

The Siwalik Group of the Potwar Plateau has abundant metamorphic, ophiolitic, and sedimentary grains. Lithic grains of serpentinite, serpentine schist, volcanics, and radiolarian chert reflect sources in the uplifted subduction complex. Volcanic lithics are subordinate and consist of microlitic, lathwork, and felsitic grains that in many cases are altered, partially oxidized, and chloritized. These characteristics suggest a paleovolcanic origin for these grains (e.g., Zuffa 1987). Volcanic tuff and bentonitic layers (Johnson G.D. et al. 1982; Johnson N.M. et al. 1982) are also present in the upper Siwalik section, indicating volcanic events coeval with sedimentation.

The Siwalik Group in Nepal (Surai Khola and Bakiya Khola) has abundant metasedimentary and sedimentary lithic grains.

A comparison with pre- and post-Siwalik sandstones of the Himalayan and surrounding zones confirms the deep and rapid erosion of the infracrustal crystalline rocks cropping out along the suture belt. Progressive exhumation and erosion of the midcrustal terranes has occurred from the Eocene to the present. The composition of Eocene to Pliocene sandstones (e.g., Murrees, Makran, Nias, and Siwaliks) is quartzolithic; the composition has shifted toward quartzofeldspathic during the Pleistocene to the present (remnant ocean sands of the Bengal and Indus Fan) (Fig. 5). This compositional change may be related to uplift of the High Himalaya.

The compositions of sandstones from the Himalayan area provide an excellent example of the changing nature of a collisional-belt source area through time. Rapid uplift results in significant changes in sandstone compositions that primarily reflect deeper erosion of the growing orogen. Nonetheless, all of these sands and sandstones reflect their recycled-orogen provenance.

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