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Provenance of the Lower Tertiary Murree redbeds (Hazara–Kashmir Syntaxis, Pakistan) and initial rising of the Himalayas

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Abstract

The Murree Supergroup of northern Pakistan is represented by an over 6 km thick succession of deltaic redbeds and intercalated impure foraminiferal limestones of latest Paleocene to Middle Eocene (Ilerdian to Lutetian) age, cropping out in the northern part of the Hazara Syntaxis, and by redbeds of younger age (early Middle Eocene to Early Miocene) cropping out in the southern part of the Syntaxis (Rawalpindi area).

The quartzolithic composition of the Murree redbeds testifies to a "collision orogen" provenance. Detritus was derived from a suture belt including thrust sheets of metasedimentary and subordinately sedimentary rocks, volcanic or volcaniclastic rocks, and ophiolites. Phyllite rock fragments are most common in the Ilerdian sandstones, whereas volcanic and carbonate rock fragments are more abundant in the Lutetian sandstones. Minor quantities of chert and serpentineschist, indicating contribution from uplifted subduction complex sources, as well as siltstone, shale and limestone grains, are invariably present. Detrital modes of sandstones and southwestward progradation of Tertiary clastic wedges both testify to provenance from the proto-Himalayan chain located to the north, and uplifted since the very first stages of the India/Asia continental collision at the end of the Paleocene.

The coeval Chulung La redbeds of the Tethys Himalaya instead, consisting of volcanic and subordinate ophiolitic detritus, testify to exclusive provenance from the obducting Trans-Himalayan arc–trench system. This major petrographic difference may be accounted for by the different structural setting of the Chulung La "piggy-back" and Murree foreland basins. These two distinct collisional basins have been separated probably since the onset of collision by a fold-thrust belt, beginning to rise in the position occupied today by the High and Lesser Himalayan structural domains.

Throughout the Murree Supergroup, main petrographic parameters do not vary greatly, and volcanic, sedimentary, low-grade metasedimentary and ophiolitic detritus persisted until the Early Miocene, indicating slow progressive growth of the chain. Only during the Middle Miocene, when the highly metamorphosed rocks of the High Himalaya were carried southward along the Main Central Thrust (MCT), the mountain range began to rise to dramatic heights, and huge amounts of detritus started to feed the Siwalik foreland basin sandstones and the remnant ocean turbidites of the Indus and Bengal Fans.

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1. Introduction

Collision between India and Asia began at Early Ilerdian times (*Morozovella velascoensis* foraminiferal Zone), close to the Paleocene/Eocene boundary (Powell, 1979; Garzanti et al., 1987). Since then, the Himalayan chain has continued to rise, while enormous quantities of terrigenous detritus accumulated in foreland and remnant ocean basins (Fig. 1; Graham et al., 1975; Critelli and Garzanti, 1991). Tertiary fluvio-deltaic orogenic clastics are widely distributed in the northern part of the Indian subcontinent. In the Late Pliocene and Pleistocene, they have been deformed, uplifted and incorporated south of the Main Boundary Thrust in the Sub-Himalayan foothills, which are separated from the Indo-Gangetic plain by the active Main Frontal Thrust of the orogenic belt (Gansser, 1964).

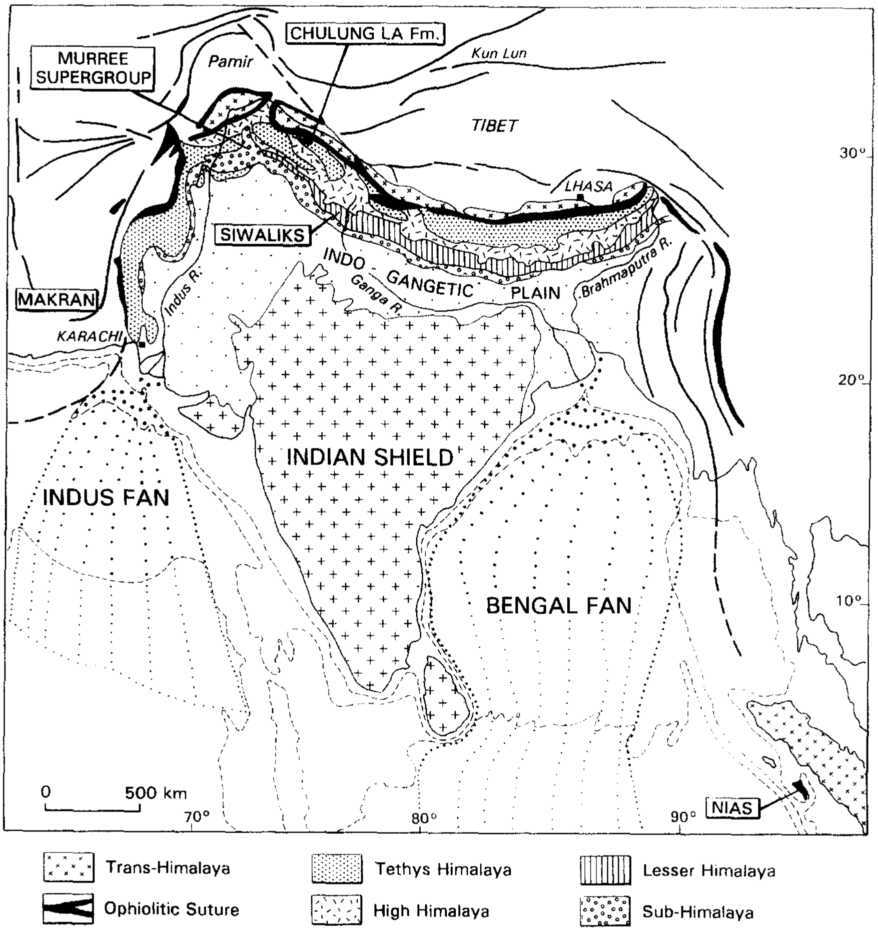


Fig. 1. The Himalayan Range began to rise at about 54 Ma, when the Tethyan oceanic crust was finally consumed and the Indian passive continental margin came into contact with the Asian active margin. Deformed rocks belonging to these structural domains —once far apart—are juxtaposed in E–W-running elongated belts on either side of the Indus–Yarlo ophiolitic suture (Trans-Himalayan arc–trench system to the north; Tethys Himalayan, High Himalayan and Lesser Himalayan sedimentary and metamorphic rocks to the south). Locations of Fig. 2 (Murree Supergroup) and Fig. 7 (Chulung La Fm.) are shown. Since collision onset, enormous quantities of detritus have been shed to ancient and recent foreland basins (Murrees and Siwaliks, deformed and uplifted in the Sub-Himalayan belt; Indo-Gangetic Plain) and remnant ocean basins (Indus and Bengal Fan). These "recycled orogen" clastics crop out today in a vast area from Makran (Pakistan) to Nias Island (Indonesia).

This study is based on detailed field mapping and sampling of the Murree redbeds in the Hazara–Kashmir Syntaxis carried out by Paul Bossart, Robert Ottiger and other researchers of the ETH Zürich under the guidance of John Ramsay. Our aim is to provide quantitative petrographic information on the Murree Supergroup, the early foreland basin deposits of northern Pakistan (Fig. 2). Their mineralogical composition will be briefly compared both with the coeval redbeds of the Tethys Himalaya to the north and with the younger orogenic clastic wedges shed from the Himalayan suture belt to the south, in order to draw some inferences on the evolution of the Himalayan Range in the very first stages of continental collision.

The reader will find further information on the general geodynamic scenario and early collisional clastics in Garzanti et al. (1987) and Garzanti and Van Haver (1988); sedimentological data and interpretation of depositional environments for the Murree redbeds are provided in Bossart and Ottiger (1989).

2. Structural and stratigraphic setting

The Hazara–Kashmir Syntaxis is a structural re-entrant, formed owing to clockwise rotation of the overthrust direction by about 45° relative to the Indian craton, during progressive indentation of India into Asia (Bossart et al., 1989; Greco,

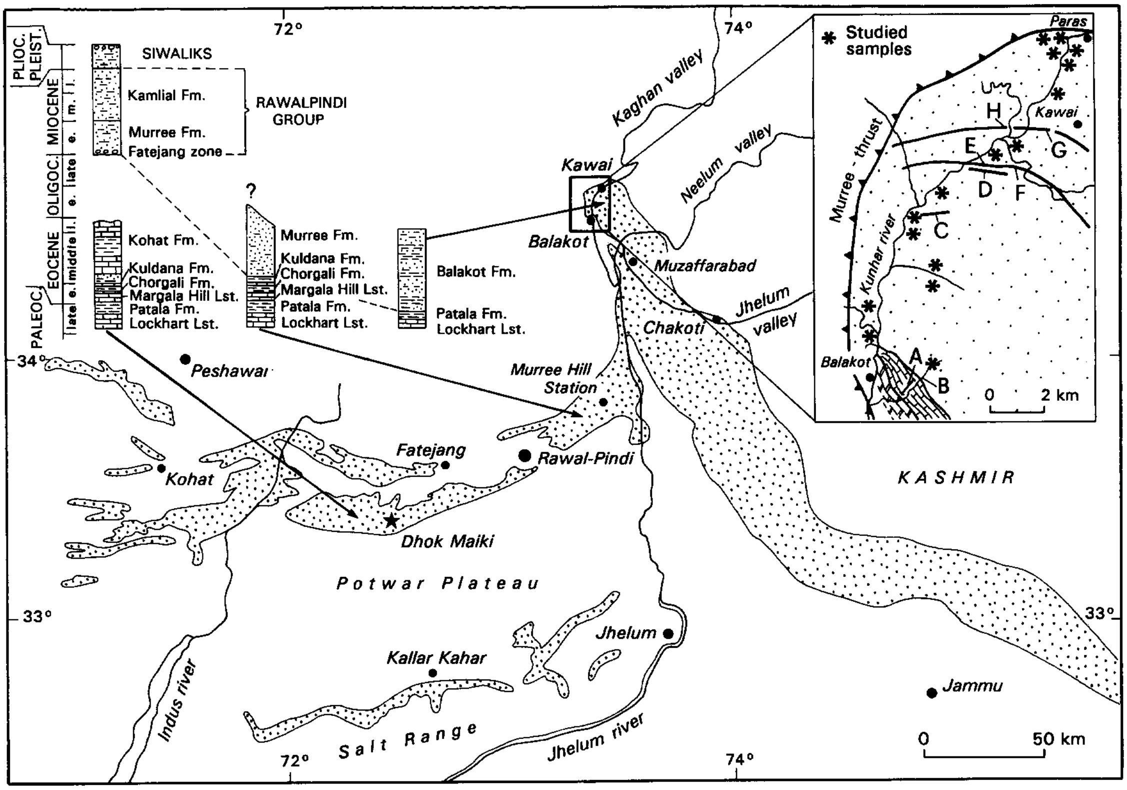


Fig. 2. Outcrop area and stratigraphy of the Murree Supergroup (northern Pakistan and Western India; after Bossart and Ottiger 1989). *Dhok Maiki* = type locality of the Murree Formation as defined by the Stratigraphical Committee of Pakistan. The inset shows a simplified geologic map of the apex of the Hazara–Kashmir Syntaxis, with outcrop area of the Balakot Fm. and location of most samples studied (but for 5 collected in the *upper part* of the profile about 8 km SE of Paras); *A* to *H* indicate nummulitid-bearing fossiliferous sections and marker beds mentioned in text. Strata young consistently towards the north and northeast.

Table 1
Point-counting data for the Murree redbeds

	Balakot Fm.													
	Lower								Middle		Upper			
	218a	300b	270h	2	4	142A	7	260d	226d	196c	168b	132a	168e	132b
Quartz (single crystals)	41.2	42.5	40.9	43.2	46.6	41.8	55.8	36.0	58.0	44.9	37.3	40.9	41.3	44.8
Coarse-grained polycrystalline quartz	–	–	–	0.2	–	–	0.7	–	0.9	–	1.4	0.7	0.5	0.5
Fine-grained polycrystalline quartz	–	–	–	0.7	–	–	1.0	–	1.7	–	0.2	–	–	0.3
Quartz in medium-grade metamorphic rock fgm.	0.5	0.5	–	1.2	1.1	–	0.5	0.6	–	–	0.2	0.2	0.2	0.5
Quartz in low-grade metamorphic rock fgm.	3.1	2.4	4.7	2.5	1.8	0.3	1.7	3.0	–	0.5	0.2	0.5	1.4	1.8
Quartz in sandstone	–	–	–	0.2	–	–	0.5	–	0.3	–	0.2	–	–	–
Quartz in plutonic or gneissic rock fgm.	–	–	–	1.7	0.2	–	–	–	1.2	–	–	0.2	0.2	0.8
Calcite replacement on quartz	–	–	–	–	–	1.3	–	–	–	–	–	–	–	–
K-feldspar (single grains)	–	–	–	0.7	0.2	0.5	0.5	–	–	1.1	–	1.1	–	–
K-feldspar in plutonic or gneissic rock fgm.	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Calcite replacement on K-feldspar	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Plagioclase (single grains)	3.8	2.4	3.1	2.0	0.4	2.0	2.9	3.2	3.2	1.4	3.0	7.5	2.1	5.6
Plagioclase in intermediate volcanic rock fgm.	–	–	–	–	–	–	–	–	–	–	0.2	–	–	–
Plagioclase in medium-grade metamorphic rock	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Plagioclase in low-grade metamorphic rock fgm.	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Plagioclase in granitic or gneissic rock fgm.	–	–	–	–	–	–	–	–	0.3	–	–	–	–	0.5
Calcite replacement on plagioclase	–	–	–	–	–	0.3	–	–	–	–	–	–	–	–
Felsitic volcanic rock fgm.	–	–	–	0.2	–	–	–	–	0.3	0.3	–	–	0.2	–
Microlitic volcanic rock fgm.	–	1.2	–	0.2	–	0.5	0.7	–	0.3	–	2.1	2.7	0.5	2.6
Vitric volcanic rock fgm.	1.6	2.8	1.2	0.5	2.0	2.3	2.2	1.7	2.3	1.4	16.1	8.6	7.7	4.9
Intermediate volcanic rock fgm.	–	0.9	–	0.2	0.2	0.3	0.5	–	0.9	–	2.3	2.3	3.7	3.6
Serpentinite	–	0.7	–	0.5	0.2	0.8	0.2	–	–	–	0.7	0.9	2.3	1.3
Serpentineschist	0.2	0.5	0.5	–	0.2	0.3	0.2	0.4	–	–	0.2	–	–	0.3
Phyllite	27.0	11.4	20.0	24.9	10.8	2.5	15.9	20.6	3.5	18.2	1.1	2.5	0.9	0.8
Shale	–	1.7	0.5	8.5	4.8	1.0	0.7	0.2	1.2	2.2	1.8	–	2.6	0.8
Chert	1.9	1.9	10.6	1.5	0.9	1.5	1.2	1.9	2.6	1.1	8.9	8.4	6.5	9.2
Siltstone	–	1.2	0.2	–	0.9	–	–	–	2.0	0.5	0.5	–	3.0	4.3
Calcite replacement on fine-grained lithic	–	–	–	–	–	–	–	–	–	0.3	–	–	0.5	–
Micas and chlorites (single crystals)	0.2	0.5	–	–	–	–	–	–						
Micas and chlorites in low-grade metamorphic	–	–	0.5	–	–	–	0.2	0.4	–	–	–	–	–	–
Other minerals	0.7	0.2	3.5	0.5	0.9	0.5	0.5	0.9	0.3	1.4	–	9.1	0.9	1.0
Rip-up clast	–	5.2	–	–	2.2	–	–	–	2.9	0.3	–	–	0.5	1.5
Iron oxides	–	–	–	–	–	0.5	–	0.2	–	–	–	–	–	–
Micrite and biomicrite limestone	0.5	0.9	–	–	–	0.3	2.2	0.4	–	–	0.5	–	–	1.5
Sparite and microsparite limestone	–	–	–	0.2	–	0.3	1.0	0.4	–	–	–	0.5	1.0	2.6
Bioclasts	–	–	–	–	0.2	0.3	–	–	–	–	–	–	–	–
Intraclasts	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Undetermined limeclasts	–	0.2	–	–	–	–	–	–	–	–	0.5	–	0.2	1.3
Caliche	–	–	–	–	–	–	–	–	–	–	1.4	–	–	–
Siliciclastic matrix	3.5	3.1	8.0	5.0	0.9	9.1	4.2	10.6	5.8	12.5	6.3	3.0	0.7	4.1
Carbonate matrix	0.5	0.2	–	–	–	–	0.2	–	–	–	–	–	–	–
Carbonate cement (sparite)	–	–	–	–	–	–	0.7	–	–	–	–	–	–	–
Calcite replacement on undetermined grains	14.6	18.5	2.8	0.5	24.0	31.6	3.9	19.1	4.4	10.9	13.8	9.3	22.1	4.6
Other cement	–	–	0.7	–	0.4	–	–	–	0.3	0.3	–	–	–	–
Alterites	0.7	0.9	2.3	2.7	0.9	1.0	1.7	0.4	6.7	2.7	1.1	–	0.5	0.8
Neogenic quartz	–	0.2	0.5	2.2	0.2	1.0	0.2	–	0.3	–	–	1.6	0.5	–
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The first 8 samples (from the left) are from the lower part of the Balakot Formation, the next 2 from the middle part and the following 11 from the upper part. The last 7 samples (to the right) are from more southern outcrops of the Hazara–Kashmir Syntaxis.

Balakot Fm.							Southern outcrops						
Upper													
13	14	288r	288h	198	19	290e	296g	296f	264h	264m	264a	294b	266a
37.6	32.1	31.0	37.6	42.0	46.1	57.1	30.3	51.1	67.1	35.3	37.2	47.3	36.4
0.2	0.4	–	0.8	–	0.2	–	1.5	0.4	1.2	0.7	0.4	–	–
–	0.2	–	–	–	–	0.3	0.9	1.5	0.4	0.4	–	–	–
0.5	–	–	–	–	0.5	–	–	–	–	1.4	0.6	0.4	0.5
0.5	0.4	–	–	–	0.5	–	0.5	0.2	–	0.7	–	1.9	0.5
–	–	–	–	–	–	–	–	–	–	1.1	–	–	0.2
–	–	–	0.3	–	0.2	–	0.2	0.2	–	0.2	–	–	–
–	–	–	–	–	–	–	–	–	–	0.2	–	–	–
–	–	–	–	–	–	0.5	0.9	0.9	1.6	1.6	–	–	–
–	–	–	–	–	–	–	0.2	–	–	0.2	–	–	–
–	–	–	–	–	–	–	–	–	–	0.2	–	–	–
2.3	7.7	5.2	2.5	8.0	3.1	5.6	10.7	6.4	4.7	5.2	4.5	3.4	1.8
–	0.8	–	0.8	0.5	–	–	1.2	0.2	–	–	–	–	–
–	–	–	–	–	–	–	–	–	–	0.2	–	–	–
0.2	–	–	–	–	–	–	–	–	–	0.2	–	–	–
–	–	–	–	–	–	–	–	–	–	0.2	–	–	–
–	–	–	–	–	–	–	0.3	–	–	–	–	–	–
0.7	–	–	–	–	–	0.8	2.4	1.5	1.6	0.5	–	–	0.2
1.2	2.2	2.7	1.9	0.2	0.5	1.9	3.7	3.6	–	6.2	3.1	0.2	0.5
6.9	8.4	16.6	19.3	3.6	4.0	4.6	2.9	1.7	1.6	1.1	11.0	3.2	1.6
3.2	3.7	1.0	2.2	1.7	2.6	–	2.4	0.4	0.4	–	0.2	0.2	0.9
1.2	0.6	0.5	1.9	–	0.5	0.5	0.9	0.9	–	1.6	0.8	0.4	0.2
–	0.2	–	0.8	–	–	–	0.9	0.2	0.4	0.4	0.8	0.4	–
3.7	2.8	1.0	0.5	1.9	3.1	1.6	2.0	5.1	5.8	13.5	2.1	7.3	6.8
1.2	1.2	0.5	1.4	2.9	2.1	0.3	4.3	2.6	1.9	3.7	3.9	0.2	–
5.8	7.7	13.6	10.6	2.2	4.5	4.3	4.0	4.3	8.2	1.4	8.1	6.8	10.0
0.7	–	0.7	–	2.7	0.2	–	0.9	0.9	–	1.2	–	–	4.1
–	0.2	0.2	–	–	0.2	–	0.8	–	–	0.2	–	0.2	–
–	0.4	0.5	–	–	0.2	–	0.6	2.3	–	3.4	0.8	–	–
–	–	–	–	–	–	–	–	–	0.4	–	–	–	–
–	13.4	0.7	–	0.2	–	–	0.7	–	–	2.5	–	0.9	0.2
–	–	–	–	–	–	–	–	–	–	–	–	–	1.8
–	–	–	–	–	–	–	0.3	0.6	–	0.5	–	0.2	–
3.0	0.8	1.0	0.5	0.7	3.6	0.3	0.6	0.2	–	0.7	0.4	3.0	2.5
7.6	1.0	0.2	–	0.2	2.6	–	–	–	–	0.2	0.6	0.6	0.7
–	–	1.5	–	–	–	–	0.2	–	–	0.2	–	–	–
–	–	–	0.3	–	–	–	–	0.6	–	0.4	0.4	–	–
0.7	–	6.5	3.3	0.7	0.2	1.3	0.2	–	–	–	1.0	0.9	10.3
–	–	0.2	–	–	–	1.6	–	–	–	–	–	–	2.1
3.9	0.8	2.5	1.1	6.0	5.0	3.5	–	2.3	1.6	–	5.8	4.3	5.9
0.2	–	–	–	–	–	–	–	–	–	–	–	–	–
–	–	–	–	–	–	–	0.7	0.2	2.3	2.3	–	0.6	–
3.5	13.0	12.7	7.1	24.6	17.3	12.9	23.9	4.7	0.8	11.0	10.3	16.0	12.8
2.7	0.4	–	–	0.7	–	–	–	1.7	–	–	6.6	–	–
2.1	1.2	1.2	1.4	1.2	1.7	2.9	0.7	4.7	–	1.2	1.0	0.6	–
10.4	0.4	–	5.7	–	1.1	–	0.2	0.6	–	–	0.4	1.0	–
100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 2
Recalculated detrital modes for the Murree redbeds (petrographic parameters after Ingersoll and Suczek, 1979)

Sample numbers	QtFL (%)			QmFLt (%)			QmPK (%)			QpLvmLsm (%)			LmLvLs (%)		
	Qt	F	L	Qm	F	Lt	Qm	P	K	Qp	Lvm	Lsm	Lm	Lv	Ls
Upper Murree Formation															
168b	63	4	33	51	4	45	92	8	–	29	59	12	5	61	34
132a	66	11	23	55	11	34	83	15	2	33	54	13	12	55	33
168e	67	3	30	58	3	39	95	5	–	23	47	30	9	48	43
132b	67	7	26	56	7	37	89	11	–	28	37	35	9	38	53
13	59	3	38	51	3	46	94	6	–	16	36	48	13	36	51
14	58	12	30	47	12	41	80	20	–	27	53	20	11	53	36
288r	60	7	33	41	7	52	86	14	–	36	55	9	3	55	42
288h	61	4	35	48	4	48	92	8	–	28	66	6	1	68	31
198	66	13	21	63	13	24	83	17	–	13	36	51	12	36	52
19	70	4	26	64	4	32	94	6	–	19	30	51	16	31	53
290e	79	8	13	74	8	18	90	9	1	31	54	15	11	55	34
X	65	7	28	55	7	38	89	11	–	26	48	26	9	49	42
SD	6	4	7	9	4	10	5	5	–	7	12	17	5	12	9
Middle Murree Formation															
226d	83	4	13	79	4	17	95	5	–	33	24	43	26	28	46
196c	65	3	32	64	3	33	95	3	2	5	7	88	86	7	7
X	74	3	23	72	3	25	95	4	1	19	15	66	56	17	27
SD	12	1	13	11	1	11	–	1	1	20	12	32	42	15	28
Lower Murree Formation															
300b	67	3	30	64	3	33	95	5	–	7	24	69	54	24	22
270h	69	4	27	56	4	40	94	6	–	28	4	68	66	4	30
2	57	3	40	56	3	41	95	4	1	6	4	90	70	4	26
218a	58	5	37	56	5	39	92	8	–	5	5	90	88	5	7
4	72	1	27	70	1	29	98	1	1	4	12	88	63	12	29
142a	84	4	12	81	4	15	95	4	1	15	41	44	28	41	31
7	69	4	27	68	4	28	94	5	1	10	13	77	66	14	20
260d	61	5	34	58	5	37	93	7	–	6	7	87	83	7	10
X	67	4	29	63	4	33	94	5	1	10	14	76	64	14	22
SD	9	1	9	9	1	9	2	2	1	8	13	16	18	13	9
Southern outcrops of Murree Formation															
296g	52	18	30	46	18	36	72	26	2	22	50	28	9	54	37
296f	70	9	21	65	9	26	88	11	1	26	36	38	25	39	36
264h	81	7	12	72	7	21	92	6	2	44	18	38	31	19	50
264m	53	10	37	51	10	39	84	12	4	7	29	64	54	18	28
264a	63	6	31	52	6	42	89	11	–	26	50	24	8	51	41
294b	74	5	21	65	5	30	94	6	–	28	18	54	39	18	43
266a	71	3	26	57	3	40	95	5	–	34	12	54	27	12	61
X	66	8	26	59	8	33	88	11	1	27	30	43	28	30	42
SD	11	5	8	9	5	8	8	7	2	11	16	15	16	17	11

Qt = total quartz (Qm = monocrystalline; Qp = polycrystalline, including chert); F = total feldspars (P = plagioclase; K = K-feldspar); L = "aphanite" lithics (Lvm = volcanic and metavolcanic; Lsm = sedimentary and metasedimentary; Lm = metamorphic, including serpentineschist; Lv = volcanic, including serpentinite; Ls = sedimentary, including chert). X = mean; SD = standard deviation.

1991). It consists of a stack of thrust sheets made by the Lesser Himalayan Precambrian to Mesozoic metasediments, which have been carried southwestward onto the Tertiary Murree redbeds. Below this Murree Thrust, corresponding to the Main Boundary Thrust of India, the structure is dominated by the large domal-shaped Muzaffarabad anticline.

At the anticlinal core, between Balakot and Muzaffarabad, the Upper Precambrian to Cambrian, chert-bearing and locally quartzose or stromatolitic carbonates of the Abbottabad Formation are exposed (Bossart et al., 1988). They are unconformably overlain by the 420 m thick Lockhart Limestone, deposited in shallow-water environments and yielding corals, bryozoans, Dasycladacean algae, Nummulites and Assilines of Ilerdian age (Bossart, 1986; profile A in Fig. 2).

The Lockhart Limestone is conformably overlain by the 230 m thick Patala Formation, which is characterized by increasing quartzose detritus and consists of marly limestones with locally interbedded coal-bearing siltstones and pure quartzarenite beds in the lower part. Nummulites and Assilines in this unit also indicate a latest Paleocene/earliest Eocene age. Felsitic volcanic, phyllite, chert and serpentineschist rock fragments characterize instead the greenish nummulitic sandstones interbedded in the uppermost part of the unit. The Patala Fm. passes upward to the Murree reddish siltstones, interbedded at the very base with bioclastic packstones containing benthic foraminifera of mid-Ilerdian age (*Fasciolites ellipsoidalis* group; fossiliferous site B in Fig. 2).

Deltaic red and green sandstones are 6 to 8 km thick (Balakot Fm. of Bossart and Ottiger, 1989, included in the Murree Supergroup). Impure foraminiferal limestones are interbedded at successive stratigraphic intervals until the Middle Lutetian, documented at about two thirds from the base of the profile. Continuous foreland basin sedimentation thus occurred in northern Pakistan at extreme accumulation rates, decreasing from around 2500 m/m.y. in the very first earliest Eocene stage of continental collision and nappe thrusting, down to 750 m/m.y. in the Lutetian (Bossart and Ottiger, 1989).

The transition from platform carbonate sedimentation to a rapidly subsiding foreland basin, filled with detritus comprising serpentineschist rock fragments and chromian spinels derived from the ophiolitic suture in the north, is ascribed to initial obduction of the Kohistan arc–trench allochthon onto the Indian continental margin (Garzanti, 1986; Ottiger, 1986). Successive migration of the orogenic front led to a southward displacement of the Murree redbed facies belt, which prograded onto progressively younger shallow-marine deposits. The southernmost outcrops of fluviatile redbeds belonging to the Murree Supergroup (Kohat–Potwar region and Salt Range) are in fact Early Miocene in age (Murree Formation, representing the lower part of the Rawalpidi Group; Fig. 2; Bossart and Ottiger, 1989, p. 137).

3. Sandstone petrography

In order to characterize the detrital modes of the northern Pakistan Murree redbeds, 28 sandstone samples collected by P. Bossart and R. Ottiger were selected. Among these, 21 were sampled along the Kunhar River section (Balakot Fm.) in the apex area of the Hazara Syntaxis: 8 are representative of the Ilerdian *lower part* of the profile (below fossiliferous marker bed D of Bossart and Ottiger, 1989), only 2 represent the Cuisian *middle part* of the profile (between marker beds D and G–H), and the final 11 samples represent the Lutetian *upper part* of the profile (above marker bed G–H; see inset in Fig. 2 for sample location). The other 7 samples were collected for comparison from younger outcrops in the southern part of the Syntaxis (Muzaffarabad area and Jhelum Valley; samples 264m, 266a), in the lower Middle Eocene Kuldana Formation (264a) and in the younger "Murree Formation" (sensu Wynne, 1874, in Bossart and Ottiger, 1989) of the Murree–Kuldana hills (264h, 296f, 296g), and finally in the Dhok Maiki type section of the Lower Miocene Murree Formation (294b; see Fig. 2 for sample location).

Sandstone point counts were performed following the Gazzi-Dickinson method (Ingersoll et al., 1984; Zuffa, 1985). For each thin section, 400 to 600 points were counted (Table 1). Recalculated grain parameters are given in Table 2.

3.1. Petrographic composition of the Murree redbeds

The sandstones of the Murree Supergroup (Fig. 2) have a quartzolithic composition.

Quartz grains are mostly monocrystalline, but polycrystalline grains, with both fine and coarse crystal size, occur (C/Q up to 0.07).

Plagioclase is common (P/F mostly 0.74 to 1) and increases upward, from the lower and middle parts of the Balakot Fm. (0.4–3.8%; albite–oligoclase composition) to the upper Balakot Fm. and southern outcrops of the Syntaxis (1.8–12.2%;

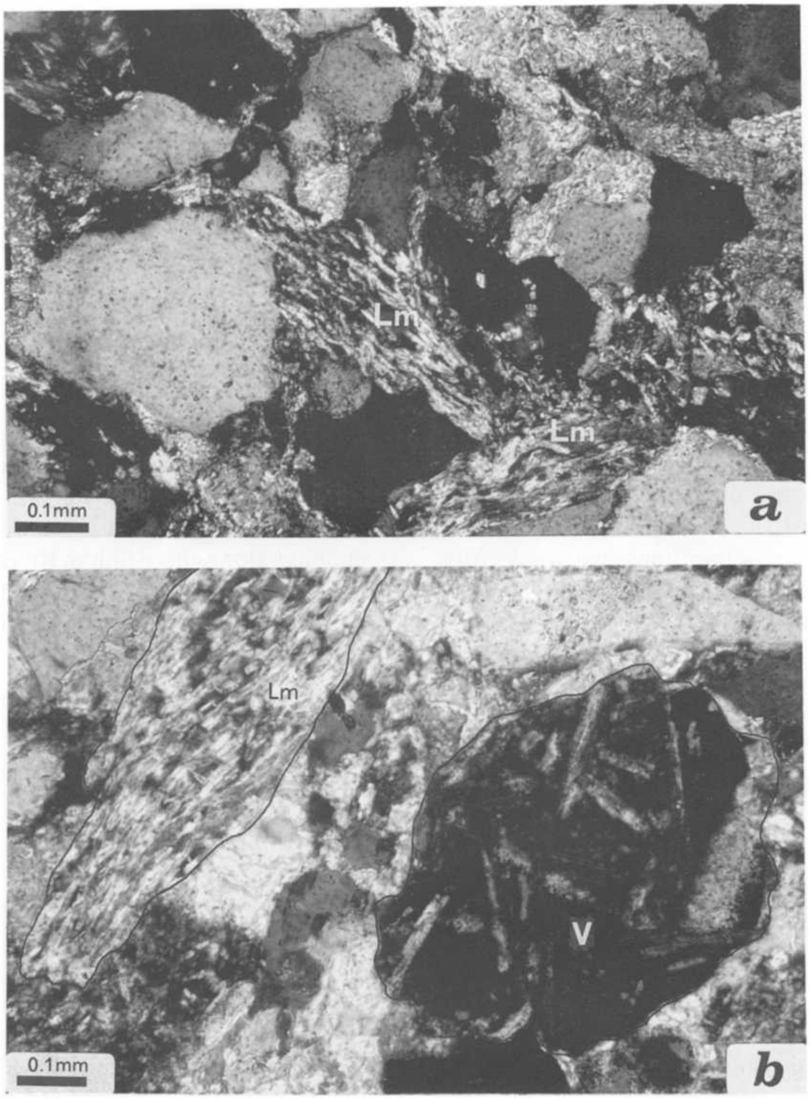


Fig. 3. Photomicrographs of main framework grains, Murree Supergroup: (a) phyllite rock fragment (*Lm*); (b) phyllite (*Lm*) and microlitic volcanic (*V*) rock fragments; (c) lathwork volcanic rock fragment (*V*); (d) serpentineschist grain (*Ss*); (e) radiolarian chert (*ch*), microlitic volcanic (*V*), limeclast (*CE*) and caliche (*ca*) grains; (f) very fine-grained quartzose sandstone grain (*Lss*); (g) siltstone (*Lss*) and micritic limestone (*CE*) grains; (h) extrabasinal carbonate grain (*CE*). Crossed nicols, but (e) and (h) plane-polarized light.

An_{15-40}). K-feldspar is negligible in most of the Balakot Fm., and occurs sporadically in the southern outcrops.

Fine-grained lithic fragments include, in order of abundance:

(a) Low-grade metamorphic lithics (Figs. 3a, 3b; quartz–mica phyllite, slate and schist), which are abundant in the lower Balakot Fm. (13.1–33.4%) and decrease upwards (4.7–20.4% in the middle part; 1.5–5.2% in the upper part; 6.0–17.2% in the southern outcrops).

(b) Volcanic lithics (Figs. 3b, 3c), which instead increase upward (1.1–4.9% in the lower Balakot Fm.; 1.7–3.8% in the middle part; 5.5–23.4% in the upper part; 3.2–14.3% in the southern outcrops). Volcanic grains have mainly vitric (increasing from a maximum of 2.8% in the lower part to up to 19.3% in the upper Balakot Fm.),

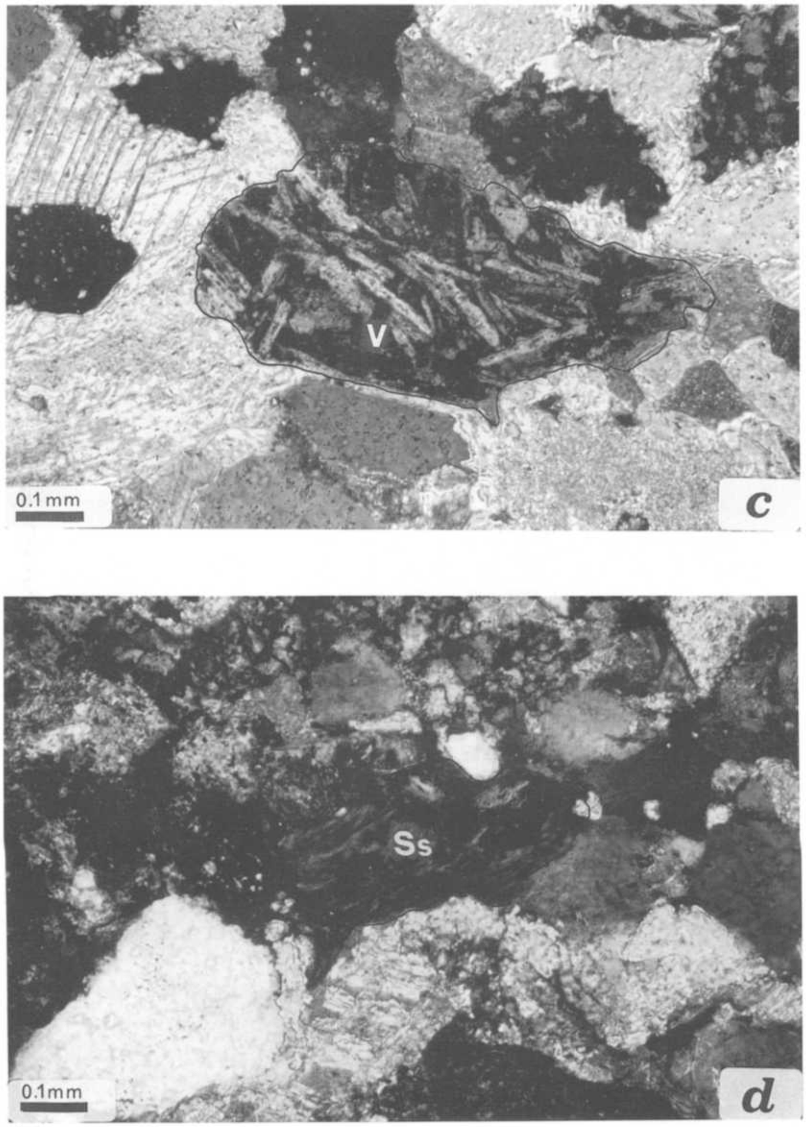
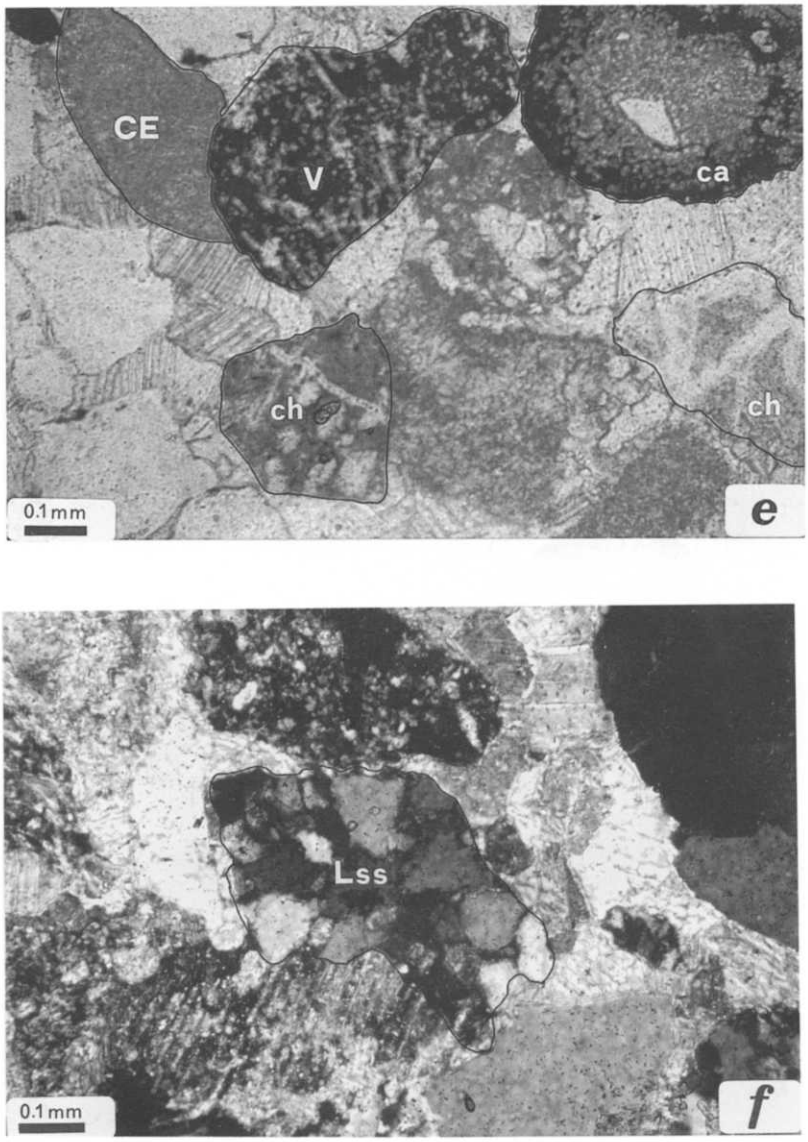


Fig. 3 (continued).

and subordinately microlitic (increasing from up to 1.2 to up to 2.7%), lathwork (increasing from up to 0.9 to up to 3.2%) and felsitic textures, pointing to andesitic-dacitic to subordinately rhyolitic composition. In samples from the southern outcrops, both microlitic and felsitic types reach their maximum abundance (up to 6.2% and 2.4%, respectively), whereas vitric and lathwork types are depleted with respect to the upper Balakot Fm. (up to 11% and 2.4%, respectively).

(c) Ophiolitic lithics (Fig. 3d; serpentinite and serpentineschist, with massive cellular and schistose textures, respectively), reaching a maximum of 2.7% in the upper Balakot Fm.

(d) Sedimentary lithics (Figs. 3e-3h; chert, carbonate, shale, siltstone, fine-grained sand-



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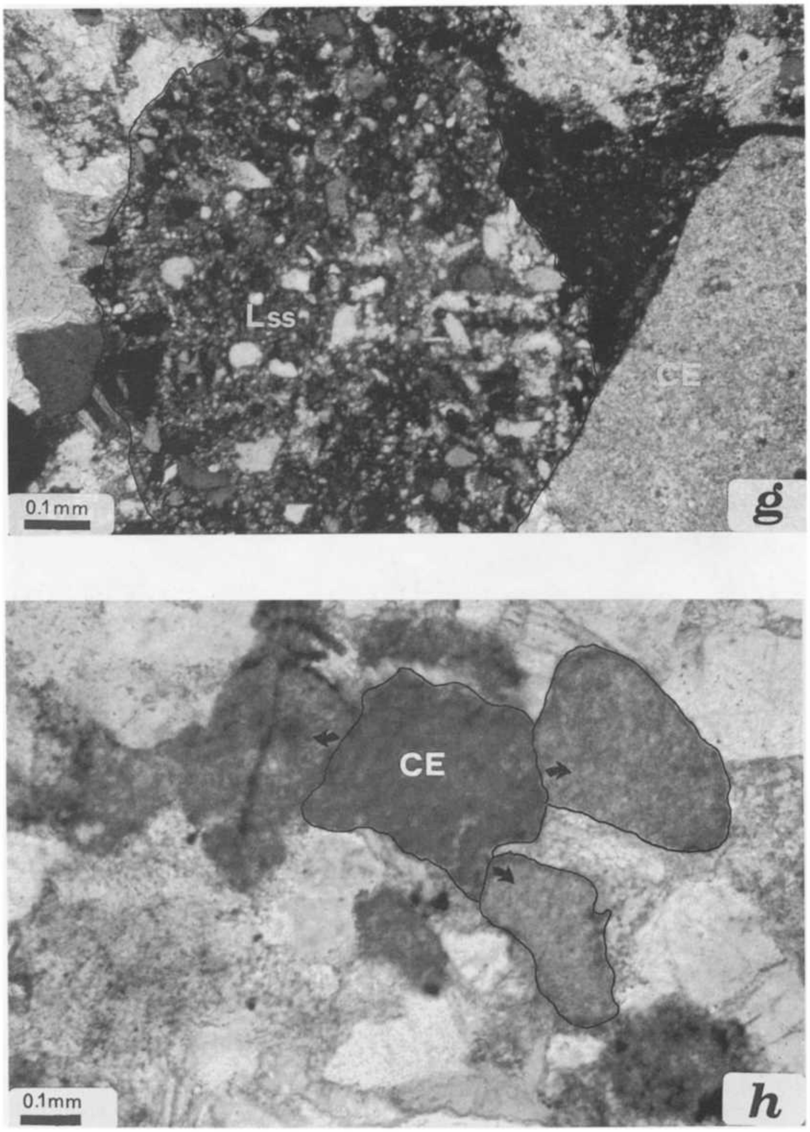
stone). Chert is invariably abundant, with up to 10.6% and 13.6% in the lower and upper Balakot Fm., respectively, and 10.0% in the southern outcrops. Extrabasinal carbonates (micrite, biomicrite, sparite, microsparite) and limeclasts are occasionally abundant (up to over 10.6% and 10.3%, respectively) in the upper Balakot Fm. and in the southern outcrops.

Coarse-grained rock fragments are represented by metamorphic (quartz–mica schist and gneiss), plutonic (quartz–feldspar associations) and sandstone to metasandstone varieties.

Chromian spinels, opaques (Fig. 4a), muscovite, chlorite and subordinate tourmaline, zircon, epidote and amphibole are found. Rip-up argillitic and siltstone clasts, calcareous intra-



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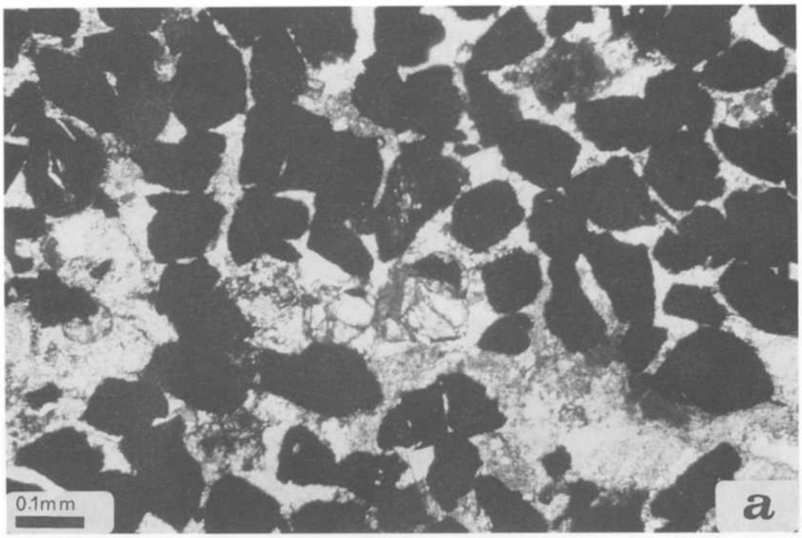
clasts and bioclasts, caliche (Fig. 4b) and silcrete (Fig. 4c) oversized particles occur in several samples.

Interstitial components include siliciclastic matrix, iron oxides, chloritic or illitic epimatrix, quartz overgrowths, phyllosilicate cement (Fig. 4d) and abundant replacements of authigenic calcite. Intense textural–mineralogical modifications occurred during very low-grade (prehnite–pumpellyite facies) Himalayan metamorphism (Greco, 1991).

3.2. Provenance of the Murree redbeds

The Murree redbeds consist of mostly noncarbonate extrabasinal detritus with quartzolithic



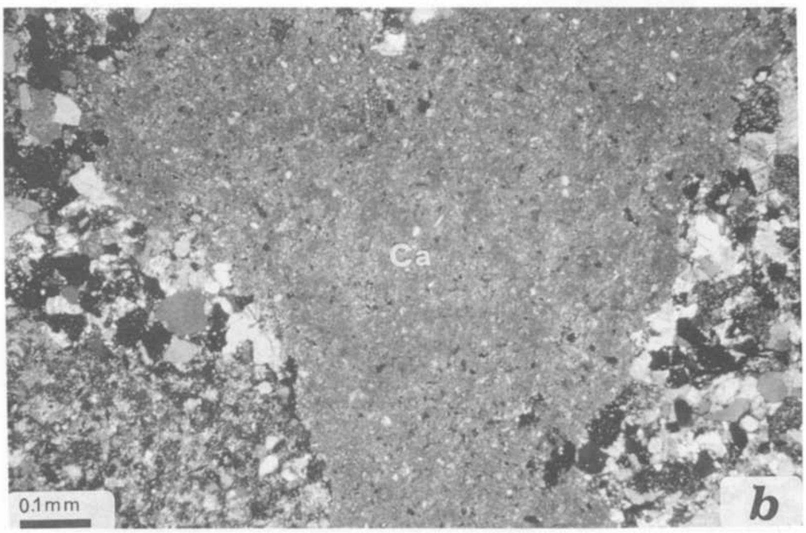
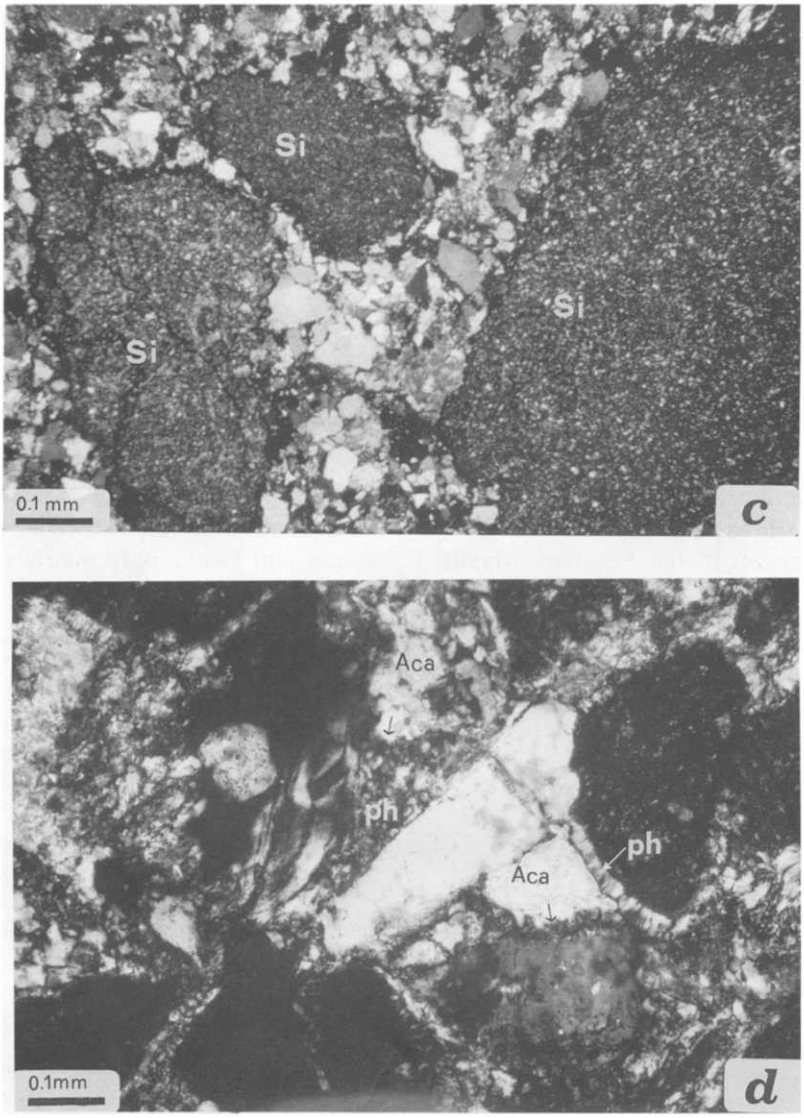


Fig. 4. Photomicrographs of accessory framework and interstitial components, Murree Supergroup: (a) laminae of opaque and heavy minerals; (b) oversized caliche fragment (*Ca*); (c) oversized silcrete particles (*Si*); (d) both early phyllosilicate cements (*ph*; white arrow) and framework grains are replaced by late diagenetic calcite (*Aca*; black arrow). Crossed nicols, but (a) plane-polarized light.

composition, testifying to a "collision orogen" provenance (Dickinson and Suczek, 1979; Dickinson, 1985).

Main petrographic parameters do not change greatly in the Hazara Syntaxis from Ilerdian through Lutetian sandstones, and remain similar also in the lower Middle Eocene Kuldanas, and in the Oligocene to Lower Miocene Murree redbeds of the Rawalpindi area (Fig. 5; Table 2). Detrital feldspars are subordinate, indicating very little contribution from infracrustal crystalline rocks. K-feldspar is invariably sporadic, whilst plagioclase slightly increases from Ilerdian and Cuisian to Lutetian and post-Lutetian sandstones.

Composition of rock fragments indicates that detritus was derived from a suture belt including mainly low-grade metasedimentary rocks, volcanic or volcaniclastic rocks, and subordinately sedimentary rocks and ophiolites. Invariably high



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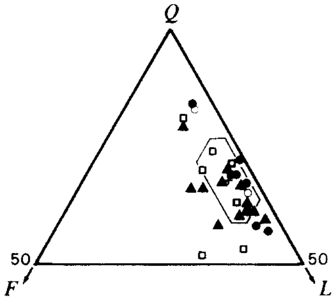

Fig. 5. Detrital modes of the Murree Supergroup (point-counting data given in Table 1). Polygon is one standard deviation each side of the mean (cross). Dots represent lower part of the Balakot Fm.; circles the middle part, triangles the upper part, and squares the southern outcrops. Q = total quartz; F = feldspars; L = aphanite rock fragments including extrabasinal carbonates and chert.

quartz content and low feldspar values may be at least partly ascribed to recycling of terrigenous source rocks. Low-grade metamorphic rock fragments (mainly phyllites) are most abundant in the Ilerdian, with subordinate amounts of mainly vitric volcanic grains (Fig. 6). Vitric, microlitic, and lathwork "andesitic-dacitic" volcanic particles became more common in the Lutetian. Siltstone and shale grains are constantly present, as well as chert and ophiolite detritus, reaching a maximum in the Lutetian; extrabasinal carbonate particles are also more common in the Lutetian. Mainly vitric, microlitic and felsitic volcanics, chert, phyllites, shales and carbonates continued to be eroded and transported to the foreland basin from the Lutetian to the Early Miocene, as indicated by detrital modes of the Rawalpindi area redbeds (Fig. 6).

Sandstone petrography thus testifies that in the earliest stages of continental collision (Ilerdian and Cuisian), detritus was largely derived from low-grade metapelites. Increased volcanic, ophiolitic and chert detritus in the Lutetian points to increased supply from arc-trench system sources, including arc volcanics and oceanic sequences incorporated in the subduction complex, as also indicated by common occurrence of chromian spinels.

3.3. Comparison with the coeval Chulung La Formation

The Chulung La deltaic redbeds (Zanskar Range, northern India, Fig. 7) are the youngest unit of the Tethys Himalayan succession, deposited on the northern continental margin of the Indian Plate (Garzanti et al., 1987). They unconformably overlie the shallow-water Dibling Limestone of Late Paleocene age, the top of which consists of lagoonal mudstones/wackestones intercalated with biocalcarenites, greenish siltstones and locally pure quartz sandstones in the lower part. This interval (21 to 24 m thick Litho-

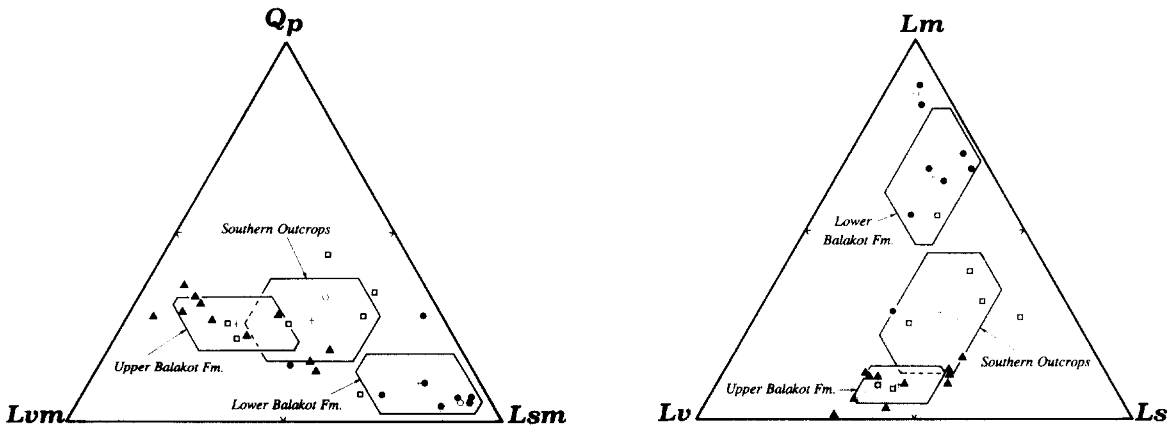

Fig. 6. Qp-Lvm-Lsm and Lm-Lv-Ls lithic populations in the Murree Supergroup. Symbols and abbreviations as in Fig. 5 and Table 2.

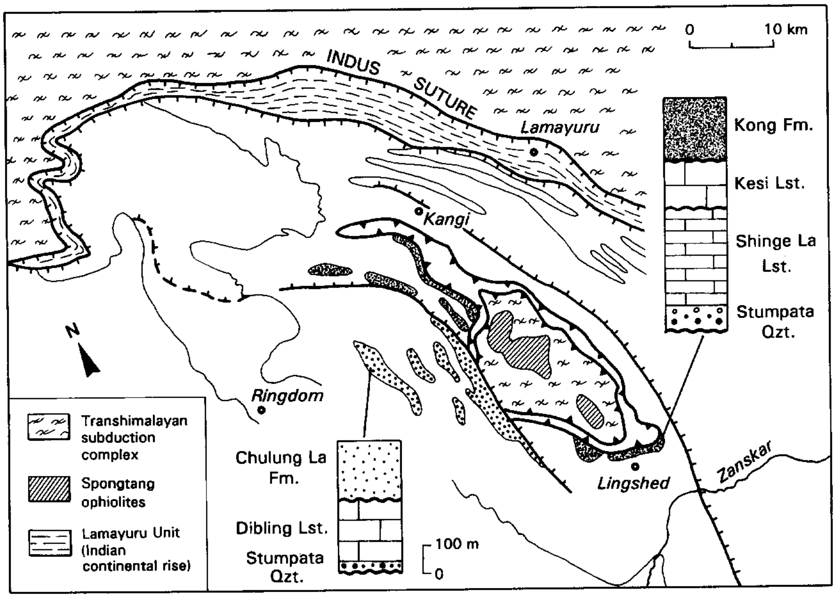

Fig. 7. Outcrop area and stratigraphy of the Chulung La Fm. and Kong Fm., exposed at the core of the Zanskar Synclinorium (Zanskar Range, northern India; geological map after Fuchs, 1986). The Stumpata Quartzarenite is ascribed to the Early Paleocene; the Dibling Fm. and Shinge La Fm. to the Late Paleocene (Nicora et al., 1987). The Kesi Limestone is Late Ilerdian to Early Cuisian in age (Baud et al., 1985, in Garzanti et al., 1987).

zone C of Nicora et al., 1987) is dated at the late Early Ilerdian *Fasciolites ellipsoidalis* Zone. On the northern Indian margin, onset of volcanic detritus at the base of the shallow-marine Kong Formation, is dated at the Ilerdian/Cuisian boundary (*Morozovella aragonensis* Zone; Baud et al., 1985).

The Chulung La collisional redbeds show predominant volcanic detritus from lavas and volcaniclastics, with subordinate sedimentary (carbonate rock fragments, single globotruncanids), plutonic (quartz–feldspar associations, chessboard-albites) and ophiolitic (serpentine-schists, basalts, cherts and chromian spinels; Fig. 8) detritus. Metasedimentary detritus occurs only in traces (phyllites/total lithics less than 0.01; polycrystalline quartz/total quartz less than 0.1).

All of these lithologies compare either with turbidites and ophiolitic suites incorporated in the Spongtang oceanic klippe (Colchen and Reuber, 1987), a remnant of the Trans-Himalayan subduction complex obducted directly on top of shallow-marine Cuisian sediments of the Indian margin, or with calc-alkalic magmatic suites of the Trans-Himalayan arc.

Detrital modes show much closer correspondence with the coeval clastics of the Indus collisional basin in the north (Middle Ilerdian to

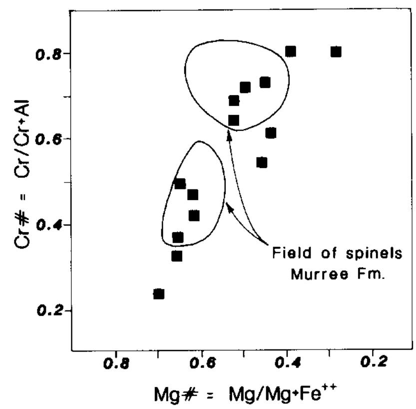

Fig. 8. Chemistry of spinel grains from the Chulung La sandstones (squares) and Murree redbeds (outlined fields; data after K. Honegger, pers. commun., 1986; Bossart and Ottiger, 1989). Both units contain red Cr-rich spinels as well as yellow-brown Al-rich spinels derived from peridotites and gabbros formed either in mid-ocean ridge (Cr# < 0.6 and Mg# > 0.5) or island arc settings (higher Cr# and lower Mg#; Dick and Bullen, 1984).

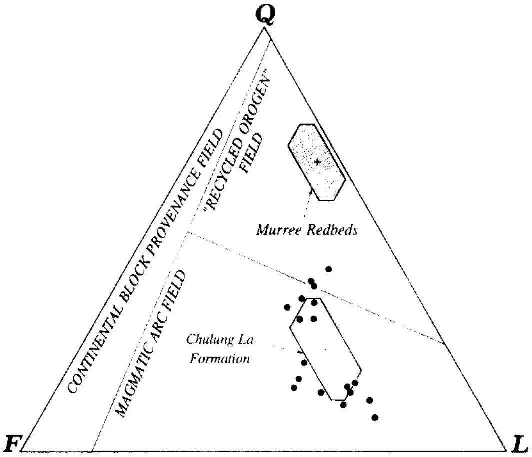

Fig. 9. Detrital modes of the Chulung La feldspathic volcanic arenites (Garzanti, 1986; Garzanti et al., 1987) are markedly different from those of the Murree litharenites. The former plot in the "magmatic arc" provenance field (drawn after Dickinson, 1985), indicating exclusive provenance from the Trans-Himalayan arc–trench system, whereas the latter plot in the "recycled orogen" provenance field. This suggests that a proto-High/Lesser Himalaya belt, made of sedimentary and low-grade metamorphic thrust sheets, has separated the Chulung La "piggy-back" basin from the Murree foreland basin since the first Early Eocene stages of continental collision.

Cuisian Nummulitic Limestones; Garzanti and Van Haver, 1988) than with the Murree Supergroup in the south. The Chulung La samples in fact plot in the "magmatic arc" provenance field (Fig. 9; Dickinson and Suczek, 1979; Dickinson, 1985), indicating exclusive provenance from the Trans-Himalayan arc–trench system (Garzanti, 1986), although they were deposited on the Indian Plate margin during the first stages of continental subduction.

3.4. Comparison with younger orogenic clastic wedges

Petrographic composition of the Murree redbeds compares—much better than that of the Chulung La redbeds—with Tertiary to recent foreland basin to remnant ocean sandstones derived from the Himalayan suture belt, as for instance the Siwalik "molasse" exposed in the Sub-Himalayan belt, the Nias trench/slope sandstones, or the Indus and Brahmaputra River sands (see Fig. 1 for location and Table 3 for data and references). The Murree Supergroup only differs, particularly with respect to the Brahmaputra River, Bengal Fan, and Indus Fan sands, for their low feldspar content and negligible quantities of K-feldspar (the latter is the only feature they have in common with the Chulung La Formation), whereas distinctive of the Siwalik Group, Bengal Fan, and Ganges River arenites is the virtual lack of volcanic detritus.

Table 3

Recalculated detrital modes of modern sands and Tertiary sandstones derived from the Himalayan Chain (after Ingersoll and Suczek, 1979; Moore, 1979; Parkash et al., 1980; Suczek and Ingersoll, 1985; Garzanti, 1986; Critelli et al., 1990; Critelli and Garzanti, 1993)

	N	Qt	F	L	Qm	P	K	Qp	Lvm	Lsm	Lm	Lv	Ls
Indus	1	61	7	32	–	–	–	–	–	–	35	11	54
Ganges	1	74	10	16	–	–	–	–	–	–	64	0	36
Brahmaputra	2	51	26	24	–	–	–	–	–	–	40	27	33
Indus Fan	15	44	30	26	59	27	14	4	10	86	52	11	37
Bengal Fan	22	58	28	13	67	22	11	6	5	89	87	4	9
Siwaliks	29	57	7	36	88	12		11	0	89	29	0	71
Nias	24	73	11	16	86	9	5	17	23	60	35	29	36
Makran	62	56	10	34	83	12	5	9	36	55	31	37	32
Chulung La	18	24	26	50	44	55	1	5	93	2	2	96	2
Indus Group	26	24	34	41	41	45	14	8	68	25	13	70	17
Murree Group	28	68	5	26	92	8	1	21	27	52	39	28	33

Available data for modern river sands are in QFR rather than QFL mode (Potter, 1986). Note that the Chulung La Fm. (Garzanti, 1986) and coeval Indus Group feldspatholithic sandstones (Garzanti and Van Haver, 1988) are much less quartzose and richer in volcanic detritus than all other quartzolithic "recycled orogen" clastic wedges.

Overall petrographic similarity among these Tertiary and Quaternary "collision orogen" clastic wedges found around the Indian subcontinent confirms that they were all derived from the rising Himalayas in the north.

4. Conclusions

The northern spur of India began to collide with the Trans-Himalayan arc–trench system around the Paleocene/Eocene boundary (Early Ilerdian; Garzanti et al., 1987).

In the first stages of collision, the old and rigid Indian continental lithosphere was bent and dragged in subduction to depths of several tens of kilometres underneath the Asian margin (Pognante and Spencer, 1991). Flexural response to loading by the overriding Asian accretionary prism caused strong subsidence on the northern edge of the Indian Plate, where collisional basins were rapidly filled by huge amounts of detritus derived from the slowly rising proto-Himalayan chain.

Onset of continental collision is recorded on the Indian margin by a basal unconformity, which is overlain by shallow-marine limestones with intercalated quartzarenitic layers occurring both in the lower Patala Fm. (northern Pakistan) and in Lithozone C at the top of the Dibling Fm. (northern India). This temporary increase of pure quartzose detritus in the very first stage of collision is ascribed to flexural uplift of a peripheral bulge located on the Indian craton to the south, where older sedimentary and crystalline rocks were eroded.

The Patala and Dibling units are followed in turn by deltaic sediments, with a low-angle unconformity recognized in the Zanskar Range (Garzanti et al., 1987, fig. 8). Lack of deep-water facies even in the basal part of the collisional basins' stratigraphic succession might be accounted for by shallow northeastward subduction of the cold and rigid Indian lithosphere underneath the Kohistan–Ladakh arc–trench system (Doglioni, 1990).

The sudden arrival of abundant quartzolithic detritus, including serpentineschist rock fragments and chromian spinels derived from both island-arc and mid-ocean ridge ultramafic rocks (Fig. 8), indicate that both the Murree and Chulung La redbeds were fed from the Tethyan suture in the north (Garzanti et al., 1987; Bossart and Ottiger, 1989), and not from the south as inferred by previous authors (Gansser, 1964).

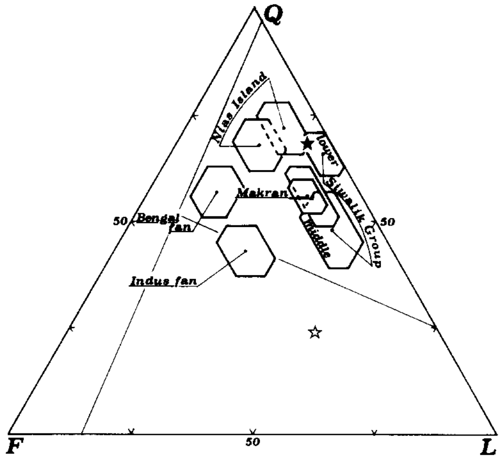

Fig. 10. Detrital modes of the Murree Supergroup (black star) compare much more closely than those of the Chulung La Formation (white star) with Tertiary to recent, foreland basin to remnant ocean, "recycled orogenic" sandstones derived from the Himalayan suture belt. Provenance from proto-Himalayan reliefs is thus suggested for the Murree redbeds (see Table 3 for data sets).

This major petrographic change is recorded just below (Hazara–Kashmir) or directly above (Tethys Himalaya) biocalcarenitic layers dated at the *Fasciolites ellipsoidalis* Zone. Such a small time lag (possibly 1 m.y.) is consistent with slightly diachronous collision, beginning earlier in the northwestern Nanga Parbat area (latest Paleocene), and progressively later (earliest Eocene) towards the east, as deduced from several independent lines of evidence (Powell, 1979; Blondeau et al., 1986; Pognante and Spencer, 1991).

It is noteworthy that, among all Tertiary clastic wedges shed from the Himalayan suture belt, the greatest mineralogical differences are observed between the Murree and Chulung La redbeds (Table 3; Fig. 10), which were both deposited in collisional basins fed from proto-Himalayan reliefs at the same time and in very similar sedimentary environments.

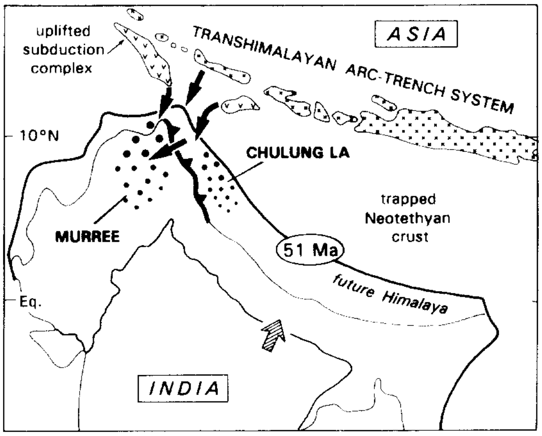

Fig. 11. Cartoon depicting the impending collision between the northwestern Indian spur and the Trans-Himalayan arc–trench system in the Early Eocene (Cuisian). The Chulung La redbeds, directly fed from uplifted subduction complex Timor- and Sumba-type sources, were separated from the Murree foreland basin by a thrust-belt shedding sedimentary and metasedimentary detritus to the south (modified after Garzanti et al., 1987).

Detrital modes of the Chulung La Formation are feldspatholithic, volcanic-rich and quartz-poor, and thus identical to "magmatic arc" sandstones (Dickinson, 1985). Since they compare closely with syn-collisional clastics derived from and deposited within the Ladakh arc–trench system (Garzanti and Van Haver, 1988), it can be safely concluded that the Chulung La delta was fed entirely and directly from the obducting Trans-Himalayan accretionary prism (Fig. 11).

Conversely, detrital modes of the Murree Supergroup plot in the middle of the "recycled orogen" provenance field. Even though detritus from calc-alkalic igneous and ophiolitic rocks incorporated in the Trans-Himalayan arc–trench system is invariably significant and even increases in younger units, low-grade metapelitic rock fragments are predominant, particularly in the Middle Ilerdian to Cuisian lower part of the Balakot Formation.

It is difficult to ascribe this petrographic feature of the Murree redbeds to an unknown metapelitic source terrane located to the north of or within the suture zone, and Mesozoic continental rise pelites of the Indian margin (western equivalents of the Lamayuru Unit of Ladakh) could not have undergone metamorphism, uplift and erosion at the instant of collision. Abundant phyllite rock fragments were thus most likely derived from proto-Lesser/High Himalayan reliefs made of mildly metamorphosed supracrustal Indian margin rocks, possibly mainly Late Proterozoic to Cambrian pelites overprinted by low-grade Pan-African metamorphism. Petrographic evidence suggests that this fold-thrust belt began to be uplifted just south of the Tethys Himalayan Zone since the onset of collision, separating the Chulung La "piggy-back" basin from the Murree foreland basin (Fig. 12).

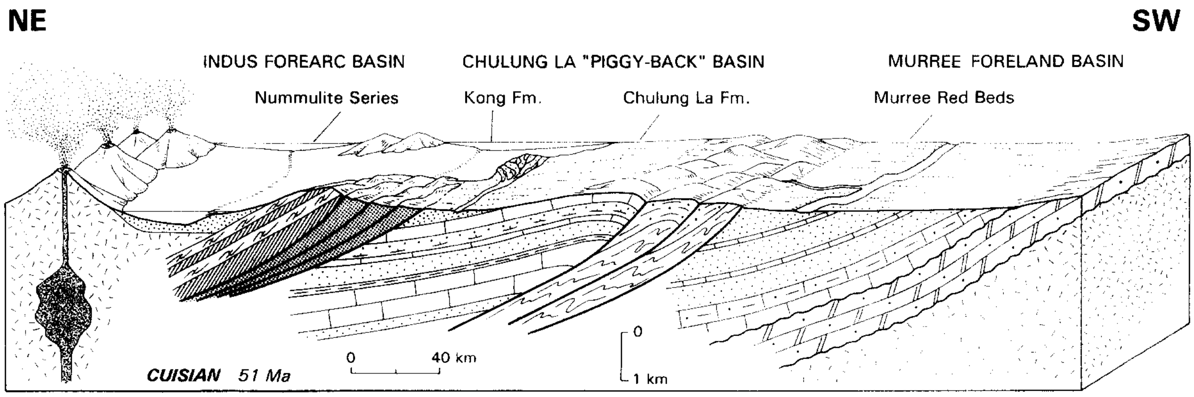

Fig. 12. The profile depicts the proto-Himalayan fold-thrust belt at Cuisian times. Petrographic data indicate that thrust sheets of sedimentary and metasedimentary rocks have separated the Chulung La "piggy-back" basin from the Murree foreland basin since collision onset, around the Paleocene/Eocene boundary.

Direct stratigraphic superposition of Late Paleocene limestones on top of Precambrian–Cambrian carbonates in the Hazara Syntaxis is consistent with a palaeogeographic position much closer to the Indian craton with respect to the Tethys Himalayan succession, which consists of thick Palaeozoic and Mesozoic sediments deposited in front of the southern shores of Neo-Tethys (Gaetani and Garzanti, 1991).

The overall petrographical affinity between the Murree Supergroup and younger orogenic sandstones largely derived from the High Himalaya also argues in favour of a common source, which evolved during the Tertiary from lower- to higher-grade metamorphic rocks. Such progressive evolution from low-grade metasedimentary parent rocks for the Upper Eocene–Lower Oligocene Dagshai sandstones, to higher-grade sources for the Upper Oligocene–Lower Miocene Kasauli sandstones, has long been documented in the Himalayan foothills to the east (Chaudhri, 1971). Moreover, petrographic composition of the Upper Oligocene–Lower Miocene Rawalpindi Group of the Kohar–Potwar plateau (northwestern Pakistan), indicates that abundant sedimentary and metasedimentary detritus was derived from Indian Plate metasediments uplifted in the north (Ahmed and Friend, 1988).

Throughout the Murree Supergroup itself, from the Ilerdian–Cuisian part of the Balakot Fm. to the Lower Miocene Murree redbeds of the Rawalpindi area, detrital modes changed gradually. Slight increase of detrital feldspars and polycrystalline quartz through time points to progressive deepening of erosion into infracrustal crystalline rocks, until in the Early Miocene (Burdigalian) a huge hot wedge of Indian crust was rapidly uplifted and carried hundreds of kilometres southward along the Main Central Thrust (MCT). Rise of the Himalayas at that time is indicated both by isotopic data on the High Himalaya Crystalline (Le Fort, 1989; Hodges et al., 1992) and by petrographic composition of the Siwalik foreland basin sandstones (Chaudhri, 1972; Parkash et al., 1980; Abid et al., 1983). This major palaeogeographic change, also indicated by onset of monsoonal upwelling in the Arabian Sea (Prell et al., 1988), was recorded by remnant ocean turbidites at both sides of the Indian Peninsula (Copeland and Harrison, 1990; Amano and Taira, 1992; France-Lanord et al., 1992), and even by changes in detrital modes of sandstones incorporated in accretionary wedges as far as Nias Island (Indonesia; Moore, 1979) and Makran (Critelli et al., 1990).

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