Early-Middle Miocene paleodrainage and tectonics in the Pakistan Himalaya

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ABSTRACT

The 18–14 Ma Kamlial Formation Himalayan foreland basin sedimentary rocks in the Chinji Village region, Potwar Plateau, Pakistan, are characterized by: (1) lithofacies indicative of deposition by a large river; (2) a dominant magmatic arc provenance completely unlike the 'recycled orogen' foreland basin deposits stratigraphically below, above, or coeval with these rocks; and (3) subordinate contribution from a rapidly exhuming source, interpreted as either the Nanga Parbat Haramosh Massif or the southern margin of the Asian crust. The start of Kamlial Formation deposition at this locality at 18 Ma marks a major break with the older Murree Formation rocks, which were deposited by rivers draining predominantly the Himalayan thrust stack south of the arc. We interpret this change as the result of diversion of the paleo-Indus River to its present position, which crosses the Kohistan arc and Himalayas and debouches into the foreland. If the rapidly exhuming subordinate source region were the Nanga Parbat Haramosh Massif, then initiation of its uplift would have resulted in significant arc detritus to the basin as the overlying arc carapace was exhumed. As the carapace was progressively breached, arc material would have become a less substantial component of detritus to the basin, consistent with the reported petrography of the overlying Siwalik deposits.

Keywords: Himalaya, Indus River, detrital minerals, exhumation, foreland basin, Nanga Parbat.

INTRODUCTION

The Himalayan orogen formed due to the collision between India and Eurasia that began ca. 55 Ma. The sedimentary record of material eroded from the mountain belt and preserved in foreland basins provides a history of erosion, tectonism, and paleodrainage in the orogen. This study concentrates on the foreland basin sedimentary rocks of the Kamlial Formation in the Chitta Parwala section, Chinji Village, Potwar Plateau area of Pakistan (Fig. 1), deposited between 18–14 Ma (Johnson et al., 1985).

The foreland basin study area in the Potwar Plateau is now drained by the Indus River and its tributaries. Today the Indus River flows west along the line of suture zone and then cuts south over the Himalayas, perpendicular to the strike of the orogen, to the foreland basin and finally the Indus Fan (Fig. 1). Yet, the route of the paleo-Indus remains controversial. While some researchers consider the path of the Indus River to be antecedent, others suggest that it first cut through the Himalayan belt and debouched into the foreland basin in the Early Miocene, or at 11 Ma, with earlier routing perhaps into the Katawaz remnant ocean basin (Abbasi and Friend, 1989; Qayyum et al., 1997, 2001; Brookfield, 1998; Shroder and Bishop, 2000; Clift et al., 2001b). The suggested interrelationships and feedback between tectonism, denudation, and drainage evolution of the Indus River (e.g., Shroder and Bishop, 2000; Zeitler et al., 2001a, b) make reconstruction of the paleodrainage and tectonics of the region an important goal.

GEOLOGICAL BACKGROUND

Mountain Belt Evolution

The mountain belt in Pakistan consists of three tectonostratigraphic units that formed during a series of orogenic events that occurred both prior to and during India-Asia collision (Fig. 1). Farthest north lies the southern margin of the Asian crust, including the Hindu Kush and the Karakoram. These belts include a Paleozoic–Mesozoic succession intruded by

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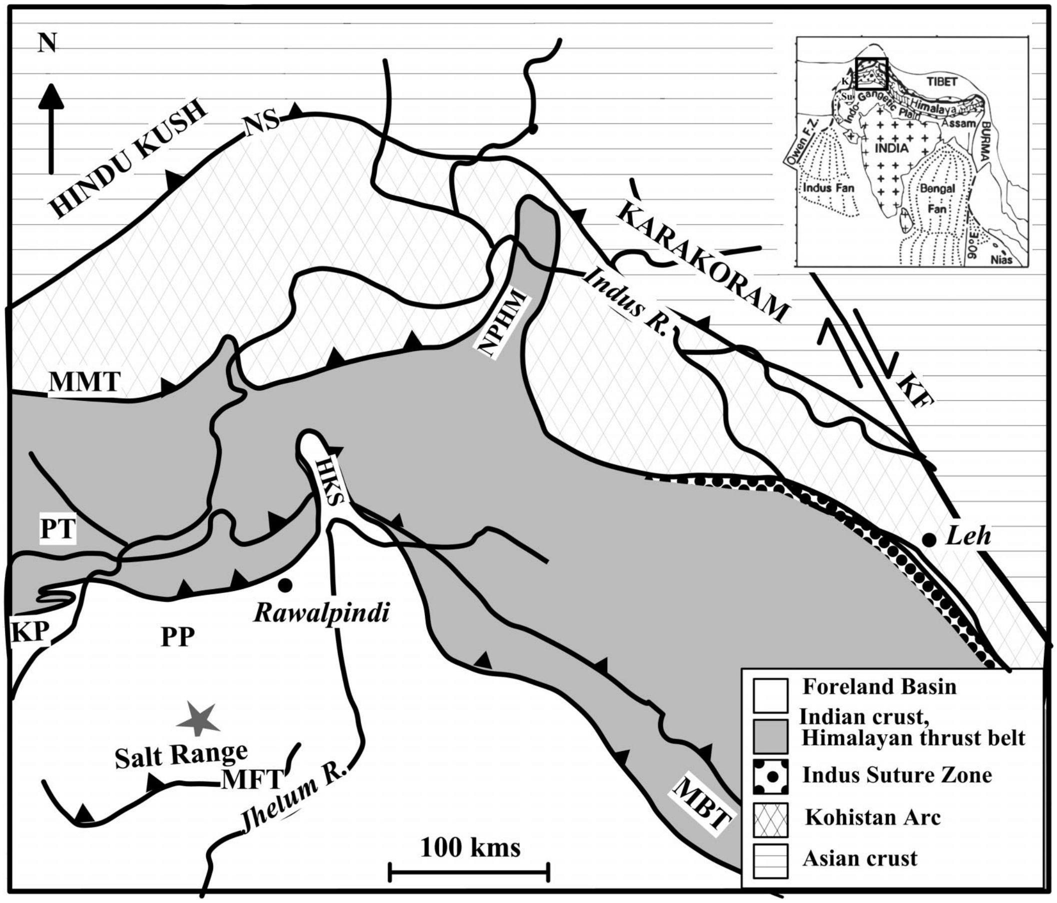

Figure 1. Geological map showing locations for region under study and present-day drainage configuration. Area of study, Chitta Parwala section, Chinji Village area; Potwar Plateau is indicated by star. HKS—Hazara-Kashmir syntaxis, KF—Karakoram Fault, MMT—Main Mantle Thrust, PT—Panjal Thrust, KP—Kohat Plateau, MBT—Main Boundary Thrust, MFT—Main Frontal Thrust, NS—Northern Suture, NPHM—Nanga Parbat Haramosh Massif syntaxis, PP—Potwar plateau. Inset: location of main map, as indicated by box, K—Katawaz basin, Su—Sulaiman Range.

a Jurassic to Cretaceous batholith and affected by metamorphic events pre- and post- India-Eurasia collision (Debon et al., 1987; Gaetani et al., 1990; Searle, 1996; Hildebrand et al., 2001; Fraser et al., 2001). Sandwiched between the Asian crust along the Northern or Shyok Suture to the north and the Indian crust along the Main Mantle Thrust (MMT) to the south is the Cretaceous–Eocene Kohistan Island Arc, intruded by the Kohistan batholith, which shows pre- and post-collisional stages of formation. A south-to-north transect provides a complete section through the arc, from the deeper crustal levels of the ultramafic-layered igneous complexes in the south to structurally higher seafloor sedimentary rocks and basic andesitic and rhyolitic volcanic rocks in the north (Treloar et al., 1989; Khan et al., 1993). South of the Main Mantle Thrust is the Himalayan thrust stack consisting of Indian continental crust cover of Paleozoic–Mesozoic sedimentary protolith, metamorphosed to greenschist to amphibolite grade during the Himalayan orogeny, locally imbricated with basement gneisses that retain Proterozoic and Phanerozoic cooling ages (Treloar and Rex, 1990). Cambro–Ordovician, Carboniferous, and Permian intrusions are also found within the thrust stack (Le Fort et al., 1980; Smith et al., 1994; Anczkiewicz et al., 1998a, b; DiPietro and Isachsen, 2001).

Collision between Asia and the Kohistan arc along the Northern or Shyok Suture took place between 70 and 100 Ma (Coward et al., 1986; Treloar et al., 1989; Gaetani et al., 1993). In Kohistan, cooling occurred ca. 80 Ma, although a later phase of cooling in the east is associated with the more recent rapid uplift of the Nanga Parbat Haramosh Massif (Zeitler, 1985; Treloar et al., 1989). At ca. 55 Ma (Klootwijk et al., 1991), the Kohistan Arc collided with the Indian crust along the Main Mantle Thrust, along which lies mélange containing serpentinite and blueschists. Subsequently, the northern margin of the Indian crust underwent tectonic thickening, medium- to high-pressure metamorphism, plutonism, and deformation beginning at ca. 50 Ma. Between 45 and 25 Ma, post-metamorphic thrusting occurred during which time the rocks followed decreasing pressure-temperature paths probably due to tectonic unroofing associated with thrusting. A period of rapid cooling between 25 and 20 Ma is tentatively associated with tectonic denudation, as the overlying Kohistan Arc slid northward on normal faults. From ca. 20 Ma, faulting ceased and the Kohistan arc and Indian crust have only undergone simple uplift and erosion (Treloar et al., 1989, 1991; Chamberlain et al., 1991; Pognante and Spencer, 1991; Chamberlain and Zeitler, 1996; Burg et al., 1996). The exception is the region of the Nanga Parbat

Haramosh Massif in the western syntaxis region. The Nanga Parbat Haramosh Massif is an anomalous region of the Indian crust that has been undergoing metamorphism to granulite grade and extremely rapid exhumation since at least 10 Ma (Treloar et al., 1989; Zeitler, 1985; Zeitler et al., 1989, 1993). Constraints on the timing of initiation of this event are poor, since the Late Neogene events have obliterated evidence of much of the massif's earlier history. However, Early Miocene mineral ages indicate an earlier anatectic and cooling history (Schneider et al., 1999; Treloar et al., 2000; Pecher et al., 2002). Originally mantled by the overthrust Kohistan arc, the Nanga Parbat Haramosh Massif's major uplift has also affected the arc rocks above and adjacent to it.

The Foreland Basin Deposits (Table 1)

The Kamlial Formation (e.g., Wadia, 1928; Cotter, 1933; Shah, 1977; Johnson et al., 1985) forms part of more than 10 km of sediment that fills the Himalayan foreland basin. The Kamlial Formation succession is more than 400 m thick and is exposed in the Kohat and Potwar Plateau regions. In the northern regions of the plateaus its lower contact with the underlying Murree Formation is conformable and transitional, but in the Chinji Village study area, in the southern region of the Potwar Plateau (Fig. 1), the Murree Formation is absent and the Kamlial Formation rests unconformably upon Eocene marine strata. The Kamlial Formation is conformably overlain by the Chinji Formation of the Siwalik Group. In the region of study—Chitta Parwala section, Chinji Village area, Potwar Plateau—magnetostratigraphic studies have dated the Kamlial Formation succession at 18 to 14 Ma (Johnson et al., 1985). Data Repository item DR1[1] provides information on the age of the samples used in this research and their location in the section. The Kamlial Formation deposits consist of alluvial sandstones, mudstones, and caliche. In the Chinji Village study area, arenaceous lithofacies predominate. Individual sandstone stories are on average 7–10 m thick, with a maximum thickness of 19 m. Amalgamated multistory sandstone bodies have a total thickness of a maximum of 58 m and an average of 17.6 m. Sandstone-fine unit cycles are an average of 25 m thick. These facies indicate deposition by a large river (Stix, 1982; Willis, 1993; Hutt, 1996). Such detailed sedimentological information does not exist for Kamlial Formation rocks in other regions. Qualitative descriptions indicate that arenaceous facies generally predominate over argillaceous units, but with regional variations (e.g., Wadia, 1928; Cotter, 1933; Gill, 1951).

TABLE 1. GENERALIZED FORELAND BASIN STRATIGRAPHY, POTWAR REGION, PAKISTAN

Formation	Age
Chinji Fm., Siwalik Group	<14 Ma[†]
Kamlial Fm.	18–14 Ma[‡]
Murree Fm.	Early Miocene "southern outcrops"[#] < 37 Ma (Balakot Formation – "northern outcrops") [§]
Marine strata, e.g. Chorgali Fm.	Eocene[††]

Note that in the Chitta Parwala region of study, the Murree Formation is absent and the Kamlial Formation rests unconformably on Eocene limestones.

[†] Burbank et al. (1996) and references therein.

[‡] Johnson et al. (1985).

[§] Najman et al. (2001).

[#] Fatmi (1973), Abbasi and Friend (1989).

[††] Shah (1977); Johnson et al. (1985).

The Murree Formation encompasses the Balakot Formation in the Hazara–Kashmir Syntaxis to the north and extends south into the Kohat and Potwar plateaus and east into India (e.g., Pinfold, 1918; Wadia, 1928; Gill, 1951; Bossart and Ottiger, 1989; Singh and Singh, 1995; Najman et al., 2002). The Balakot Formation is dated by ^{40}Ar-^{39}Ar ages of detrital micas at younger than 37 Ma (Najman et al., 2001) and the younger southern Murree Formation outcrops at Early Miocene (Fatmi, 1973; Abbasi and Friend, 1989). Lithofacies are interpreted to record alluvial and tidal depositional environments. Published descriptions of the Murree Formation are less detailed and quantitative compared to those of the Kamlial Formation at the Chinji Village area (see references above). Regional lithofacies variations are significant, but generally the Murree Formation appears to have a fine-grained rock:sandstone ratio of $\geq 50\%$, and a recognizably higher proportion of mudstone compared to that of the Kamlial Formation succession in the Chinji Village region. Where measured and recorded, sandstone units in the Murree Formation are also considerably thinner than Kamlial Formation strata at the Chinji Village study area, but such quantitative records only exist for the Murree Formation in the Hazara–Kashmir syntaxis (Balakot Formation; Bossart and Ottiger, 1989; Najman et al., 2002), and to the east at Jammu (Singh and Singh, 1995). No bed thicknesses are recorded in the literature for the Murree Formation in the Kohat and Plateau plateaus, as far as we are aware.

Conformably overlying the Kamlial Formation lies the Chinji Formation of the Siwalik Group, dated at its base at 14 Ma in the Chitta Parwala section (Johnson et al., 1985). The Siwalik Group is deposited basin-wide from Pakistan through Nepal to eastern India. These rocks consist of sandstones, mudstones, and conglomerate upsection. They are interpreted as braided fluvial deposits (Burbank et al., 1996, and references therein).

Prior Provenance and Paleodrainage Studies of the Kamlial Formation

Prior provenance work on the Kamlial Formation is restricted to a detrital zircon fission-track study (Cerveny et al., 1988); petrographic and facies study of the Kamlial Formation in the Chinji Village area, Potwar Plateau (Stix, 1982; Johnson et al., 1985; Cerveny et al., 1989; Hutt, 1996; this study); and a petrographic study of a lithostratigraphically correlated section in the eastern part of the Kohat Plateau to the west (Abbasi and Friend, 1989; Pivnik and Wells, 1996). In addition, there is a short petrographic description of locally derived sedimentary rocks at the western edge of the Kohat basin, which the authors correlated with the Kamlial Formation (Abbasi and Khan, 2003). In the eastern Kohat Plateau section, Kamlial Formation sandstones contain abundant quartz and common sedimentary to metamorphic lithics with only minimal evidence of volcanic detritus. From the relative lack of arc material and the absence of distinctive blue-green hornblende, (noted for its first appearance at 11 Ma and interpreted as indicative of arc unroofing; Cerveny et al., 1989), Abbasi and Friend (1989) considered that the paleo-Indus River first cut through the

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[1] GSA Data Repository item 2003138, DR1—Sample locations and ages at Chitta Parwala section, Potwar Plateau, DR2—Petrographic composition of analyzed sandstone samples from the Kamlial Formation, DR3—Dense mineral assemblages in analyzed sandstone samples from the Kamlial Formation, DR4—Recalculated key indices for framework composition and dense-mineral suites, DR5—Detailed description of Kamlial Formation sandstone petrography at Chitta Parwala section, Potwar Plateau, DR6—All data, DR7—Ar/Ar total fusion, DR8—incremental heating data of single detrital white mica grains from the Kamlial Formation sediments, is available on the Web at http://www.geosociety.org/pubs/ft2003.htm. Requests may also be sent to editing@geosociety.org.

arc after deposition of the Kamlial Formation, since the Middle-Miocene. Kamlial Formation sandstone composition in the eastern part of the Kohat Plateau is in complete contrast to the Kamlial Formation sandstones of the Chitta Parwala section, Potwar Plateau, where abundant igneous material indicates dominant arc provenance since 18 Ma (Hutt, 1996, this study).

Paleocurrent data in the Chinji Village Potwar Plateau study area (Stix, 1982; Johnson et al., 1985; Hutt, 1996) demonstrate predominant flow toward the east, east-southeast, and southeast, similar to that recorded in the overlying Siwalik rocks in the area, but different from the more southward-directed paleocurrents further west in the Kohat Plateau. These southeast-directed orientations have been interpreted as indicative of either (1) local slopes on large alluvial fans, not necessarily representative of the main direction of regional flow (Willis, 1993); or (2) axial drainage in the Potwar Plateau region, flowing east toward the Ganges River catchment at these times and later (Raynolds, 1981; Beck and Burbank, 1990; Burbank et al., 1996). In the second scenario, the drainage divide would have lain well west of its present-day position, separating a southerly-flowing river in the Sulaiman foredeep from the easterly-draining system of the Potwar plateau. Hutt (1996) also reported a subsidiary set of north-directed paleocurrents from which she interpreted the presence of a subsidiary southern source, although there is no petrographic distinction between the two drainage types.

Although most attempts at reconstruction of the hinterland tectonics from the Pakistan foreland basin record in this area have been restricted to the timing of erosion of the arc based on the appearance of blue-green hornblende subsequent to Kamlial Formation times (e.g., Johnson et al., 1985; Cerveny et al., 1989), one notable exception is that of Cerveny et al. (1988). They compared detrital zircon fission-track ages with host sediment depositional age and showed that there was only a short lag time throughout the period 17 Ma to present day. This suggests that regions experiencing rapid exhumation, perhaps analogous to the Nanga Parbat Haramosh Massif, had contributed sediment to the basin throughout this period. However, the sampling throughout the period of study was sparse; only one Kamlial Formation sample and three Siwalik Formation samples were analyzed from the Chinji area, and the study can therefore only provide a first-order approximation.

PETROGRAPHIC AND DENSE MINERAL DATA FROM THE KAMLIAL FORMATION, CHITTA PARWALA SECTION

Petrography was determined by counting 300 framework points on each of 12 samples using the Gazzi-Dickinson method, and we also counted 200–250 transparent dense minerals on 10 samples. (Results are summarized in Figs. 2 and 3, and more detail is supplied in Data Repository item DR2–5 [see text footnote 1]). Analyzed samples are mostly fine-grained sandstones, ranging from 1.5–3 ϕ in median diameter. Traditional ternary parameters and plots (QmFLt, QmPK, QpLvmLsm, LmLvLs; Dickinson, 1985; Ingersoll et al., 1993) were supplemented, specifically where lithic grains are concerned, by an extended spectrum of key indices. Metamorphic grains were classified according to both composition and metamorphic grade, which were largely inferred from degree of recrystallization of mica flakes (Garzanti and Vezzoli, 2003).

The Kamlial Formation consists of quartz-poor, lithofeldspathic sandstones (Fig. 2). Detritus was derived from several distinct sources, including dominant volcano–plutonic rocks, subordinate sedimentary to very low-grade metasedimentary rocks, and minor higher-grade metamorphic rocks and ophiolites. Detrital modes straddle the boundary between ‘‘magmatic arc’’ and ‘‘recycled orogen’’ provenance fields in standard quartz-feldspar-lithics (QFL) plots (Dickinson, 1985). As illustrated in Figure 2, this is significantly different not only from the petrography of the Murree Formation below (Najman and Garzanti, unpub. data) and the Siwalik Formation above ‘Gabir/Chinji section’ between 9 and 11 Ma (Critelli and Ingersoll, 1994), but also from the Kamlial Formation of the eastern region of the Kohat Plateau to the west (Abbasi and Friend, 1989). All these other clastic wedges plot in the ‘‘recycled orogen’’ provenance field of Dickinson (1985; Fig. 2, QFL plot). Thus, the Kamlial Formation of the Chitta Parwala section is the only Himalayan foreland basin unit studied so far (see also DeCelles et al., 1998a, 1998b; Najman and Garzanti, 2000; White et al., 2002), apart from the Chulung La Formation of the Tethys Himalaya (Garzanti et al., 1996) and locally derived sedimentary rocks adjacent to ophiolites (Abbasi and Khan, 2003), that is characterized by a distinct ‘‘magmatic arc’’ signature. Dense mineral assemblages include garnet and epidote, with subordinate tourmaline rutile, sphene, zircon, staurolite, chloritoid, chrome spinel, and amphiboles (hornblende, glaucophane, tremolite).

Anomalous Samples

Intercalated in the upper part of the unit, at 14.9 and 14.3 Ma, are sandstones (in particular, sample CP96–6A) with significantly lower proportions of feldspars and volcanic detritus (lithic grains, volcanic quartz, plagioclase) and higher very low- to low-grade metapelite and metafelsite lithics, with virtually no metabasite (Fig. 2). Dense minerals in sample 6A, significantly different from the remainder of the Kamlial Formation samples, are dominated by garnet (77%) and tourmaline (18%) with some chloritoid and staurolite and negligible epidotes (1%) (Fig. 3).

Unravelling Mixed Provenances

We used a simple empirical forward approach to estimate the end-member proportions (arc and metasedimentary thrust belt) in the mixed-source Kamlial Formation sandstones. End-member compositions were assigned according to two approaches, modern and ancient, using data from modern river sediments and ancient sandstones, respectively, eroded from the arc and Himalayan thrust belt source regions (Garzanti et al., 2003). The results obtained according to these different approaches are consistent, indicating that arc to oceanic rocks of the suture zone supplied about two-thirds of bulk detritus contained in the Kamlial Formation, with mostly metasedimentary rocks accounting for the remainder. Arc and oceanic rocks, however, supplied less than a quarter of detritus to anomalous sample 6A, the remainder being chiefly accounted for by sedimentary and metamorphic sources up to garnet grade.

Ar-Ar MICA DATA

We analyzed more than 300 individual detrital white mica grains from the Kamlial Formation sandstones using total fusion and incremental heating ^{40}Ar–^{39}Ar techniques similar to that employed by Richards et al. (1999) and White et al. (2002), but with all crystals degassed. Figures 4 and 5 and Data Repository items DR6–8 (see text footnote 1) summarize Ar–Ar mica age data obtained from the Kamlial Formation. For all but one of the samples (CP96–6A, depositional age 14.3 Ma), the white mica population is dominated by grains of Himalayan age (<55 Ma), with the remain-

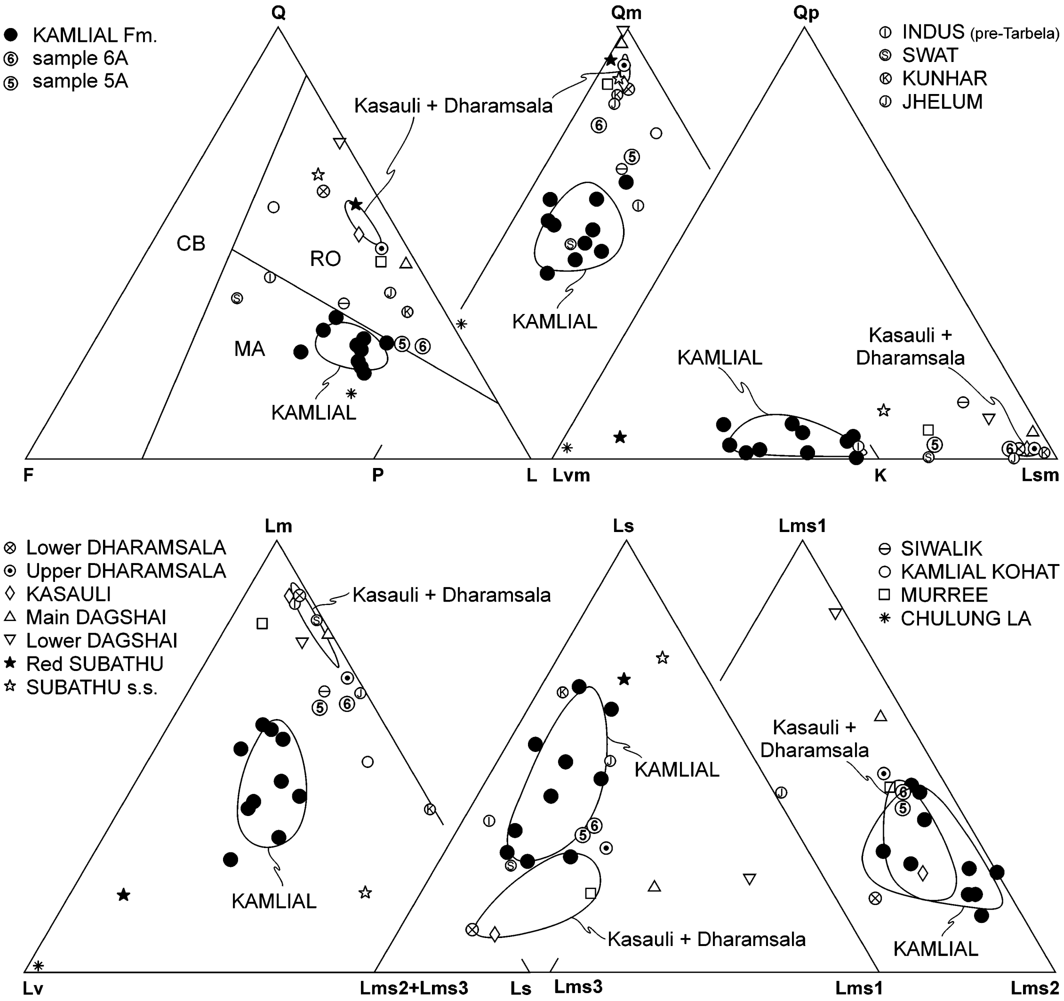

Figure 2. Detrital modes of Tertiary Himalayan sandstones. Kamlial Formation displays distinct petrographic composition with respect to other clastic wedges of Himalayan foreland basin (data from references in text) and is closer to arc-sourced Tethyan Chulung La Formation. Only anomalous samples 5A and 6A straddle the boundary between "magmatic arc" (MA) and "recycled orogen" (RO) provenance fields (Dickinson, 1985; CB—"continental block"); their lithic population is indistinguishable from Upper Dharamsala Formation samples, which were sourced by very low grade accreted Indian-margin sequences (White et al., 2002). Q—quartz (Qm—monocrystalline, Qp—polycrystalline); F—feldspars (P—plagioclase, K—K-spar); L—lithic fragments (including carbonate and chert lithics); Lm—metamorphic (metamorphic grade: Lms_1—slate to metasandstone, Lms_2—phyllite to quartz /sericite, Lms_3—quartz/mica to micaschist and gneiss); Lv—volcanic (Lvm—volcanic and metavolcanic); Ls—sedimentary (Lsm—sedimentary and metasedimentary). 99% confidence regions of mean, calculated after Weltje (2002), are shown for typical Kamlial and broadly coeval Kasauli + Dharamsala units.

der of the population spanning ages back to ca. 450 Ma. Within the Himalayan-aged population, the youngest subpopulation decreases in age up-section through time, from a ca. 25-Ma mode in rocks deposited at 18 Ma, to a ca. 14-Ma mode in sedimentary rocks deposited at 14 Ma. The lag time, defined as the difference between the youngest detrital mica age and the depositional age of its host sediment, is therefore short throughout the time of deposition of the Kamlial Formation and decreases up-section with a lag time between 5 and 7 Ma, typical for the basal two samples of the succession and <2 Ma for the overlying main part of the succession. Sample CP96–6A is an anomalous sample. It is dominated by a pre-Himalayan-aged mica population spanning 77–443 Ma. It has a lag time of 15 m.y., which was calculated from the rare occurrence of Himalayan-aged micas; two grains of the older sub-population are dated at 33 and 53 Ma. There are no Neogene-aged mica grains. The anomalous mica population is coupled with a distinctive petrography with only limited contribution from the arc-suture zone source, as described above.

Constraints to Crustal Exhumation Rates from Mica Population Ages

It is possible to estimate exhumation rates from lag times, given an appropriate thermal structure for the crust and ignoring radiogenic heat production (cf. Moore and England, 2001). We assume that the initial crustal thermal profile comprises a linear gradient from zero at the surface to 700 °C at 35 km. Below this, temperatures are constant at ~700 °C. The thermal evolution for exhumation of this crust is calculated from equation 20 of Bickle

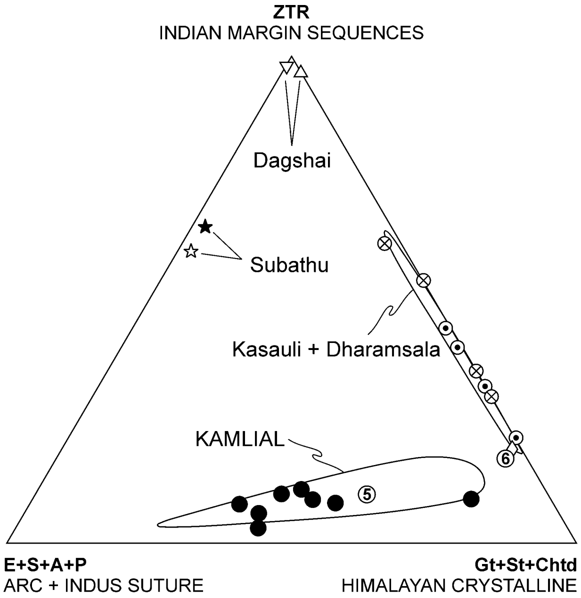

Figure 3. Dense minerals in Tertiary Himalayan sandstones. During initial collision (late Paleocene/Early Eocene), detritus was derived from Indus suture zone and thrust sheets of Indian-margin sediments (Subathu Formation). Subsequently, very low grade Indian margin sequences were eroded to feed the Dagshai Formation, with first unroofing of garnet to staurolite-bearing Himalayan crystalline nappes recorded by Lower to Middle Miocene Kasauli to Dharamsala Formations (Najman and Garzanti, 2000; White et al., 2002). Epidote-rich Kamlial suites, instead, were chiefly eroded from arc sources. Supply from Himalayan metamorphic nappes is dominant only for anomalous sample 6A. Legend as in Figure 3. ZTR—zircon, tourmaline, rutile; E—epidote; S—spinel; A—amphibole; P—pyroxene; Gt—garnet; St—staurolite; Chtd—chloritoid. 99% confidence regions of mean, calculated after Weltje (2002), are shown for Kamlial and broadly coeval Kasauli + Dharamsala units.

and McKenzie (1987). This thermal structure is appropriate for a Barrovian-style metamorphic crust formed as a result of crustal thickening (e.g., Vance and Harris, 1999; Vance et al., 2003). Vertical exhumation of such crust (700 °C maintained at 35 km depth from surface, surface maintained at zero temperature) establishes an equilibrium geotherm within a few Ma (Bickle and McKenzie, 1987, equation 18). For a crustal thermal diffusivity of 10^{-6} m^2/s and a mica blocking temperature of 350 °C, an exhumation rate of 4.5 mm/yr results in an equilibrium lag time of 1.1 m.y. (similar to the lag time displayed for the majority of Kamlial Formation samples, i.e., those samples aged $\leq$ 17.4 Ma), while an exhumation rate of 1.7 mm/yr would result in an equilibrium lag time of 6 m.y. (similar to the lag times displayed by the two basal Kamlial samples) (equation 20, Bickle and McKenzie, 1987).

This difference in lag times between the basal and main Kamlial samples may be explained by (1) increasing exhumation rate of the source area, (2) a change in source area, or (3) nonrepresentative sampling in the basal samples, i.e., our analyses of $\sim$60 grains, picked randomly, failed to incorporate any of the zero-aged grain population that was present. Assuming a single source (scenario 1), the decrease in lag time occurs abruptly, within $\sim$0.3 m.y. It is interesting to calculate how rapidly minimum lag times would change if the exhumation rate were instantaneously increased. Such model curves are shown on Figure 6. The curves model a range of exhumation rates from 2, 1.7, 1.0, 0.5, and 0.1 mm/yr to 4.5 mm/yr at times prior to 17.4 Ma, satisfying the criteria that micas reset after the accelerations in exhumation rate are exposed by 17.4 Ma. Figure 6 shows that, assuming a single source for the Himalayan-aged mica population, if the crust was previously being exhumed at rates $> \sim$0.5 mm/yr, it would not be possible to obtain the observed very rapid transition of lag times from ca. 6 Ma to $<$ 2 Ma. Alternatively, if sources switched (scenario 2) or we failed to analyze the youngest micas in the lowermost samples (scenario 3), initiation of rapid exhumation must have occurred prior to ca. 20 Ma for plausible initial exhumation rates (Fig. 6). Therefore, regardless of scenario, the data show increased exhumation by ca. 20 Ma.

INTERPRETATIONS

Provenance

The Kamlial Formation at Chitta Parwala, Potwar Plateau, is of mixed provenance: two-thirds of detritus was supplied by an uplifted arc–trench system, with continental margin sedimentary and metasedimentary sources accounting for the remaining third. Relative contributions are reversed in samples 5A and 6A, in which continental margin detritus including garnet-bearing medium-grade metamorphic rocks predominate. Mica ages indicate contribution both from regions affected and unaffected by Himalayan metamorphism. There remains little doubt that the dominant source to the foreland basin by this time was the rising orogen to the north. In spite of eastward and subordinate northward-directed paleocurrent data, we do not consider southern and western sources to be significant: paleocurrent and cathodolumiscence data given as evidence of erosion from the Precambrian crystalline basement of the southern peripheral forebulge (Hutt, 1996) can equally be explained by crevasse splay and erosion from an igneous arc source. Moreover, the peripheral forebulge, of low relief, would be unlikely to have contributed significant detritus, and its petrographic composition and age contrast radically with the Kamlial Formation data. To the west of the foreland basin lie the sedimentary and ophiolitic Sulaiman ranges (Waheed and Wells, 1990). While these ophiolites were obducted prior to Eocene time (e.g., Treloar and Izatt, 1993; Beck et al., 1996), we do not consider this a likely source for the igneous-derived detritus in the Kamlial Formation sandstones of Chitta Parwala section, Potwar Plateau, because (1) the more westerly Kamlial Formation in the Kohat Plateau shows no evidence of significant ophiolitic detritus, except for locally derived sedimentary rocks at the western margins (Abbasi and Friend, 1989; Abbasi and Khan, 2003), although we note the regionally incomplete nature of available data, and (2) based on sedimentological changes at 18 Ma in the Sulaiman range foreland basin, a major south-flowing trunk river is interpreted as having been established at this time (Friedman et al., 1992; Downing et al., 1993). Such paleodrainage would preclude western-derived ophiolitic material from being transported to the Potwar Plateau.

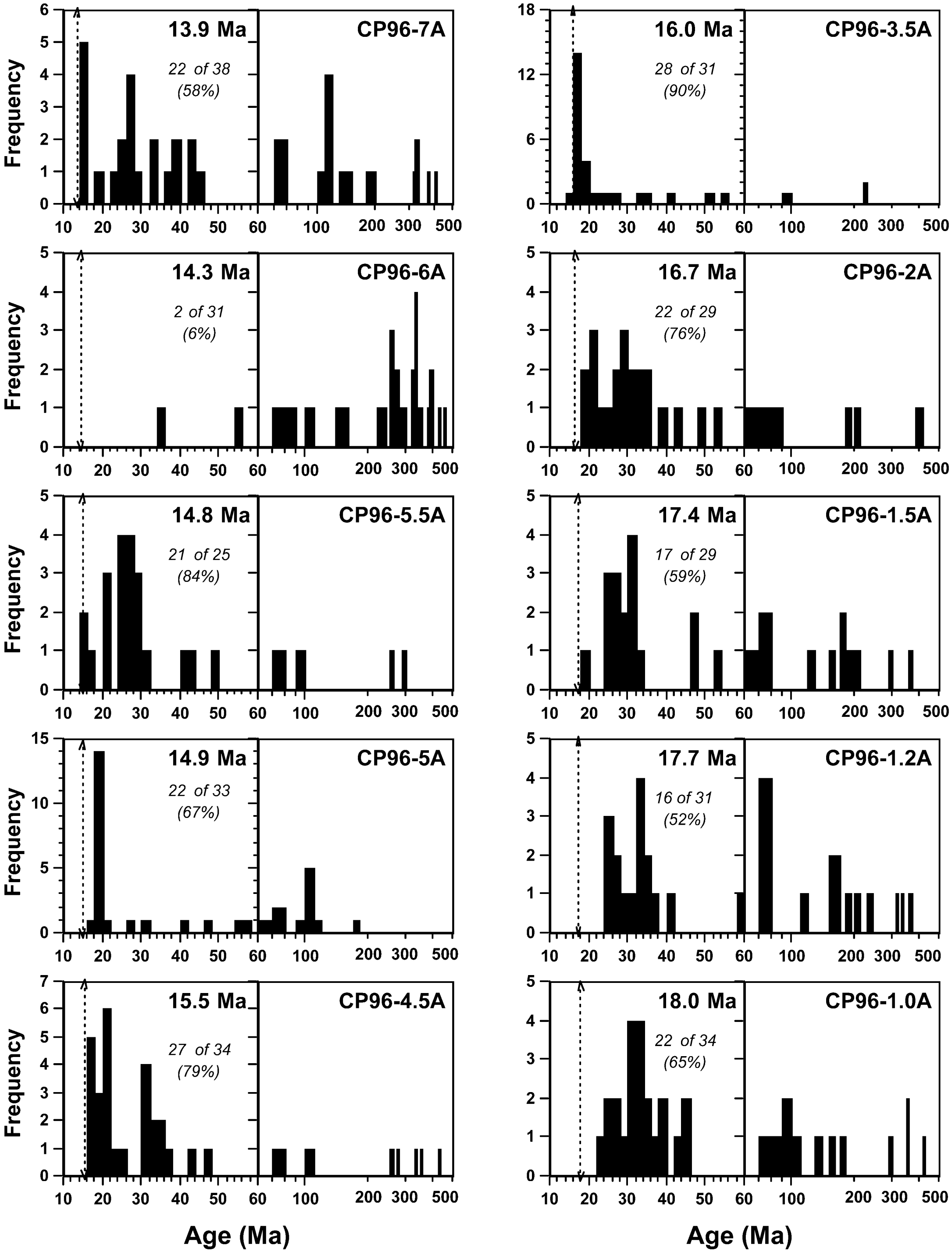

Figure 4. Histograms of detrital white mica ages. Depositional ages of sediment samples given in Ma and shown with dotted arrows. Number of grains younger than 60 Ma given as percentage of total number analyzed per sample. Mica ages between 10–60 Ma sorted in 2 m.y. wide bins and shown in a linear scale; ages older than 60 Ma sorted in 10 m.y. bins and shown on a logarithmic scale.

Petrographic Constraints

The obvious sources for the dominant igneous component are the Kohistan arc and Indus suture zone/Main Mantle Thrust. Occurrence of rare blueschist grains and blue sodic amphiboles support minor but significant supply from ophiolites and mélange pinched along the suture zone. Appropriate sources for the subsidiary sedimentary and very low to medium grade metasedimentary detritus can be found both north and south of the arc, in the Karakoram and Himalayan thrust belts. Although the present-day Himalayan thrust belt exposes little sedimentary and low-grade metamorphic material, this does not preclude it from consideration as a source region in the past, because higher stratigraphic and/or structural levels of Indian crust cover rocks were

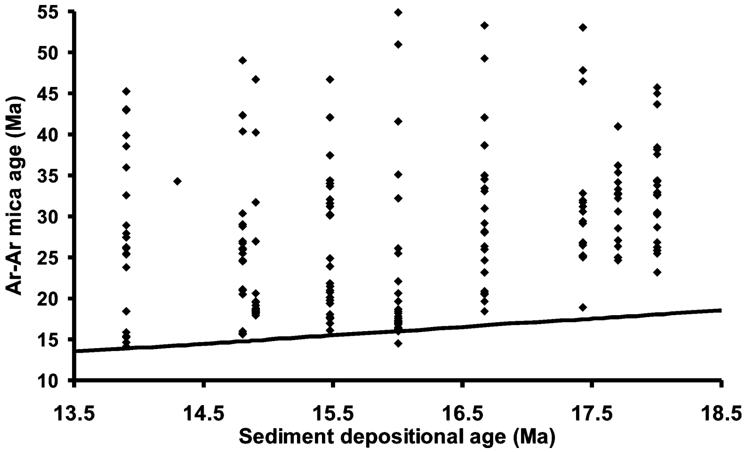

Figure 5. Ar-Ar detrital mica ages (<55 Ma Himalayan-aged grains only are shown) plotted against sample depositional age, as determined by magnetostratigraphy. Solid 1:1 line shows "zero lag time," when mica age equals sediment depositional age.

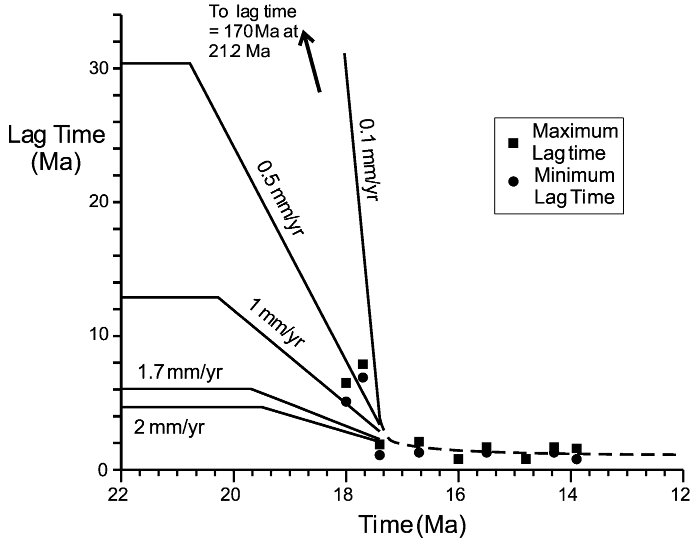

Figure 6. Plot of mica lag times, maximum—black squares, minimum—black circles, where maximum and minimum represent 2σ errors on youngest mica Ar-Ar ages with no account taken of errors in stratigraphic age. Solid lines represent evolution in lag times for crust initially exhuming at rates shown and then with exhumation accelerated to 4.5 mm/yr at a time (19.7 Ma for 1.7 mm/yr to 21.2 Ma for 0.1 mm/yr). These times are chosen so that micas at their blocking temperature at the time at which exhumation accelerates reach the surface at 17.4 Ma and therefore have model ages between 2.3 Ma and 3.8 Ma. Dashed line shows lag times for micas that closed after increase in exhumation rate. Thermal model used for calculation is described in text.

likely never buried to depths sufficient to cause metamorphism to amphibolite grade as seen in the rocks currently exposed. Moreover, we consider this region the most likely source for the metasedimentary detritus because the Indian margin must have been contributing material to the basin in view of its paleogeographic position south of the arc. Both lithic and dense mineral populations of samples CP96–6A and 5A are, in fact, very similar to those of sedimentary suites clearly derived from such Indian margin units, e.g., the coeval Upper Dharamsala foreland basin deposits in India (White et al., 2002) (Figs. 2 and 3).

Constraints from Pre-Himalayan-Aged Micas

The pre-Himalayan micas can all be attributed to an Indian crust Himalayan provenance. Lithologies with minerals of appropriate ages in the thrust belt south of the Main Mantle Thrust in Pakistan include Cambrian–Ordovician and Permo–Carboniferous igneous and metamorphic rocks (e.g., Treloar and Rex, 1990; Smith et al., 1994; DiPietro and Isachsen, 2001). Although there is no known Jurassic–Cretaceous event in the Himalayan thrust belt to explain the occurrence of micas of this age in the Kamlial sandstones, Treloar and Rex (1990) report mica ages of ca. 175 Ma from this thrust belt that may be the result of alteration, and White et al. (2002) report a similar aged population of altered detrital micas from the coeval Dharamsala Formation foreland basin sediments in India, which are clearly derived from the Indian margin thrust stack. However, although a combination of detectable alteration of older mica grains and suitable lithologies in the Himalayan thrust belt make a contribution from other sources unnecessary, it is still possible that Asian sources or the Kohistan arc (with mineral cooling ages mostly between 75–90 Ma, Zeitler, 1985; Treloar et al., 1989; Chamberlain et al., 1991) supplied a proportion of the pre-Himalayan-aged detrital mica grains.

Constraints from Himalayan-Aged Micas

Himalayan-aged micas (youngest grain aged 14 Ma) were eroded from a source exhuming rapidly since ca. 20 Ma. Outside the Nanga Parbat syntaxial region, the Indian crust thrust stack and the Kohistan arc are both inadmissible as sources for these grains, since micas exposed at the surface today are older than those found in the ≤ 17.4 Ma aged Kamlial Formation rocks (Maluski and Matte, 1984; Zeitler, 1985; Treloar et al.,1989; Treloar and Rex, 1990). Micas of suitable age are found today in the Indian crust in the Nanga Parbat region and in regions of the Asian crust (e.g., Karakoram Batholith and Karakoram Fault area; Dunlop et al., 1998; Searle et al., 1998).

Mica ^{40}Ar–^{39}Ar ages in the Nanga Parbat Syntaxis are 4–6 Ma (George et al., 1995), a result of very rapid exhumation of the massif since 10 Ma. Initiation of exhumation likely started prior to 10 Ma, as evidenced by the decreasing mineral cooling ages across the Kohistan arc: In the western region of the arc, unaffected by uplift of the Nanga Parbat Haramosh Massif, average zircon fission-track ages range between 30 and 52 Ma. By contrast, in the vicinity of the Nanga Parbat Har-

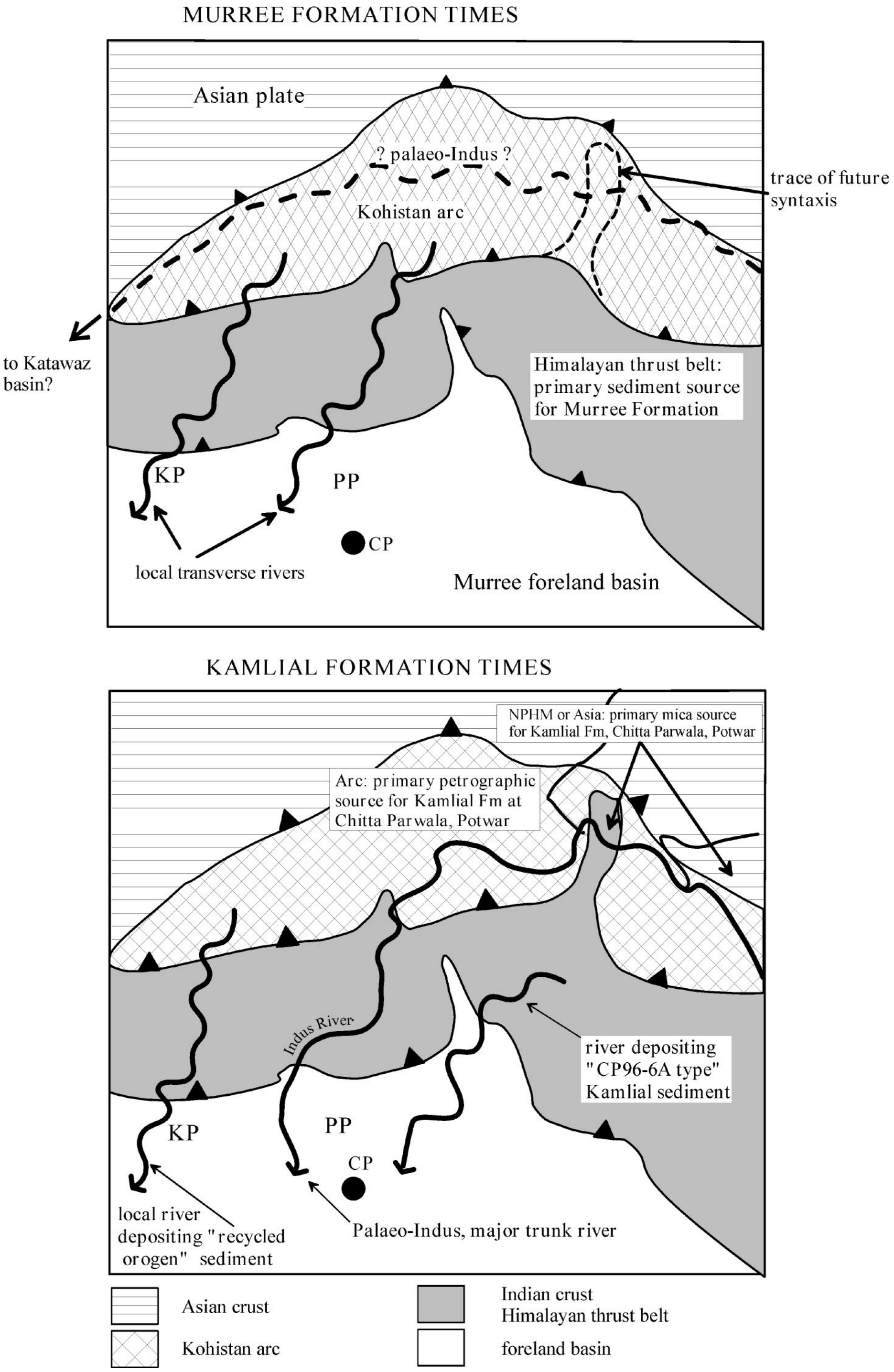

Figure 7. Cartoon drainage evolution maps; see text for details. Note that present-day hinterland thrust boundaries are only intended for orientation and were likely different, at least to some extent, in Miocene times. KP—Kohat Plateau, PP—Potwar Plateau, CP—Chitta Parwala Kamlial Formation studied section. A: Murree Formation times: Rivers depositing sediment to foreland basin have catchment areas predominantly located in Himalayan thrust belt and reach no further back than arc's southern fringe. Paleo-Indus River in Paleogene is shown as dashed line; debate continues about its presence (Searle et al., 1990) or absence (Sinclair and Jaffey, 2001) and interpreted exit through Katawaz basin rather than foreland basin (Qayyum et al., 1997). B: Kamlial Formation times: Initiation of Indus River drainage into foreland basin and establishment of position comparable to its modern day route. Major petrographic source for sediments at Chitta Parwala, Potwar Plateau, is Kohistan arc; source for rapidly exhuming micas is NPHM or Asia. More local transverse rivers, predominantly draining Himalayan thrust stack, are represented by Kamlial Formation sediments in Kohat Plateau region (Abbasi and Friend, 1989) and in Potwar region by sample CP96–6A type compositions.

amosh Massif to the east, ages lie in the range of 11–16 Ma (Zeitler, 1985), indicating initiation of exhumation prior to this time. In addition, mineral cooling ages of 16–20 Ma are found in the Indian crust cover metasediments on the margins of the Nanga Parbat syntaxis (Treloar et al., 2000; Pecher et al., 2002), which Treloar et al. consider to be dominantly a function of uplift-related exhumation, which occurred during a crustal-scale folding event that defined the early stages of syntaxial growth. Schneider et al. (1999) report mineral crystallization ages that suggest Early Miocene anatexis and pre-10 Ma movement on a major Nanga Parbat shear zone. The Nanga Parbat Haramosh Massif may therefore be a suitable source for Kamlial Formation detrital micas with zero lag time. Early exhumation of the region at 4.5 mm/yr is at odds with both the lack of evidence for the required ~80 km of crust that should therefore have been denuded if these rates were sustained to present day and the lack of suitably aged migmatites in the core of syntaxis. The absence of migmatites may be explained by (1) the nature of the protolith, which consists of Proterozoic gneisses already affected by prior metamorphism and therefore not amenable to melting; (2) the fact that these rates need not have been sustained continuously for the duration of exhumation to present day; and/or (3) lateral transport of hot crust by ductile flow that could have occurred.

Areas of the Karakoram fault and batholith show evidence of rapid exhumation co-eval with the time of deposition of the Kamlial Formation, but this exhumation initiated after 17 Ma (Parrish and Tirrul, 1989; Searle et al., 1989, 1992; Scharer et al., 1990; Searle and Tirrul, 1991; Krol et al., 1996; Searle, 1996; Dunlap et al., 1998). Therefore, this region is an unlikely source for Kamlial Formation micas eroded from a source modeled as exhuming rapidly since 20 Ma. Nevertheless, an Asian source cannot be completely ruled out, since the geology of the Asian crust is largely known only at reconnaissance level.

Provenance of Anomalous Sample CP96–6A

Provenance of sample CP96–6A is drastically different from that of the other Kamlial Formation samples, with predominant derivation from very low to medium-grade metamorphic and sedimentary sources with predominantly pre-Himalayan aged micas. The lack of significant arc/suture zone contribution necessitates a dominant source south of the Main Mantle Thrust for which the obvious candidate is the Himalayan thrust belt. The thrust belt contains (1) micas of appropriate pre-Himalayan age, (2) suitable low-grade metamorphic lithologies, and (3) a tectonic history consistent with a now-eroded sedimentary component outcropping at higher structural or stratigraphic levels and not thrust to depths sufficient to result in amphibolite-grade metamorphism as displayed at the surface today. The absence from sample CP96–6A of Himalayan-aged micas in the range 23–30 Ma is perhaps a little surprising; we suggest that this may be due to heterogeneity within the thrust stack. Both the sedimentary/metasedimentary lithic and dense mineral populations for anomalous sample 6A (and sample 5A to a lesser extent) compare very closely with those of the coeval Indian crust-derived Upper Dharamsala subgroup (Figs. 2 and 3), indicating provenance from the same type of sedimentary to low-grade metasedimentary thrust units, and thus strengthening the argument for a more local Indian-margin-thrust-stack source for sample 6A.

Modern Analogue Comparison

Further insights into the provenance of the Kamlial Formation sandstones can be gained independently through comparison with detrital modes of sediments carried by various modern tributaries of the Indus River (Garzanti et al., 2003). It should be remembered, however, that Miocene source rocks have by now been largely or completely removed by erosion. Upper structural levels are consequently underrepresented in the high ranges today, and deeper levels are overrepresented, with respect to the Miocene.

Comparison of the Kamlial Formation sandstones with modern sand of the Indus River systems shows that:

(1) the composition of the Kamlial sandstones contrasts sharply with detritus carried by most modern tributaries of the Indus. Only those rivers draining the Kohistan arc carry such low quartz contents, but with much lower volcanic detritus than in the Kamlial Formation. This difference can be attributed to increased dissection of the arc through time. Sands of the Indus main trunk river are significantly richer in quartz but compare broadly to both modern Kohistan Rivers and Kamlial Formation sandstones. The Kamlial Formation sandstones may be interpreted as paleo-Indus deposits if major differences in composition with respect to the modern Indus are ascribed to progressive erosion, through the arc from high level volcanics to deeper-level batholiths, and higher-grade metamorphic nappes south (e.g., Nanga Parbat), along (i.e., Kohistan and Ladakh arcs), and north (i.e., Karakoram) of the Indus suture.

(2) Only sands of the Kaghan and Jhelum Rivers, draining Indian crust metamorphic rocks, have relatively low quartz and feldspar contents coupled with abundant metapelite to metafelsite and significant terrigenous to carbonate lithics, comparable to Kamlial samples 5A and 6A. Sediments of the Jhelum River in its lower reaches also include a few volcanic-lithic grains recycled from the Tertiary foreland basin deposits.

Reconstruction of Early-Middle Miocene Tectonics and Paleodrainage of the Region

Any reconstruction of the tectonics and paleodrainage of the region at 18 Ma (Fig. 7) must take into account data from the Kamlial Formation of the Chinji Village area, which shows (1) sedimentological evidence of deposition by a large river; (2) substantial increase (compared to the older Murree Formation) and predominance of arc-derived material; and (3) subsidiary contribution from a rapidly exhuming micaceous source, interpreted as the Nanga Parbat Haramosh Massif or a region of Asian crust.

Tectonics of the arc cannot explain these data. Exhumation of the arc had decreased to the extent that denudation only by passive erosion was occurring by this time (Chamberlain et al., 1991). Furthermore, the arc had only made a subordinate contribution to basin detritus even during its earlier, more rapid phase of exhumation coeval with Murree Formation sedimentation. Shifting of a preexisting drainage can also be precluded. Although our knowledge of foreland basin characteristics is regionally incomplete, available data provide no evidence of large, arc-derived rivers during Murree Formation times. Likewise, Kamlial sedimentary rocks along strike in the eastern part of the Kohat Plateau do not exhibit a magmatic arc signature, suggesting that the cause of these changes emanates more from a single ‘‘point-source’’ rather than a regionally extensive tectonic unit providing an apron of sediment to the basin. We propose the following: (Fig. 7):

Murree Formation Times (Early Miocene, ≥18 Ma)

Rivers draining to the foreland basin had catchment areas predominantly within the Himalayan thrust stack. Only a minor proportion of the drainage basins extended back into the arc. Correspondingly, the highest proportion of detritus was derived from the Indian crust Himalayan thrust belt.

Kamlial Formation Times (18–14 Ma)

Enlargement of the drainage basin deep into the arc, perhaps to the northern margin of the arc or beyond, occurred at this time. This would account for the observed increase in arc material as well as subordinate input from a rapidly exhuming northern source. This subordinate source is interpreted as the Nanga Parbat Haramosh Massif or a region of Asian crust. Initiation of rapid exhumation of the Nanga Parbat Haramosh Massif at this time would result in a rapid massive influx to the basin of material from the passively uplifted overlying arc carapace, as seen at 18 Ma. The possible delayed response in exhumation of zero lag time micas could be due to the time required for the short lag time micas to appear at the surface.

Interpretation of the Kamlial Formation at Chitta Parwala as the expression of the first diversion of the paleo-Indus River to its present position, i.e., crossing the arc and Himalayas through the Nanga Parbat Haramosh Massif and debouching into the foreland, is consistent with the provenance data and sedimentological evidence of a large river. Brookfield (1998) considers the pronounced change in direction of the Indus, from east–west along the suture zone to south across the arc massif, to be an elbow of capture reflecting stream piracy. Shroder and Bishop (2000) postulated that the river piracy, which brought the paleo-Indus to the foreland basin, was routed along the tectonic depressions caused by extensional collapse of the orogen from southwest to north of Nanga Parbat and obliquely transverse to the Kohistan–Ladakh arc. Formation of these tectonic lineaments, such as the Main Mantle Thrust, along which it is proposed the pirated river would have flowed, was complete by ca. 20–18 Ma (Treloar et al., 1989; Treloar et al., 1991; Chamberlain et al., 1991; Chamberlain and Zeitler, 1996), consistent with the start of deposition of the Kamlial Formation rocks at 18 Ma.

Whether the Kamlial deposits at Chitta Parwala, Potwar Plateau, represent the main trunk drainage of the paleo-Indus, or a major tributary draining the arc as far north as the Nanga Parbat Haramosh Massif, requires more along-strike data to establish. It is true that the Kamlial Formation rocks along-strike in the Kohat Plateau, very close to where the modern Indus flows, more closely resemble the recent Indus Fan detritus (Suczek and Ingersoll, 1985). On the other hand, differences between the Kamlial Formation of the Potwar Plateau and deposits at Potwar and those of the modern Indus Fan could be ascribed to progressive breaching of the arc and orogenic sources. The modern day Indus routes through the Nanga Parbat Haramosh Massif and may have flowed across the Potwar Plateau, close to the Chitta Parwala locality, prior to westward displacement consequent to Pliocene and later uplift of the Salt Range (Baker et al., 1988; Gee and Gee, 1989; Burbank and Beck, 1989). Thus, although the exact position of the trunk river remains uncertain, all data suggest deposition in the area by a river system that cut deep into the orogen at 18 Ma. The river is likely the paleo-Indus, consistent with (1) the timing of significantly more pronounced channel and levee complexes in the Indus Fan after the Early Miocene (Clift et al., 2001a); (2) the interpreted switch of the course of the lower reaches of the paleo-Indus in the late Early Miocene from debouching into the Katawaz basin to its present-day position into the foreland basin (Qayyum et al., 1997); and (3) the facies shift from coastal marine to southerly directed fluvial sediments in the Sulaiman foredeep, along which the Indus would have flowed, at 18 Ma (Friedman et al., 1992; Downing et al., 1993).

Siwalik Formation Times (≤14 Ma)

Much lower proportions of plagioclase, volcanic, and metavolcanic/metabasite lithics, and higher proportions of quartz and metasedimentary detritus in the overlying Siwalik Formation of the Gabhir-Chinji Village region (Critelli and Ingersoll, 1994) indicate that arc contribution decreased in this area in post-Kamlial Formation times. The first appearance of pleochroic orthopyroxenes and arc-derived, blue-green hornblende (Johnson et al., 1985) indicates erosion from the higher volcanic levels being eroded previously, into the deeper level amphibolite-granulite roots of the arc. We suggest that these changes reflect progressive breaching of the arc carapace with time, accompanied by deeper erosion into the Indian crust Nanga Parbat Haramosh Massif syntaxis.

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