Reconstructing early Himalayan tectonic evolution and paleogeography from Tertiary foreland basin sedimentary rocks, northern India

Yani Najman* *Department of Earth Sciences, Cambridge University, Downing Street, Cambridge CB2 3EQ, United Kingdom,* and *Department of Geology and Geophysics, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, United Kingdom*

Eduardo Garzanti† *Dipartimento di Scienze della Terra, Via Mangiagalli, 34-20133 Milano, Italy,* and *Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano-Bicocca, Via Emanueli 14, 20126 Milano, Italy*

ABSTRACT

The latest Paleocene–middle Eocene Subathu Formation and the Oligocene–Miocene Dagshai and Kasauli Formations of the Indian foreland basin record the early evolution of the Himalayan fold-thrust belt. Sandstone petrography of the Subathu Formation shows a predominantly recycled sedimentary source, with a distinct ophiolitic and volcanic influence that was drastically reduced by the time of deposition of the Dagshai Formation. Sandstones in the Dagshai and Kasauli Formations consist predominantly of metapelitic detritus. The metamorphic grade of metapelitic lithic grains increases with time, from dominantly very low grade at the base of the Dagshai Formation to dominantly low grade in the Kasauli sandstones. Mudstone geochemistry documents the presence of a mafic-ultramafic source during the time of deposition of the Subathu Formation that becomes significantly less important by the time of deposition of the Dagshai Formation. Compositions of Subathu Formation detrital spinels show they were either derived from both mid-ocean ridge basalt–type and arc-type ophiolites or from an ophiolite of composite origin, and that southerly derivation from the Deccan Trap continental flood basalts is unlikely. Kasauli Formation garnet compositions suggest derivation from medium-grade metamorphic rocks to amphibolite facies.

Subathu Formation composition reflects provenance influence from the Indus suture zone during latest Paleocene–middle Eocene time, indicating initiation of continent-continent collision and development of the foreland basin by this time. Suture-zone influence was drastically reduced by the time of deposition of the Dagshai Formation, when the embryonic thrust belt provided a barrier sufficient to partially separate the suture zone from the Himalayan foreland basin. The first appearance of Himalayan metamorphic detritus occurs in the Dagshai Formation at the close of Oligocene time, whereas the Kasauli Formation records erosion to deeper metamorphic levels during earliest Miocene time. The occurrence of garnet and higher grade metamorphic lithic grains during early Neogene time is coincident with the timing of displacement along the Main Central thrust and South Tibetan detachment zone.

Composition of early foreland basin sediments from Pakistan (Balakot, Murree and Kamlial Formations) to Nepal (Bhainskati and Dumri Formations) and Bangladesh (Kopili, Barail Formations; Surma Group) indicates diachronous arrival of ophiolitic to low-grade metamorphic detritus derived respectively from the Indus Suture and early Himalayan thrust sheets in the north. This is consistent with progressively later closure of Neotethys along the suture, from latest Paleocene time in the west to Eocene time or even later in the east.

Keywords: Himalaya, foreland basin, sediment provenance, tectonics, paleogeography, continental collision.

INTRODUCTION

The sediments deposited in the Himalayan collisional and foreland basins provide a record of the orogen's evolution through time. This paper describes the earliest sediments in the peripheral foreland basin in northern India: the latest Paleocene to Miocene Subathu, Dagshai, and Kasauli Formations. Using these sediments, we document the as-yet poorly constrained early stages of India-Eurasia collision, Himalayan tectonic evolution, and paleogeography. An integrated approach is taken, using conventional bulk-composition detrital modes analysis, a powerful tool in reconstructing Himalayan evolution (e.g., Garzanti et al., 1987, 1996) along with single-grain and whole-rock geochemical analyses to provide additional detail. Comparison with similar studies of other Himalayan sedimentary basins, including the peripheral foreland basin along strike in Pakistan (Bossart and Ottiger, 1989; Critelli and Garzanti, 1994), Nepal (Bhainskati and Dumri Formations; DeCelles et al., 1998a), the Bengal basin (Uddin and Lundberg, 1998), the Chulung-La piggyback basin in the Tethys Himalaya (Critelli and Garzanti, 1994; Garzanti et al., 1996), and the Indus forearc sediments in the suture zone (Garzanti and Van Haver, 1988) allows a regional picture to be established.

GEOLOGICAL FRAMEWORK

The Himalaya consists of six lithotectonic zones (Gansser, 1964) (Fig. 1A). From north to south, these belts and their representative rock types are as follows.

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*E-mail: y.najman@glg.ed.ac.uk.

†E-mail: eduardo.garzanti@unimi.it.

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1. The Trans-Himalayan zone consists of Upper Cretaceous to Eocene calc-alkaline plutons, interpreted as the Andean-type northern margin of Tethys (Honegger et al., 1982; Coulon et al., 1986; Le Fort, 1996).

2. The Indus suture zone is the zone of collision between India and Eurasia. This zone is composed of deep-water Indian continental rise sediments, Trans-Himalayan accretionary complexes, ophiolites and ophiolitic melange, island arc volcanic rocks, and forearc basin sedimentary rocks (Searle, 1983; Garzanti and Van Haver, 1988; Reuber et al., 1987; Reuber, 1989; Robertson and Degnan, 1993).

3. The Tibetan or Tethys Himalayan zone is composed of Cambrian to Paleocene sediments (the Tibetan Sedimentary Series) deposited on the Indian continental terrace (Fuchs, 1982, Gaetani and Garzanti, 1991), unconformably overlain by the Chulung La collisional deposits (Critelli and Garzanti, 1994).

4. The Greater Himalaya consists of Indian continental crust and sedimentary rocks of mainly Late Proterozoic–Cambrian age (Parrish and Hodges, 1996), now regionally metamorphosed and intruded by leucogranite crustal melts in the uppermost part (e.g., Le Fort et al., 1987; Treloar and Searle, 1993, and papers therein).

5. The Lesser Himalaya is composed of nonmetamorphosed or weakly metamorphosed Indian continental crust and sedimentary rocks that range in age from Middle Proterozoic to Paleozoic (Valdiya, 1980; Valdiya and Bhatia, 1980; Parrish and Hodges, 1996), and Paleogene foreland basin sedimentary rocks (Srikantia and Bhargava, 1967; Srikantia and Sharma, 1970; Sakai, 1989; DeCelles et al., 1998a).

6. The Sub-Himalaya is composed of Paleogene and Neogene sediments eroded from the rising orogen and deposited in the peripheral foreland basin in front of the mountain belt (Parkash et al., 1980; Johnson et al., 1985; Harrison et al., 1993; Najman et al., 1993; Critelli and Garzanti, 1994; DeCelles et al., 1998b).

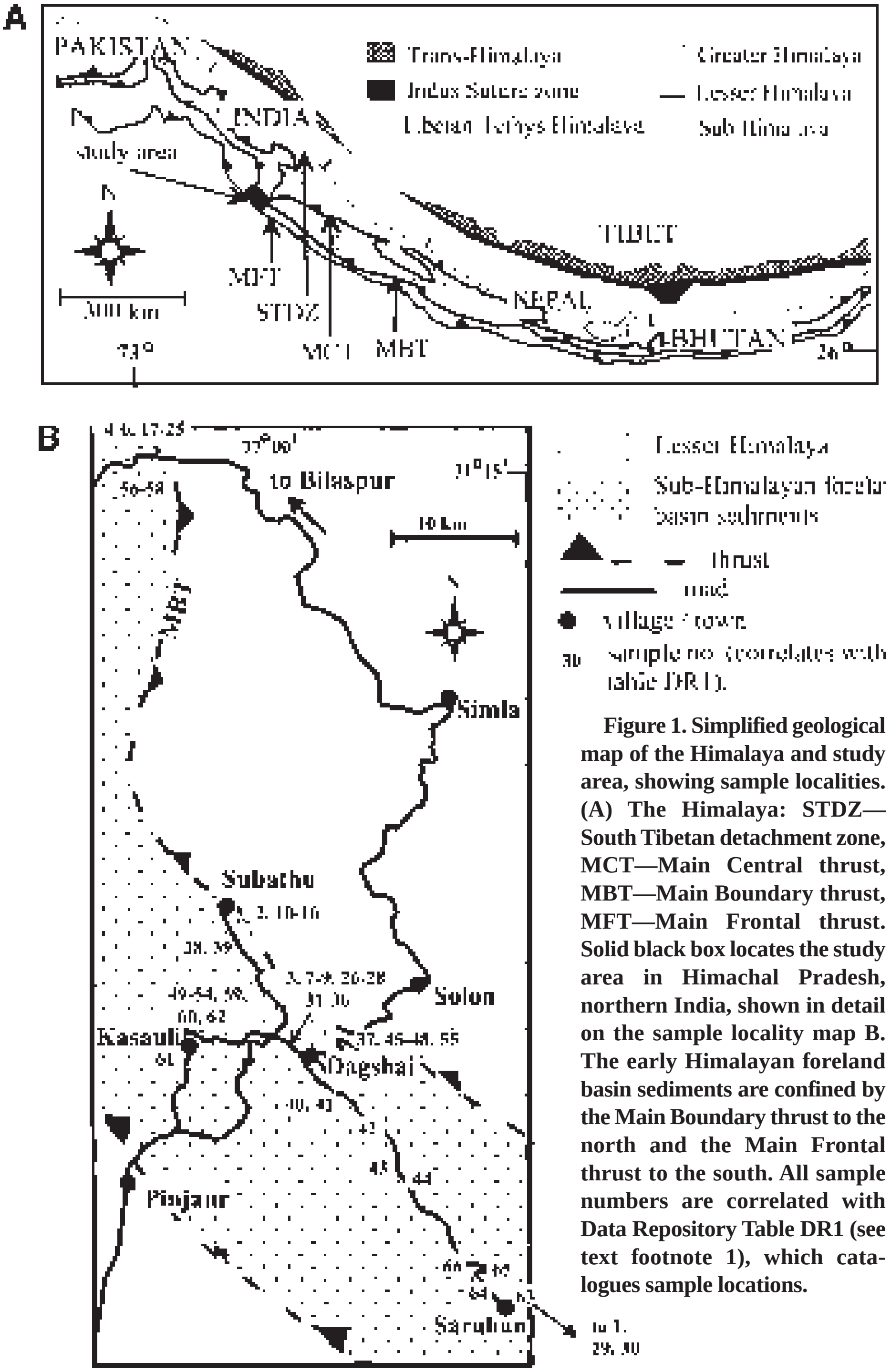

Figure 1. Simplified geological map of the Himalaya and study area, showing sample localities. (A) The Himalaya: STDZ—South Tibetan detachment zone, MCT—Main Central thrust, MBT—Main Boundary thrust, MFT—Main Frontal thrust. Solid black box locates the study area in Himachal Pradesh, northern India, shown in detail on the sample locality map B. The early Himalayan foreland basin sediments are confined by the Main Boundary thrust to the north and the Main Frontal thrust to the south. All sample numbers are correlated with Data Repository Table DR1 (see text footnote 1), which catalogues sample locations.

Prior to final closure of the Neotethys, oceanic lithosphere was being subducted beneath the Eurasian active margin, exposed today in the Trans-Himalayan belt. Collision between India and Eurasia, along the Indus suture zone, and the subsequent formation of the Himalaya, began ca. 55 Ma (i.e., latest Paleocene) in the west (Le Fort, 1996, and references therein; Rowley, 1996, and references therein). Subsequent to collision, metamorphism of the subducting Indian crust took place, possibly diachronous from west to east. Eclogite facies metamorphism occurred by 49 Ma (Pognante and Spencer, 1991; Tonarini et al., 1993). Two main phases of later metamorphism have also been recognized: phase 1 metamorphism (M1) ca. 40 Ma (but younging eastward) is Barrovian metamorphism of the Greater Himalaya, the result of crustal thickening due to thrust stacking. The climax of phase 2 metamorphism (M2) and production of leucogranite melts ca. 20 Ma (also younging eastward) is associated with movement along the Main Central thrust and normal faulting at the base of the Tethyan Himalayan zone along the South Tibetan detachment zone (Staubli, 1989; Searle and Rex, 1989; Metcalfe, 1993). The Main Central thrust, active at 24–21 Ma (Hubbard and Harrison, 1989; Harrison et al., 1995) was responsible for bringing the Greater Himalaya over the Lesser Himalaya. Continued convergence of India with Eurasia resulted in southward propagation of the thrust belt (Fig. 1): the Main Boundary thrust, active in

TABLE 1. SUMMARY CHART OF THE STRATIGRAPHIC RELATIONSHIPS, AGES, AND FACIES OF THE HIMALAYAN FORELAND BASIN SEDIMENTARY UNITS IN THE STUDY REGION, HIMACHAL PRADESH, NORTHERN INDIA

Unit	Subunit	Age	Facies
Siwalik Group	Upper Middle Lower	14–0 Ma*	Alluvial†
Kasauli Formation	Kasauli	<22 Ma§	Alluvial#
	Kumahatti-Solon		
Dagshai Formation	Main Dagshai	<28–25 Ma§	Alluvial#
	Lower Dagshai		
	Basal Dagshai	<30 Ma**	
	Passage beds		
Subathu Formation	Subathu Formation (sensu stricto) and Red Subathu	Latest Paleocene–middle Eocene††	Shallow marine§§

*Johnson et al. (1985).
†Burbank et al. (1996).
§Najman et al. (1997).
#Najman et al. (1993).
**Najman et al. (1999).
††Mathur (1979).
§§Mathur (1978).

middle-late Miocene (Hodges et al., 1988; Meigs et al., 1995) or Pliocene time (DeCelles et al., 1998b), thrust the Lesser Himalaya over the Sub-Himalaya, and the active Main Frontal thrust lies to the south of the Sub-Himalaya, separating it from the Indian foreland basin (Indo-Gangetic plain) to the south (Powers et al., 1998).

STRATIGRAPHY AND FACIES OF THE INDIAN HIMALAYAN FORELAND BASIN

In northern India, the Sub-Himalayan foreland basin rocks consist of, from oldest to youngest, the Subathu, Dagshai, and Kasauli Formations and the Siwalik Group (Gansser, 1964; Bhatia, 1982) (Table 1). This paper focuses on the early (pre-Siwalik) rocks of the foreland basin in Himachal Pradesh, northern India (Fig. 1B). The Siwalik rocks are well documented by Parkash et al. (1980), Meigs et al. (1995), Burbank et al. (1996) and references therein, Harrison et al. (1993), and DeCelles et al. (1998b).

At the base of the sequence are the shallow-marine rocks of the Subathu Formation. These were dated by Mathur (1978) as latest Paleocene to middle Eocene age on the basis of marine fauna, mainly large foraminifera. In the neighboring region to the west, Blondeau et al. (1986) suggested an early Eocene age. Rocks are dominantly limestones and mudstones with some fine-grained sandstones (Mathur, 1978). Red, bioturbated fine-grained sandstones, siltstones, and mudstones are also found within the Subathu Formation (Red Subathu) interpreted by one of us (Najman) as delta plain, coastal, and tidal flat facies. The contact between the Subathu and Dagshai Formations is marked by a thin sequence of variegated shales capped by a hard white-gray quartz-rich sandstone and/or a softer green-colored sandstone (the passage beds of Mathur, 1979). Dating of the green sandstone has shown it to be younger than 30 Ma (Najman et al., 1999) and therefore we assign this distinctive sandstone to the basal Dagshai Formation. Previous facies analyses interpreted the sandstone bed as deposited in a shoreline barrier and/or beach environment (Singh and Khanna, 1980; Raiverman et al., 1983; Srivastava and Casshyap, 1983).

The Dagshai Formation was thought to stratigraphically intertongue with the Subathu Formation (Raiverman and Raman, 1971) or conformably or unconformably overlie it (Bhatia and Mathur, 1965; Chaudhri, 1968, 1976). Mapping (Najman et al., 1993) has shown that the Dagshai Formation is above the Subathu Formation, and isotopic dating of detrital white micas has shown the Dagshai Formation to be younger than 28 Ma (Najman et al., 1997). The sandstones, siltstones, mudstones, and caliche of the Dagshai Formation have been variously interpreted as turbiditic, tidal flat, and alluvial (e.g., Raiverman and Seshavataram, 1965; Raiverman and Raman, 1971; Najman et al., 1993; Singh and Singh, 1995), the alluvial facies now being the generally accepted interpretation.

The overlying Kasauli Formation consists of gray sandstones and subordinate mudstones. Depositional age is constrained as younger than 28–22 Ma by Ar-Ar dating of detrital micas (Najman et al., 1997) and early-middle Miocene by plant fossils (Fiestmantel, 1882). A range of depositional environments has been suggested, similar to those for the Dagshai Formation, with an alluvial facies as the generally accepted interpretation (Singh, 1978; Najman et al., 1993; Najman, unpublished data). Paleocurrent data are similar to those of the Dagshai Formation (Najman et al., 1993; Najman, unpublished data).

PROVENANCE STUDIES

A variety of techniques were used, described as follows, to provide comprehensive documentation of changes through time. All samples can be located in Figure 1B, which can be correlated with Data Repository Table DR1[1] (sample locations). Due to the tectonized nature of the region and therefore the lack of complete sedimentary sections and impossibility of along-strike correlation, it is often not possible to identify the stratigraphic placement of a sample more accurately than an assignment to its formation. Red beds (Red Subathu) of distinctive provenance are found interbedded within the green Subathu Formation succession at one stratigraphic horizon at one locality, but the stratigraphic relationship within the overall Subathu Formation unit (Subathu Formation sensu stricto) is unclear. Within the Dagshai Formation, we have attempted to subdivide the unit based on mapped stratigraphy where a reasonable degree of certainty can be deduced. The Dagshai Formation stratigraphic succession has thus been subdivided into (1) the basal section, i.e., the quartz-rich and green sandstones found at the Subathu-Dagshai contact; (2) the lower section, near the Subathu-Dagshai contact; and (3) the Main Dagshai Formation, not obviously near the lower or upper contact. The Kumahatti-Solon beds are transitional between the Dagshai Formation and the Kasauli Formation: the sedimentology of this unit resembles that of the Kasauli Formation; however, it has closer petrographic affinities with the Dagshai Formation. The overlying Kasauli Formation is undivided.

Sandstone Petrography: Methods and Results

Methods. We counted 300 points on 37 selected samples according to the Gazzi-Dickinson point-counting method (e.g., Ingersoll et al., 1984; Zuffa, 1985). A classification scheme including 20 classes and about 80 subclasses of grain types was devised to record a complete quantitative data set, with particularly detailed information on rock fragments. The main interstitial and authigenic components were also distinguished. Point-count results are summarized in Table DR2 (see text footnote 1). Along with traditional parameters and standard plots (Fig. 2B; e.g., Dickinson and Suczek, 1979; Ingersoll, 1983), a wider spectrum of eight key indexes (Q—total quartz, F—total feldspars, Lv—volcanic lithic grains, Lc—carbonate lithic grains,

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[1] GSA Data Repository item 200032, sample location tables DR1–DR5, is available on the Web at http://www.geosociety.org/pubs/drpint.htm. Requests may also be sent to Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301; e-mail: editing@geosociety.org.

including limestone and dolostone; Lp—pelitic lithic grains, including shale and siltstone; Lch—cherty lithic grains, including chalcedony, cherty shale, and radiolarite; Lm—metamorphic lithic grains, including metapelite, metafelsite, and metabasite; Lo—serpentine-bearing lithic grains, including cellular serpentinite and serpentine schists) were used to discriminate further among distinct populations of samples, in order to emphasize petrological changes through time (Fig. 2A), and to make detailed comparisons with other Himalayan clastic suites (Table 2). Grain sizes of samples (median diameter determined in thin section by ranking and visual comparison; method summarized in Garzanti, 1986) range between 2.5 ϕ and 1 ϕ, except for the Subathu Formation and Red Subathu, where the median diameter is invariably <2.5 ϕ. Dense mineral associations were determined from grain mounts for six selected samples using standard techniques (e.g., Parfenoff et al., 1970).

Results (Table DR2 [see text footnote 1], Fig. 2, A–D). *Subathu Formation (n = 5).* Subathu Formation sensu stricto (n = 2): In the very fine-grained sandstone intercalations within the Subathu Formation, quartz dominates over feldspar and lithic fragments (average Qt = 69, F = 9, L = 22; Fig. 2B). Monocrystalline dominates over polycrystalline quartz. In the detrital feldspar component, plagioclase prevails over orthoclase and chessboard-twinned albite (average P/F 58; Moore and Liou, 1979). Lithic fragments are mainly sedimentary (shale and chert, with a few sparites), but also include volcanic (felsite), very low grade metamorphic (slate) and ophiolitic (serpentine schist) types (Lm = 18 Lv = 23 Ls = 58; Fig. 2C). Dense mineral studies show the common occurrence of red and yellow Cr spinel and rutile (Fig. 2D). Both euhedral to rounded zircon and tourmaline are also present, along with apatite, sphene, opaque minerals, and extremely rare garnet. The intrabasinal fraction consists of mud clasts, bivalves, benthic foraminifers, micritic intraclasts, and green grains (celadonite). Abundant diagenetic carbonates have selectively replaced unstable framework components, thus reducing the reliability of the point-counting data.

Red beds within the Subathu Formation (n = 3): In these very fine to fine-grained, red-colored sandstones, quartz dominates over feldspar and lithic fragments (average Qt = 60, F = 5, L = 35; Fig. 2B). Plagioclase dominates the detrital feldspar component (average P/F = 83); chessboard-twinned albite grains also occur. Lithic fragments are dominated by volcanic detritus (mostly felsitic and vitric grains, with a few microlitic types). Sedimentary grains (shale, chert, single radiolaria, and planktonic foraminifera) are subordinate and very low grade metamorphic (slate) grains are negligible, whereas serpentine schist to chlorite grains are significant (average Lm = 18, Lv = 72, Ls = 11; Fig. 2C). Red, yellow, and coffee-brown Cr spinels, rutile, and zircon dominate the dense mineral assemblage; garnet, tourmaline, and apatite are very rare (Fig. 2D). The intrabasinal fraction mainly consists of locally very abundant red hematitic mud clasts; benthic foraminifers and green grains (celadonite) also occur. Authigenic carbonates are abundant in all samples.

Dagshai Formation (n = 22). Basal and Lower Dagshai Formation (n = 8): Average detrital modes of these fine- to medium-grained sandstones are Qt = 72, F = 1, L = 28; Fig. 2B). Quartz content is highly variable, and locally as high as 92%. Monocrystalline dominates over polycrystalline quartz. The P/F ratio is not very significant due to the low feldspar content. Lithic fragments are dominantly metamorphic, with some sedimentary and volcanic material (average Lm = 78, Lv = 6, Ls = 16). The metamorphic lithic fragments are dominantly very low grade (slate, 73%), with some low-grade types (phyllite, 11%; quartz-mica aggregate, 14%). Medium-grade material is negligible (mica schist, gneiss, 2%). Sedimentary lithic grains are significant, including quartzarenite (commonly hematite-bearing and undeformed), feldspathic sandstone to micaceous siltstone, shale, red to yellow and commonly radiolarian chert; locally phosphatic or radiolarian black chert typically occurs. Volcanic detritus (mostly felsite) is minor, and ophiolitic detritus is sporadic. The dense mineral assemblage is dominated by zircon. Rutile and tourmaline are also present; spinel and epidote are very rare (Fig. 2D). The intrabasinal fraction consists of common hematitic mud clasts and sporadic green grains (celadonite, glaucony). Hematite, kaolinite, and locally carbonates are common authigenic minerals.

Main Dagshai Formation (n = 10): The fine- to medium-grained sandstone samples from the main body of the Dagshai Formation are petrographically distinct from samples from the basal and lower subunits. The detrital modes show less variation between samples, Q being mostly 40%–48% (average Qt = 48, F = 1, L = 50) (Fig. 2B). Feldspars, with plagioclase prevailing over orthoclase, chessboard-twinned albite, and microcline, are few and mainly occur within metafelsitic rock fragments. The P/F ratios, where determined, show variation from 67 to 86 (average 73). The metamorphic rock fragments are dominated by a mix of very low grade material (slate, 48%), and low-grade types (phyllite, 24%; quartz-mica aggregate, 23%). Medium-grade lithic fragments are few but significant (mica schist, gneiss, 5%; Fig. 2C). Sedimentary lithic fragments include undeformed hematite-cemented quartzarenite, feldspathic sandstone, micaceous siltstone, shale, and red to yellow and black, locally phosphatic or radiolarian, chert. Very few felsitic volcanic lithic fragments are found (Lm = 77, Lv = 2, Ls = 21; Fig. 2, A and C). The dense mineral assemblage is dominated by zircon (Fig. 2D). Subhedral or rounded yellow tourmaline (dravite), commonly included within very low grade metasedimentary grains, and rutile are common. Other minerals include common chlorite and muscovite, and rare apatite and garnet. The intrabasinal fraction consists of common hematitic mud clasts. Hematite and kaolinite are common authigenic minerals.

Kumahatti-Solon Unit (n = 4): Petrographically these fine- to medium-grained sandstones appear very similar to the underlying Dagshai Formation, apart from a slightly greater abundance of detritus derived from micaceous metamorphic rocks, including quartz-mica aggregate, mica-schist grains, and single mica flakes, and a lower P/F ratio (average 63) . Average detrital modes are Qt = 46, F = 4, L = 50. Very low grade (slate, 29%) to low-grade (phyllite, 25%; quartz-mica aggregate, 37%) and some medium-grade grains (mica schist, gneiss, 10%) dominate the lithic component. Sedimentary (terrigenous and subordinate chert grains) and rare volcanic detritus (felsite lithic fragments) are also present (average Lm = 77 Lv = 1, Ls = 22; Fig. 2C). The dense mineral assemblage is dominated by zircon and tourmaline (Fig. 2D). Rutile is common; spinel, garnet, and amphibole are rare.

Kasauli Formation (n = 10). The fine- to medium-grained Kasauli Formation sandstones have an average detrital mode of Qt = 52, F = 8, L = 40 (Fig. 2B). Total feldspars (plagioclase, orthoclase, chessboard-twinned albite, microcline) are more abundant than in underlying units (to 17%; average P/F is 57). The sandstones are dominated by low-grade metamorphic detritus (phyllite, 30%; quartz-mica aggregate, 44%), with subordinate very low (slate, 12%), and medium-grade (14%) material. Volcanic (felsites) and terrigenous sedimentary (sandstone, shale) rock fragments are minor; chert is negligible. Average total lithic mode is Lm = 87, Lv = 4, Ls = 9; Fig. 2C). The dense mineral assemblage shows an abundance of garnet (Fig. 2D). Zircon and tourmaline (dravite and schorlite) are common; spinel, rutile, and opaques are rare. Other minerals include common muscovite and biotite, epidote (clinozoisite, pistacite), sphene, and apatite.

Summary of Significant Changes with Time. The composition of the lithic fragments is dominantly sedimentary in the Subathu Formation (sensu stricto), dominantly volcanic in the Red Subathu stratigraphic unit, and dominantly metamorphic throughout the Dagshai and Kasauli Formations. The composition of the metamorphic lithic fragments increases in metamorphic grade

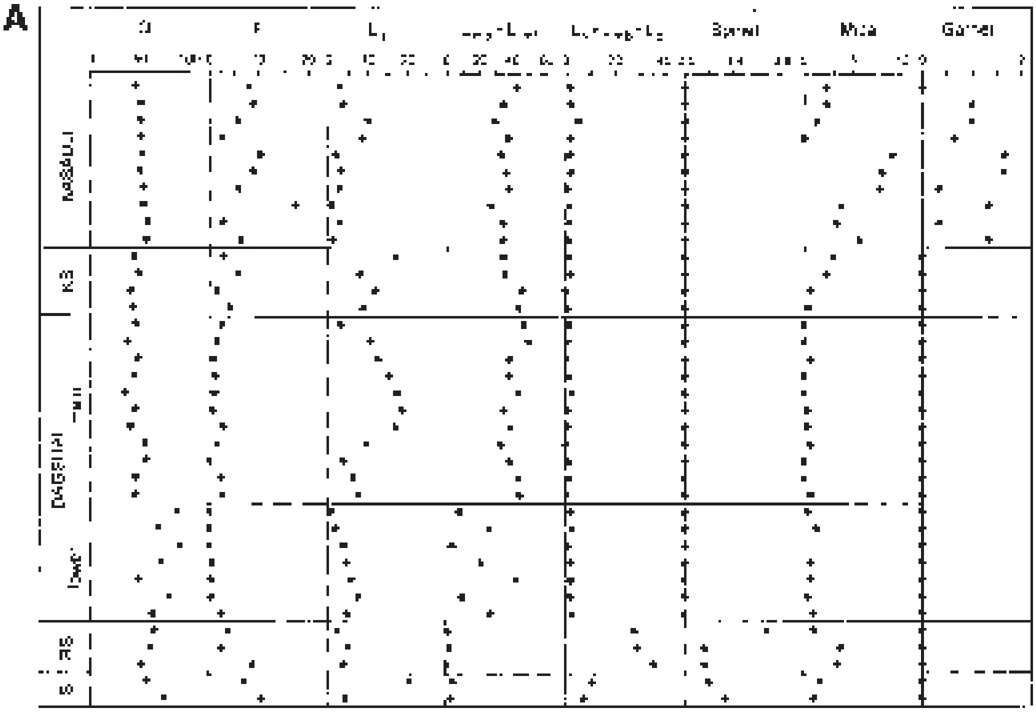


Figure 2. (A) Petrography of Indian foreland basin sandstones. Lithic fragments include sedimentary (Ls = Lc + Lp + Lch) and metasedimentary grains (Lmp—metapelite; Lmf—metafelsite) mostly derived from Indian cover rocks, and suture-derived detritus (Lv—volcanic; Lmb—metabasite; Lo—serpentine schist). Note (1) abundant metamorphic lithic fragments and steady increase in feldspars in the Dagshai and overlying units; (2) increase first in detrital micas and next in garnet in the Kumahatti-Solon (KS) and Kasauli units; (3) relative abundance of sedimentary lithic fragments in the Main Dagshai; (4) suture-derived detritus (including spinel) in the Subathu Formation, increasing from about 10% to 15% of the framework in the Subathu Formation sensu stricto (S) to close to 50% in the Red Subathu (RS).

with time. Quartz is locally very abundant in the basal and lower Dagshai stratigraphic units. Cr spinel is extremely common in the Subathu (sensu stricto) and Red Subathu rocks, and is extremely rare in the Dagshai and Kasauli Formations. Garnet is very common in the Kasauli Formation.

Other Factors That Could Affect the Sandstone Petrography. Weathering, recycling, diagenesis, and grain size can all influence sandstone petrography. Himalayan foreland basin sandstones contain a wealth of labile metamorphic lithic fragments (e.g., Cameron and Blatt, 1971; Garzanti et al., 1998, 1999), indicating that detrital modes are not drastically affected by mechanical abrasion, chemical weathering, or diagenesis. Nevertheless, the composition tends to be more quartzose with respect to first-cycle modern sands primarily derived from metamorphic source rocks and deposited in relatively arid settings (Fig. 3). Such excess quartz can be ascribed to recycling of quartzose Indian margin sandstones in the first stages of collision (Eocene to Oligocene), but weathering during prolonged storage in alluvial settings, particularly during the >10 m.y. time span when the Subathu-Dagshai unconformity developed, or even locally higher energy depositional environments, are other possibilities for the basal and lower Dagshai unit (see following).

Diagenesis had a significant impact on the invariably very fine-grained Subathu sandstones, where carbonate replacements are widespread. In the Dagshai to Kasauli units, pressure solution is a common feature and metamorphic grains are deformed and squashed, but pseudomatrix can be safely recognized as slate to phyllite rock fragments; framework grain dissolution with development of secondary porosity is minor. Although in the Dagshai-Kasauli suite grain-size control is effectively minimized by the Gazzi-Dickinson point-counting method, sedimentary rock fragments (i.e., carbonate, terrigenous, and chert grains) are consistently enriched in coarser grained samples (correlation coefficients invariably significant at the 5% confidence level), mainly at the expense of quartz grains.

Mineral Geochemistry

Spinel Geochemistry (Table DR3 [see text footnote 1]). Spinel composition reflects the degree of melting in the mantle source region (Dick and Bullen, 1984). The principal constituents of spinel behave very differently during fractional crystallization or partial melting, with Cr and Mg strongly partitioned into the solid and Al strongly partitioned into the melt. The Cr # (Cr/[Cr + Al]) of spinels reflects the degree of depletion of the mantle source, increasing Cr # reflecting increasing degrees of mantle partial melting.

Dick and Bullen (1984) demonstrated how spinel composition could be used to identify rocks from various tectonic settings subjected to differing degrees of mantle partial melting (Fig. 4A). Spinels from abyssal peridotites and basalts of mid-ocean ridge setting have Cr # <0.6. In contrast, spinels in rocks of arc-related settings, continental layered intrusives and oceanic plateau basalts have Cr # >0.6. Spinels from Alpine-type (ophiolitic) peridotites and associated volcanic rocks display a complete range of spinel values and can be divided into the following: type I ophiolites are those with spinels of the same composition as spinels from mid-ocean ridge rock (Cr # <0.6), and therefore likely represent sections of ocean lithosphere formed in this tectonic setting; type III ophiolites have a spinel composition that has a Cr # of >0.6 and therefore largely falls outside the compositional field of

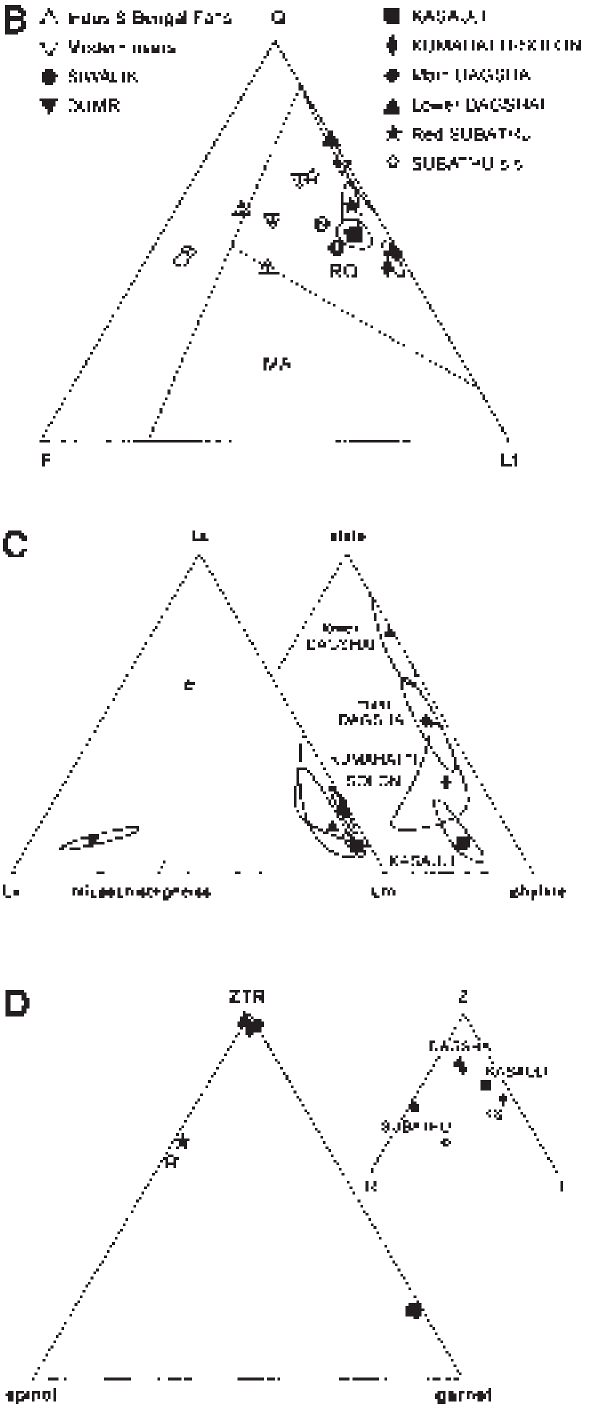


Figure 2. (B) The Indian foreland basin sandstones all plot within the "recycled orogen" (RO) provenance field of Dickinson (1985) (CB—continental block; MA—magmatic arc). Mean with 90% confidence regions, calculated after Weltje (1998), is shown for the Red Subathu, Lower Dagshai, Main Dagshai plus Kumahatti-Solon, and Kasauli Formations). The Lower Dagshai compares well with the Dumri Formation (data are from DeCelles et al., 1998a), with several samples distinctly enriched in quartz (see text). Detrital feldspars increase steadily upward from the Dagshai to the Kasauli, and even further in the Siwalik Group and modern rivers and fans (data are from: 1, Critelli and Ingersoll, 1994; 2, DeCelles et al., 1998b; 3, Ingersoll and Suczek, 1979; 4, Suczek and Ingersoll, 1985), pointing to deepening erosion levels within the core of the growing orogen. Feldspars are relatively high in the Subathu Formation due to both concentration in the very fine sand fraction and recycling of Tethyan sandstones and suture-zone volcaniclastic material. The Q pole includes polycrystalline metamorphic quartz, but not chert. (C) Lithic types in the Indian foreland basin sandstones are mainly sedimentary grains (Ls), probably derived from Tethyan sedimentary rocks, and volcanic grains (Lv), derived from volcaniclastic rocks of the suture zone, for the Subathu Formation (sensu stricto) and Red Subathu rocks, respectively. In contrast, the Dagshai and Kasauli Formations are dominated by metasedimentary detritus (Lm) derived from Indian sedimentary and metasedimentary cover rocks, documenting a steady increase from very low (dominantly slate) to low (dominantly phyllite) metamorphic grade through time. Means with 90% confidence regions (calculated after Weltje, 1998) are provided. (D) The heavy mineral suite in the Subathu Formation is characterized by abundant Cr-spinel derived from Indus suture zone ophiolitic rocks and arc material. Ultrastable heavy minerals recycled from Indian cover sedimentary and metasedimentary rocks dominate the heavy mineral suite in the Dagshai and Kumahatti-Solon units. Garnet derived from Himalayan rocks of low to medium metamorphic grade become abundant in the Kasauli Formation. Ultrastable heavy minerals are mainly rutile (R) in the Subathu Formation, zircon (Z) in the Dagshai Formation, and tourmaline (T) in the Kumahatti-Solon unit and Kasauli Formation.

mid-ocean ridge–type spinels. A subvolcanic arc provenance is inferred for these rocks; type II ophiolitic rocks have spinel compositions that span the full range of compositions of type I and III rocks. Type II peridotites and volcanic rocks are inferred to represent composite origins involving complex multistage melting histories. These may be found in tectonic settings where, for example, a young volcanic arc was constructed on older oceanic crust, or sections across the transition from arc to ocean lithosphere.

Spinels from the Subathu Formation and rarely from the Dagshai Formation have Cr # ranging from 0.2 to 0.8. Spinels of Cr # <0.6 are best assigned to rocks formed from relatively undepleted mantle, i.e., type I mid-ocean ridge–type ophiolites, or rocks associated with less depleted mantle compositions of type II ophiolites. Subathu Formation spinels of Cr # >0.6 fall in the fields described by arc-related rocks, continental intrusive rocks, and ocean plateau basalts. In the tectonic setting of the Himalayan foreland basin, spinel, if derived from the north, is most likely from Himalayan arc material or ophiolites (either type III ophiolites or rocks associated with the less depleted mantle compositions of type II ophiolites). If derived from the south, the continental flood

TABLE 2. RECALCULATED SANDSTONE/SAND POINT-COUNT DATA FOR SELECTED HIMALAYAN UNITS

UNIT	Age	Source	n	Q	F	Lv	Lc	Lp	Lch	Lm	Lo	TOT	P/F	Mica
REMNANT OCEAN BASINS														
Indus Fan	Neogene	S&I85	15	43	30	3	5	5	0	14	0	100.0	66	Yes
Bengal Fan	Neogene	I&S79	22	57	28	1	1	1	0	13	0	100.0	68	Yes
PERISUTURAL BASINS														
NEPAL														
Modern kholas	Holocene	C&I95	4	65	12	0	9	1	0	13	0	100.0	73	11
Modern rivers	Holocene	D&98b	10	55	23	0	8	0	0	13	0	100.0	58	5
Siwaliks	Middle–late Miocene	C&I95	20	65	6	0	4	5	1	18	0	100.0	61	5
Middle–Upper Siwaliks	Late Miocene–Pliocene	D&98b	22	70	17	1	4	1	1	6	0	100.0	47	5
Lower Siwaliks	Middle–late Miocene	D&98b	19	73	11	1	3	1	0	11	0	100.0	85	4
Dumri	Early Miocene	D&98a	27	74	4	1	0	2	1	18	0	100.0	100	1
Bhainskati	Early–middle Eocene	D&98a	1	95	0	0	4	0	1	0	0	100.0	N.D.	0
NORTHERN PAKISTAN														
Siwaliks	Late Miocene	C&I95	66	41	18	1	5	5	5	22	1	100.0	67	5
Murree redbeds	Middle Eocene–early Miocene?	C&G94	7	59	8	9	2	4	8	8	1	100.0	87	0
Upper Balakot Fm.	Early middle Eocene?	C&G94	11	55	7	18	3	3	10	2	1	100.0	97	0
Middle Balakot Fm.	Late early Eocene?	C&G94	2	72	4	4	0	4	2	14	0	100.0	82	0
Lower + Middle Balakot Fm.	Early Eocene?	C&G94	8	63	4	3	1	3	4	22	1	100.0	91	0
NORTHERN INDIA														
Kasauli Fm.	Approx. earliest Miocene	This work	10	52	8	2	0	4	0	35	0	100.0	57	4
Kumahatti-Solon	Approx. Oligocene–Miocene	This work	4	44	4	1	0	9	2	40	0	100.0	63	2
Main Dagshai Fm.	Approx. late Oligocene	This work	11	46	1	1	0	9	2	40	0	100.0	80	0
Basal/Lower Dagshai Fm.	Approx. late Oligocene	This work	7	70	1	1	0	3	1	23	0	100.0	67	0
Red Subathu	Late Paleocene–middle Eocene	This work	3	59	5	25	0	3	1	1	5	100.0	83	0
Subathu Fm. s.s.	Late Paleocene–middle Eocene	This work	2	66	9	6	1	9	3	3	3	100.0	58	4
EPISUTURAL BASINS														
ZANSKAR														
Chulung La green beds	Early Eocene	G86	7	37	22	39	0	1	0	0	1	100.0	95	1
Chulung La redbeds	Early Eocene	G86	11	16	28	55	1	0	0	0	0	100.0	98	0
LADAKH														
Nimu Fm.	Post–early Eocene	G&VH88	4	33	50	18	0	0	0	0	0	100.0	47	4
Nurla Fm.	Early to middle Eocene	G&VH88	8	31	35	30	3	0	0	0	0	100.0	89	1
FOREARC BASINS														
Basgò + Temesgam Fms.	Maast. to early Eocene	G&VH88	12	29	33	28	8	2	0	1	0	100.0	75	3
Nummulitic Series	Early Eocene	G&VH88, L	17	26	36	26	0	1	0	11	0	100.0	0	0
Tar + Sumdha Gompa Fms.	Late Cretaceous to Paleocene	G&VH88	8	17	28	46	8	0	0	1	0	100.0	96	1
Nindam Unit	Late Cretaceous to Paleocene?	G&VH88	5	6	27	59	7	0	0	0	0	100.0	99	1
SLOPE BASINS														
Tar Mélange	Late Cretaceous or Paleocene?	G&VH88	3	45	15	28	0	12	0	0	0	100.0	99	0

Notes: Recalculated sandstone/sand point-count data (Gazzi-Dickinson method) on selected Himalayan clastic wedges. N = number of samples. Data sources: C&I94—Critelli and Ingersoll (1994) and S. Critelli, 1997, personal commun.; D&98a, D&98b—DeCelles et al. (1998a, 1998b) and P. DeCelles, 1999, personal commun.; C&G94—Critelli and Garzanti (1994); G86—Garzanti (1986); G&VH88—Garzanti and Van Haver (1988); L—E. Le Pera, 1993, personal commun. Balakot Formation ages are question-marked because of currently unresolved discrepancy between dating based on biostratigraphy (Bossart and Ottiger, 1989) and dating based on Ar-Ar detrital mica ages (Najman and Pringle, unpublished data). Murree redbed age is question-marked because dating is not firmly based (e.g., Bossart and Ottiger, 1989). Parameters: Q—quartz; F—feldspar; Lv—volcanic lithic fragments; Lc—carbonate lithic fragments; Lp—terrigenous lithic fragments; Lch—chert; Lm—metamorphic lithic fragments; Lo—serpentine-bearing lithic fragments. P/F ratio: p—plagioclase.

basalts of the Deccan Traps are the obvious source. Literature documenting spinel compositions from continental flood basalts are sparse; data from the Deccan Traps are in the field of continental layered intrusive rocks, which may be magma reservoirs for continental flood basalts and could therefore act as a proxy for them. Here we use all available spinel data from the Deccan Traps, including spinels from tholeiitic lavas (Sen, 1986), picritic lavas (Krishnamurthy and Cox, 1977), and lherzolite xenoliths (Mukherjee and Biswas, 1988); and spinel compositions from continental layered intrusions (Dickey, 1975; Cameron, 1979; Dick and Bullen, 1984; Jan and Windley, 1990; Mues-Schumacher et al., 1996).

The Cr # of basic layered intrusion spinels is high, as is the Cr # documented for Deccan Trap spinels (Fig. 4A). A Deccan Trap source can therefore be ruled out for a large number of Himalayan foreland basin detrital spinels, which have low Cr #. Spinel TiO_2 weight percent provides an additional provenance indicator. Titanium becomes enriched in the melt relative to the solid during crystallization or melting. Dickey (1975) noted that continental layered intrusions have spinel compositions with TiO_2 weight percent >0.3. Compositions of spinels from the Deccan Traps lie in this field, distinct from all detrital spinels analyzed from the Subathu and Dagshai Formations (Fig. 4B), rendering a southerly Deccan source highly improbable. This interpretation is supported by the presence of serpentine schist lithic fragments in the Subathu Formation (Table DR2; see text footnote 1) that are derived from ophiolitic material.

It is very likely that arc and ophiolite rocks along the Indus suture zone were the main contributors to the foreland basin detrital spinel population. In the Pakistan Himalaya, mafic-ultramafic bodies at the base of the Kohistan island arc include rocks from the Shangla region (Arif and Jan, 1993), the Sapat mafic-ultramafic complex (Jan et al., 1993), the Jijal Complex (Jan and Windley, 1990), and the Chilas complex (Jan et al., 1992) which together span the range of Cr # and TiO_2 weight percentages displayed by the detrital spinels in the foreland basin. The detrital spinels could potentially have been derived from the Spontang ophiolite, India, which is unrelated to the Kohistan arc, but data are lacking.

Compositions of spinels from the Subathu Formation compare well with those from the Chulung La Formation, which is thought to have been derived from arc and ophiolitic sequences of the Indus suture zone (Garzanti et al., 1987), and with detrital spinels from the Murree Formation of the Pakistan foreland basin (Bossart and Ottiger, 1989) (Fig. 4A).

Garnet Geochemistry (Table DR4 [see text footnote 1]). Garnet zoning patterns can provide insight into the metamorphic history of the host rock. Garnets in medium-grade metamorphic rocks (greenschist and amphibolite grade) typically show growth or normal zoning, which occurs when new shells of different composition are added as the crystal grows. Diffusion is a thermally activated process that becomes exponentially more rapid with increasing temperature. At high grades of metamorphism, chemical diffusivities are sufficiently rapid for garnets to homogenize. During cooling, diffusion zoning, which is a modification of preexisting garnet composition, may affect the garnet rim. Therefore, garnets in medium-grade metamorphic rocks are most likely to display growth zoning affecting the entire grain (the typical bell-shaped profile). In contrast, garnets subjected to high temperatures typically have flat unzoned profiles in their interior, possibly with some diffusion zoning at the rim (Dietworst, 1982; Tracy, 1982; Spear, 1993).

Fragments of detrital garnet first become common in the Kasauli Formation. Electron microprobe analyses were carried out in traverses across the grains, which are of almandine composition. Zoning profiles were found to be of limited use due to the fragmental nature of the garnets. However, compositions of the garnets plotted on Mn-Fe-Mg and Ca-Fe-Mg triangular diagrams (Fig. 5, A and B) clearly show the presence of substantial zoning, from which we conclude that these garnets were most likely derived from metamorphic material subjected to medium (to amphibolite facies) rather than high-grade metamorphism.

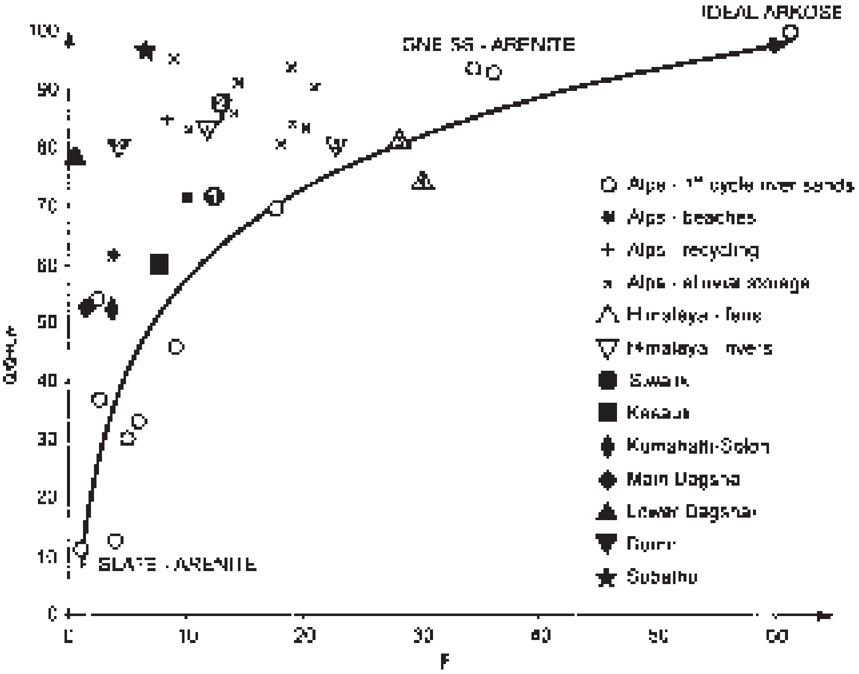


Figure 3. First-cycle alpine metamorphic-clastic detritus in modern Mediterranean settings is characterized by Q/Q + Lm ratios increasing from as low as 12% for the ideal "slate arenite" to 93%–94% for the ideal "gneiss arenite," reaching 100% for the "ideal arkose" (open circles; data from Garzanti et al., 1998, 1999; Critelli and Le Pera, 2000). This ideal logarithmic trend (arrow) is theoretically produced by deepening erosion levels within a thick-skinned, Alpine-type orogen growing during shallow subduction of continental crust (e.g., Doglioni, 1992). Excess quartz in real foreland basin sequences points to recycling, weathering during alluvial storage, destruction of nondurable grains in high-energy beach environments, or postdepositional dissolution. Apart from highly quartzose composition of Subathu to lower Dagshai and Dumri sandstones, which can be ascribed to recycling of Indian margin quartzose arenites and /or prolonged duration of weathering, the upper Dagshai -> Kasauli -> Siwalik -> modern rivers and/or fans suite (data from 1—Critelli and Ingersoll, 1994; 2—DeCelles et al., 1998b; 3—Ingersoll and Suczek, 1979; 4—Suczek and Ingersoll, 1985) compares with the ideal evolution for first-cycle detritus, indicating that detrital modes chiefly reflect provenance. Excess quartz in the Siwalik and modern rivers of Nepal and abundance of feldspars in the Bengal and Indus fans is at least in part ascribed to humid monsoonal climate and additional supply from the Trans-Himalayan batholiths, respectively.

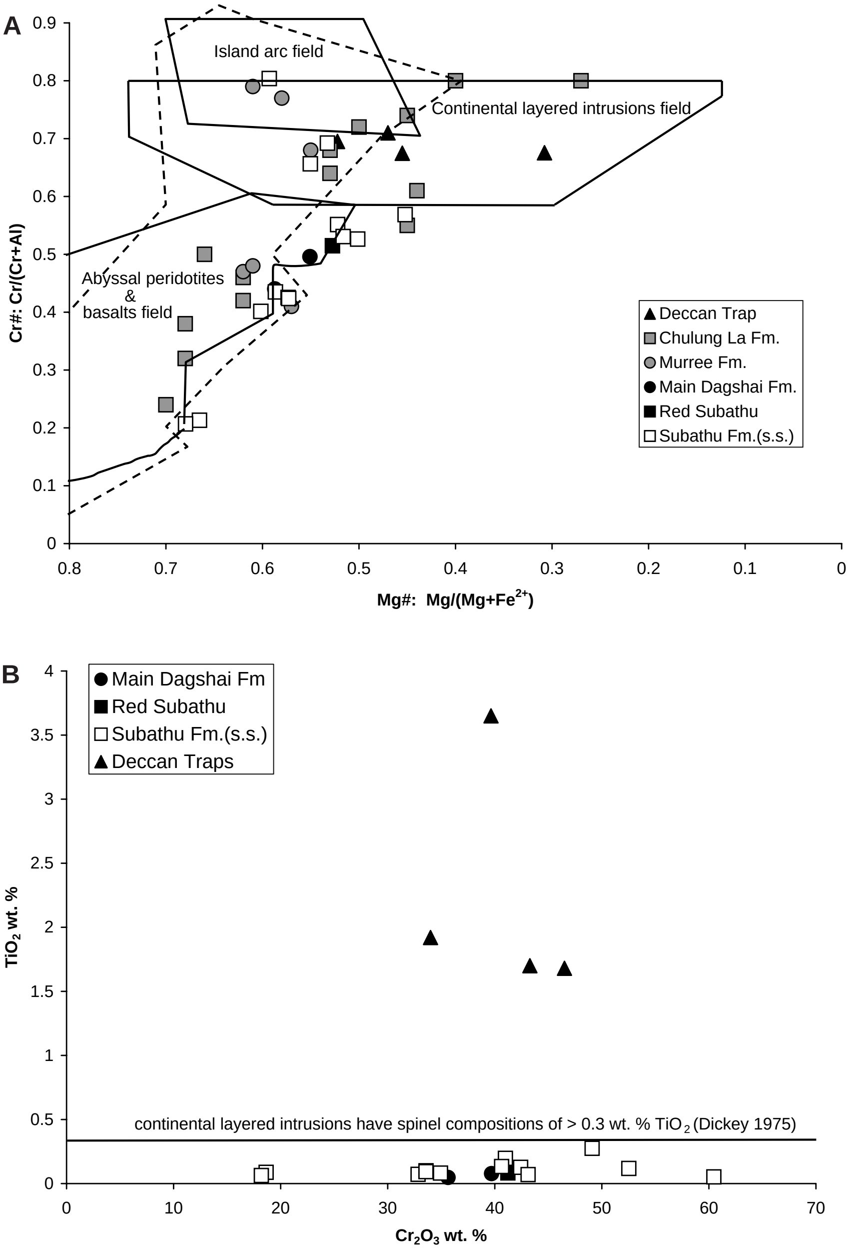
Mudstone Geochemistry (Table DR5 [see text footnote 1])

The geochemical composition of clastic sediments is often dominantly influenced by source-rock composition and therefore has often been successfully used as an indication of provenance (Wronkiewicz and Condie, 1987; Cullers et al., 1988). It is especially useful to add accuracy to detrital modal analyses, where less resistant grains may have been preferentially broken down into matrix. In this study, X-ray fluorescence analyses were used to determine the chrome and nickel concentrations of foreland basin mudstones. Nickel and chrome substitute for Mg and Fe in the early (mafic) phases of fractional crystallization; nickel is primarily found in olivine and chrome in spinel and, to a lesser extent, diopside and augite. Thus, chrome and nickel concentrations are good indicators of mafic provenance, of which there is often scant evidence in petrographic studies due to preferential breakdown of mafic nesosilicates and inosilicates.

Generally, fine-grained sediments preserve a source signature most accurately, being better mixed and more homogenous than coarser grained fractions (Wronkiewicz and Condie, 1987; Cullers et al., 1988). Our initial study confirmed that major and trace element compositions of sandstones from the Indian foreland basin were found to be variable and trends were weaker than for the corresponding mudstones; hence the mudstone samples were used in the current study. Chrome and nickel, which are found in the alumino-silicate phase, are plotted against aluminum concentration, which is negligible in carbonate, in order to compensate for carbonate dilution (Fig. 6, A and B).

In interpreting geochemical signatures in terms of provenance, due regard should be paid to other potentially influencing factors, for example weathering, diagenesis, and metamorphism (Wronkiewicz and Condie, 1987; Condie and Wronkiewicz, 1990; McLennan and Taylor, 1991). Chrome and nickel are considered to be immobile during the processes of metamorphism and hydrothermal activity (Condie and Wronkiewicz, 1990; Rollinson, 1993). Chrome is susceptible to the effects of weathering and sedimentation, but Condie and Wronkiewicz (1990) demonstrated its successful use as an indicator of provenance. The effect of adsorption of metals from seawater onto clay minerals has not been fully evaluated and therefore some of the variation between marine Subathu Formation values and continental Dagshai and Kasauli Formation values could potentially be explained by facies variation. However, a study of muds from the Amazon River delta does not show significant

Figure 4. Spinel chemistry as a provenance indicator. (A) Cr # vs. Mg #, calculated from molecular proportion data analyzed by electron microprobe (Table DR3; see text footnote 1). The fields of Dick and Bullen (1984) show distinct regions for mid-ocean ridge–type abyssal peridotites and basalts, continental layered intrusions, and arc spinels. Ophiolitic spinels (dashed line field) span the entire range of Cr #. Ophiolites with spinels of Cr # <0.6 likely represent sections of ocean lithosphere formed in a mid-ocean ridge setting (type I ophiolites), ophiolites with spinels of Cr # >0.6 represent ocean lithosphere formed in a subvolcanic arc setting (type III ophiolite), and ophiolites with spinel Cr # that span the entire composition of types I and III are interpreted as representing composite origins (type II ophiolites). Subathu Formation spinel composition is consistent with derivation from type I, II, and III ophiolites and many of the grain compositions are inconsistent with derivation from a southern Deccan Trap source. Comparative data from the Murree Formation, Pakistan foreland basin, is after Bossart and Ottiger (1989); data from the Trans-Himalayan sourced Chulung La Formation is after Critelli and Garzanti (1994), analyzed by K. Honegger. Data from the Deccan Traps are from Krishnamurthy and Cox, 1977; Sen, 1986; Mukherjee and Biswas, 1988. (B) Electron microprobe data of spinel TiO_2 vs. Cr_2O_3 weight percent (Table DR3; see text footnote 1). Continental layered intrusions invariably have high TiO_2, as have the spinels from the Deccan Trap. (TiO_2 weight percent of ophiolitic spinels is often, but not invariably, low.) Subathu and Dagshai Formation detrital spinels are uniformly low, making a southern Deccan Trap source highly improbable.



major or trace element variation as a function of distance seaward of the river mouth (Kronberg et al., 1986; Wronkiewicz and Condie, 1987).

Both nickel and chrome show a clear change in source between the times of deposition of the Subathu and Dagshai Formations. The higher nickel and chrome content in the Subathu Formation compared to the Dagshai and Kasauli Formations confirm that the mafic to ultramafic input to the basin during Subathu Formation time was reduced or greatly diluted by Dagshai Formation deposition. The Dagshai and Kasauli Formations were fed by a crustal source, comparable to that of the North Atlantic Shale Composite, which is an average for post-Archean shales taken to be representative of the upper continental crust (Gromet et al. 1984).

Summary of Results

Modal analysis shows that the sandstones from the Subathu Formation were derived from a mixture of sedimentary, volcanic, and ophiolitic rocks, the sedimentary component dominating. The relative abundance of quartz, detrital feldspar, shale fragments, and rounded ultrastable heavy minerals suggests recycling of terrigenous sequences. The presence of felsitic volcanic rock fragments, chert, serpentine schist grains, and high-Al to high-Cr chromian spinel indicates significant contributions from volcaniclastic rocks and ophiolites. High chrome and nickel concentrations in Subathu Formation mudstones confirm the presence of a mafic-ultramafic source. The abundance of volcanic rock fragments, chrome spinels, and serpentine schist grains documents a peak in volcanic and ophiolitic detritus in the Red Subathu stratigraphic unit. Both rock fragment types and Cr spinel composition attest to a northern ophiolitic source and do not favor any contribution from the Deccan Traps.

The drastic change in detrital mineralogy and mudstone geochemistry at the boundary between the Subathu Formation and the Dagshai

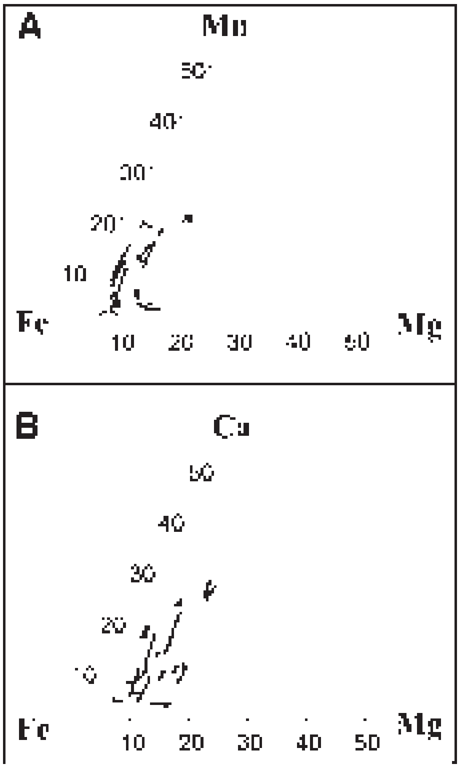


Figure 5. (A and B) Geochemistry of 15 garnets from the Kasauli Formation, clearly showing the presence of growth zoning indicative of a source region affected by low- to medium-grade metamorphism. Each line represents a traverse across an individual garnet; cores and rims are not indicated due to the fragmental nature of the grains. Data are calculated from electron microprobe molecular proportion data (Table DR4; see text footnote 1).

Formation reflects a radical change in provenance. Detrital modes show that the Dagshai Formation was dominantly derived from very low grade metamorphic material, with predominant metapelitic lithic grains, a significant component of sedimentary material, and rare volcanic and ophiolitic detritus, which rapidly becomes negligible in the main Dagshai Formation. This is also reflected in the drastic decrease in Cr-spinel and chrome and nickel concentrations in mudstones from the Subathu to the Dagshai Formation. In the basal and lower part of the Dagshai Formation, quartz is locally very abundant and slate grains dominate, whereas in the main Dagshai Formation, the metamorphic grade of lithic grains increases distinctly. The Kumahatti-Solon sandstones, which sedimentologically resemble the Kasauli Formation, lack garnet and are petrographically very similar to the main Dagshai Formation samples.

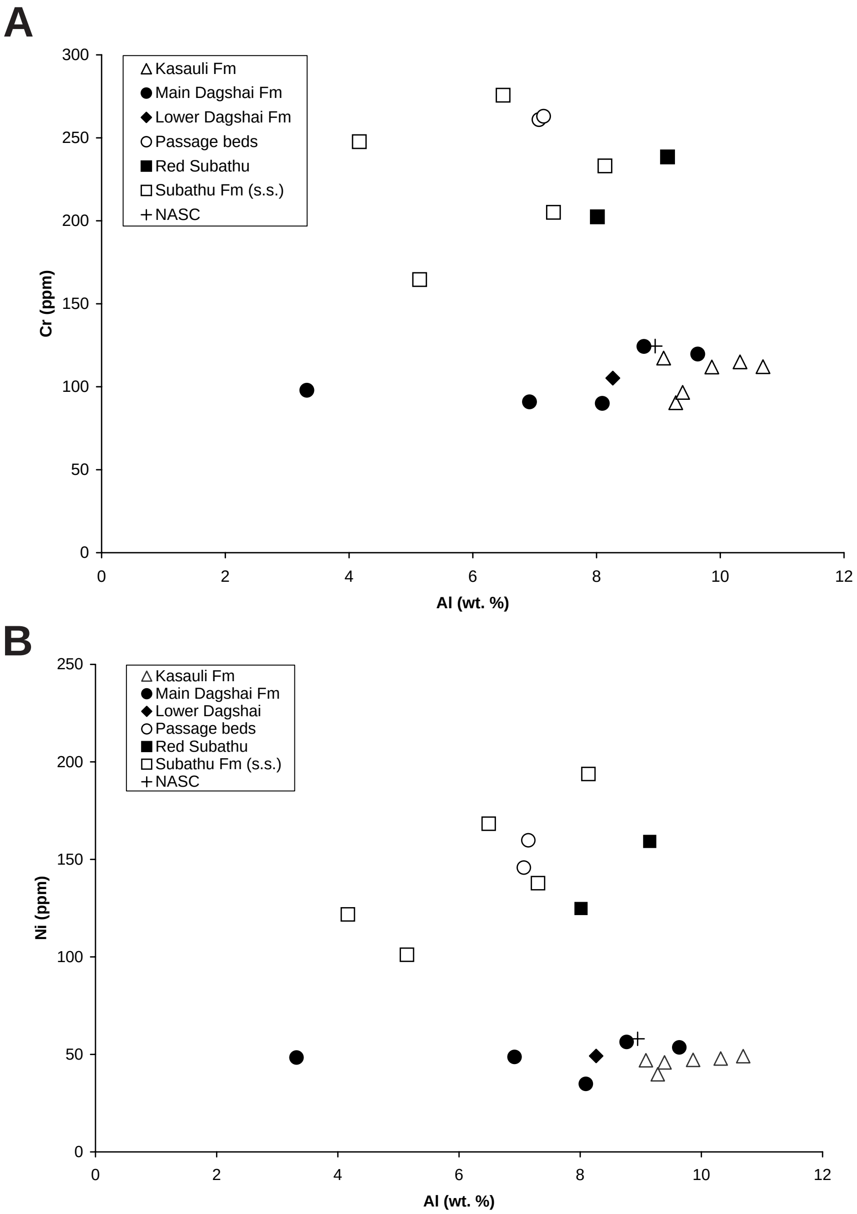


Figure 6. (A and B) X-ray fluorescence analyses of Himalayan foreland basin mudstones (Table DR5; see text footnote 1). Nickel and chrome, plotted against aluminum to correct for the effects of carbonate dilution, record mafic influence. Thus, the data indicate a higher mafic input into the Subathu Formation compared to Dagshai and Kasauli Formations. Comparison with North American Shale Composite (NASC; Gromet et al., 1984), taken as an average of upper continental crust, shows the Subathu Formation to have a higher mafic input than average. The Passage beds (Mathur, 1979) are the rocks found at the Subathu-Dagshai Formation contact, in this case, variegated mudstones.

The Kasauli Formation is dominated by low-grade metamorphic detritus. A further distinct increase with respect to the underlying Dagshai Formation is clearly documented by predominant phyllite and quartz-mica grains and abundance of garnets. Geochemical data suggest that these garnets were derived from rocks of medium metamorphic grade. Very sparse Cr-spinel indicates extremely minor mafic-ultramafic input, which is also inferred from mudstone geochemistry.

DISCUSSION

All of the studied samples from the Subathu, Dagshai, and Kasauli Formations are quartzose-lithic sandstones plotting in the “Recycled orogen” provenance field of Dickinson (1985) (Fig. 2B). Nevertheless, major petrographic changes are observed in the foreland basin succession, documenting the stepwise structural evolution of the proto-Himalayan orogen.

Syncollisional Stage (Subathu Formation)

The terrigenous rocks in the Subathu Formation were derived from a mixed source terrane in the proto-Himalaya suture belt, which included sedimentary and volcanic arc to ultramafic rocks of the Indus suture zone. A southern (Deccan Trap) influence is ruled out on the basis of overall framework and spinel composition.

The sedimentary component source is equivocal. If it was derived from the north it could have been eroded from the carbonate-terrigenous Tethys Himalayan sedimentary successions (e.g., Gaetani and Garzanti, 1991); in this case scarcity of carbonate grains in the Subathu Formation sandstones would be explained mostly by dissolution in subhumid climates. A southern source from the Indian craton or peripheral forebulge is also possible. Our preferred interpretation is of derivation mainly from the north: a northern source is documented for the igneous component and it would be possible for the adjacent sedimentary rocks of the Tibetan Sedimentary Series to contribute material.

Felsite, which is indicative of arc provenance, and ophiolitic detritus increase in the Red Subathu Formation sedimentary rocks, suggesting continuing thrusting of Trans-Himalayan rocks and final emplacement of oceanic allochthons such as the Spontang ophiolite (Garzanti and Brignoli, 1989; Searle et al., 1997).

In summary, the evidence of a northern Himalayan contribution, and the contrast in composition between the Subathu Formation sedimentary rocks and those of the Amile, Cherra, and Kopili Formations, interpreted as sediments deposited on the Indian passive margin (DeCelles et al., 1998; Uddin and Lundberg, 1998), provide clear evidence that the Subathu Formation sediments were syncollisional, and development of the Himalayan fold-thrust belt and foreland basin was under way by that time. This is in contrast to the previously widely held belief that the Subathu Formation sediments are of passive margin facies, but partly in agreement with that of DeCelles et al. (1998a), who envisioned a backbulge environment for the age and facies equivalent Bhainskati Formation of Nepal.

Early Collisional Stage (Dagshai Formation, Including the Kumahatti-Solon Unit)

A major change in provenance occurred at the base of the Dagshai Formation, when the dominant lithic fragment composition changed from sedimentary to metamorphic, while volcanic and ophiolitic detritus was strongly reduced. The predominantly northern source (as evidenced by paleocurrent directions) was the proto-Himalayan thrust belt. These southward-migrating thrust sheets, north of the Indian foreland basin, acted as a locally incomplete barrier between the suture zone and the foreland basin, thereby drastically reducing the proportion of suture- and arc-derived material reaching the basin.

The great and irregular abundance of detrital quartz in the basal part of the unit may be due to source or facies influence. Extremely scarce northeast-directed paleocurrents (with significant scatter) may suggest southerly derived detritus from the peripheral bulge, uplifted as a flexural response to active thrusting in the proto-Himalayan belt. Recycling of Indian passive margin quartzarenites in the north is another possibility. Potential facies influence includes a high-energy beach environment, which is unlikely because beach-type sedimentary structures are lacking; alternatively, excess quartz may be due to weathering of detritus stored in alluvial plains, as documented in the Andean foreland basin fluvial sediments (Johnsson et al., 1988). An attractive hypothesis is that prolonged weathering took place during the >10 m.y. time gap between deposition of the upper Subathu (middle Eocene) and basal Dagshai (younger than 30 Ma) Formations, during which time intense tropical weathering and laterite formation caused breakdown of labile grains and feldspars, which altered to kaolinite. The presence of distinctive hematite-cemented quartzarenite grains and ferricrete fragments, particularly within the basal and lower Dagshai Formation sandstones, supports this hypothesis.

The very low to low-grade metasedimentary nature of detritus, along with evidence from Sm-Nd whole-rock analyses of the Dagshai Formation suggesting Greater Himalayan affinity (Najman et al., 1998), and the presence of detrital micas of Himalayan age (Najman et al., 1997) suggest that the proto High-Himalayan thrust stack began to be unroofed at this stage. Progressive increase in metamorphic grade of lithic grains upsection (from dominantly very low grade in the lower and basal Dagshai Formation to dominantly low grade in the Kumahatti-Solon Unit) indicates unroofing of deeper levels of the metamorphic pile, either by gradual erosion or more likely by successive thrusting of progressively deeper levels. Thus, subsequent to the Eocene–late Oligocene M1 stage of Barrovian metamorphism, Himalayan metamorphic rocks were first unroofed near the beginning of Neogene time.

The subsidiary sedimentary source (Fig. 2A) was represented by sedimentary successions of unknown age deposited on the northern margin of the Indian continent. Scarcity of carbonate grains is again ascribed to dissolution. This sedimentary source provided different and more varied detritus (including several types of terrigenous and chert grains) compared to that of the Subathu Formation (largely recycled quartz and feldspars along with pelitic to a few carbonate grains interpreted as possibly derived from the Tibetan Sedimentary Series). Abundance of chert, including distinctive black and phosphatic varieties, is noteworthy. Chert is negligible in the Tibetan Sedimentary Series and is unlikely to have been totally derived from the Indus suture zone because (1) this input was very sporadic by this time and (2) black and phosphatic chert has not been found associated with the suture-derived clastic material. Cherty to phosphatic intervals are found today in the Lesser Himalayan Tal Formation (Banerjee et al., 1997), and cherty to phosphatic detritus may well have been derived from early thrusted, far distal equivalents of Lesser Himalayan sedimentary rocks exposed today. We thus favor provenance from thick pelitic successions possibly of Proterozoic or Early Cambrian age, which are typical of the northern Indian margin and are now widely exposed at several structural positions, both north and south of the High Himalayan Crystallines (e.g., Hayden, 1904; Valdiya, 1970; Brookfield, 1993). The alternative, a southern sedimentary source, is considered very unlikely in view of both overall composition (e.g., common chert grains) and paleocurrent data.

Later Collisional Stage (Kasauli Formation)

The increase in metamorphic grade of lithic fragments continues into the Kasauli Formation, accompanied by a sudden influx of garnet. In our view, such an abrupt unroofing of deeper levels of the collided orogen affected by Barrovian metamorphism cannot be explained by a gradual process such as erosion. Rapid tectonic exhumation of Himalayan metamorphic rocks is the likely effect of thrust tectonics in the source area. It may correspond to the major turning point in the evolution of the Himalayan belt, marked by initiation of movement along the Main Central thrust, which was active at 24–21 Ma and approximately coincident with normal faulting and tectonic exhumation along the South Tibetan detachment system. High-temperature M2 metamorphism and production of leucogranitic melts at the top of the Greater Himalaya also occurred around this time (Le Fort, 1989; Hubbard and Harrison, 1989; Hodges et al., 1992; Harrison et al., 1995). The Dagshai-Kasauli transition, dated as very close to the Oligocene-Miocene boundary (Najman et al., 1997), may be the response of sedimentary systems to the initiation of this major tectonic episode.

The Dagshai and Kasauli Formation clastic rocks thus record the first stages of stepwise tectonic unroofing of the Himalayan metamorphic nappe pile, prior to deposition of the Siwalik Molasse. Composition of the Kasauli sandstones approaches, but is distinct from, that of the Siwalik Group, characterized by a further increase in detrital feldspars (Fig. 2B; Hisatomi, 1990; Critelli and Ingersoll, 1994; DeCelles et al., 1998b) and by a distinctly higher grade suite of metamorphic heavy minerals derived from unroofing of the medium- to high-grade rocks of the Greater Himalaya (Chaudhri, 1972; Parkash et al., 1980).

Comparison with Coeval Himalayan Basin Sediments

To reconstruct early evolution of the Himalayan suture belt, composition of the Subathu-Dagshai-Kasauli suite is compared with coeval terrigenous units deposited along strike, from Pakistan to Nepal (Table 2) and as far east as Bangladesh.

During most of Paleocene time, prior to initial India-Asia collision, nearly pure quartzarenites were deposited in humid equatorial climates on the Indian continental margin, from Pakistan (e.g., Hangu Formation of the Potwar Plateau; basal part of the Patala Formation; Shah, 1977; Bossart and Ottiger, 1989) to the Nepal Lesser Himalaya (e.g., Amile Formation; Sakai, 1989; DeCelles et al., 1998a) and to the Tethys Himalaya sedimentary zone in the north (e.g., Stumpata Quartzarenite to Dibling Formation; Garzanti et al., 1987). On the active Asian margin of the Neotethys, arc-derived volcaniclastic sediments were deposited in a forearc basin after late Albian time (Garzanti and Van Haver, 1988).

Onset of the continental collision and initial subsidence of the Himalayan foreland basin is documented by a drastic compositional change close to the Paleocene-Eocene boundary (Garzanti et al., 1996, their Fig. 4). Detritus derived from the suture zone in the north, including felsitic to microlitic volcanic lithic fragments, chromian spinels, serpentine schist grains, and sporadic extrabasinal planktonic foraminifera, is found in collisional basins from the Tethys Himalaya (Chulung La Formation; Garzanti et al., 1987) to the foreland basin of northern Pakistan (Balakot Formation; Bossart and Ottiger, 1989; Critelli and Garzanti, 1994) and India (Subathu Formation).

However, there are major compositional differences between these earliest collisional clastic units. The Chulung La piggyback basin feldspatholithic sandstones, deposited on top of the Tethys Himalaya passive margin succession, resemble more closely the coeval Gonmaru La, Nurla, and Nimu Formations accumulated on the active margin between the extinct arc and the suture (Garzanti and Van Haver, 1988), than the Subathu Formation (Table 2). Closer similarities are found between the Indian foreland basin sediments and the Balakot and Murree Formations of the Pakistan foreland basin in the Hazara-Kashmir syntaxis region. The Pakistan sequence is reported to consist of early to middle Eocene deltaic red beds of the Balakot Formation (Bossart and Ottiger, 1989), while the Murree Formation continental red beds are undated but may represent deposition during later Eocene and Oligocene time in this region (Bossart and Ottiger, 1989).

Sandstone composition in the Subathu to lower Dagshai succession is overall similar to the Balakot and Murree Formations of northern Pakistan (Critelli and Garzanti, 1994). However compositional time trends differ markedly. Low-grade metamorphic (phyllite) grains are abundant at the base of the Balakot Formation and decrease upward, where supply from the suture zone tends to increase. The opposite is recorded in India, where metamorphic detritus appears only in the Dagshai Formation (Table 2).

There is neither unique nor obvious explanation for this major along-strike variation. Earlier appearance of metamorphic detritus in the Pakistan foreland basin might be due to earlier and/or more intense collision in the northwest (e.g., Beck et al., 1995), and consequently earlier and/or deeper thrusting of the Indian margin sedimentary cover. If this is correct, uplift of a partial topographic barrier between the suture zone and the foreland basin took place as early as earliest Eocene time. However, preliminary Ar/Ar data on detrital white micas from the Balakot Formation (Najman and Pringle, unpublished data) are considerably younger than biostratigraphic ages deduced from Nummulite assemblages collected at several stratigraphic intervals of the same unit by Bossart and Ottiger (1989). If this discrepancy is confirmed, previous structural interpretations of the Hazara syntaxis and stratigraphic ages assigned to the Balakot Formation would need revision.

The younger rocks of the Pakistan foreland basin are the Murree Formation sedimentary rocks in the more southerly location of the Kohat-Potwar Plateau; they are not well dated, but are believed to be late Oligocene–early Miocene in age (Ahmed and Friend, 1989). The Murree Formation is overlain by the Kamlial Formation, dated as 18–14 Ma (Johnson et al., 1985). The latter is overlain by the Siwalik Group of middle Miocene to Pleistocene age (14 Ma to Holocene; Johnson et al., 1985). Oligocene-Miocene sandstones of the Indian foreland basin (Main Dagshai to Kasauli units) are much richer in low-grade metasedimentary rock fragments and poorer in feldspars with respect to the age-equivalent Murree and Kamlial Formations of the Kohat district, which contain sedimentary and low-grade metamorphic detritus, including abundant garnets derived from Indian plate metasedimentary rocks uplifted in the north (Ahmed and Friend, 1989).

To the east, the early foreland basin sediments show significant variation when compared to the Indian and Pakistan rocks. In Nepal, probably as a result of significantly diachronous collision, composition is still highly quartzose in the early to middle Eocene Bhainskati Formation, whereas the unconformably overlying Dumri Formation compares well with the lower Dagshai Formation, only with less variance of quartz content (DeCelles et al., 1998a; Table 2).

Farther to the east in the Bengal-Sylhet basin, diachroneity of collision may explain the continued deposition of quartzose continental block sandstones with scarce feldspars and few lithic fragments throughout Eocene and Oligocene time (e.g., Cherra, Kopili, and Barail Formations). Initial unroofing of the metamorphic Himalayan nappe pile did not begin until deposition of the Surma Group in early to middle Miocene time (Uddin and Lundberg, 1998). Continuing Himalayan unroofing, along with progressive growth of the Indo-Burman Ranges and southward thrusting of the Shillong Plateau, is then documented in the Bengal basin and fan until the present (e.g., Copeland and Harrison, 1990; Johnson and Alam, 1991).

The progressive enrichment in feldspars through time (with gradual decrease of the P/F ratio; Garzanti et al., 1996, their Fig. 2; Uddin and Lundberg, 1998, their Fig. 7) is common to all Himalayan foreland basin clastic suites, from Pakistan to Bangladesh, reflecting progressive deepening of erosion into deeper seated granitoid crustal rocks at the core of the Himalayan thrust stack.

SYNTHESIS

The composition of the sedimentary rocks from the Himalayan foreland basin can be considered a standard reference for clastic suites deposited in foreland basins and derived from a thick-skinned collisional belt associated with intracontinental subduction. The terrigenous units of the Subathu, Dagshai, and Kasauli Formations, consisting of typical recycled orogenic quartzose-lithic sandstones (Fig. 2B; Dickinson, 1985), record the early stages of Himalayan orogeny and provide the link between the first stages of collision and the later Neogene events.

The occurrence of detritus derived from the proto-Himalaya suture belt in the Subathu Formation indicates that the foreland basin was developed by early Eocene time. The variation in petrography between the Subathu Formation and the quartzose and spinel-free Bhainskati Formation in Nepal is best explained by diachronous collision. The petrography of the Dagshai Formation, and of the Dumri Formation of Nepal and the Balakot Formation of Pakistan, indicates that the thrust belt had become a significant topographic barrier by the start of Neogene time, when metamorphic rocks of Greater Himalayan affinity started to be unroofed. The drastic change in petrography at the Subathu-Dagshai boundary, which is separated by an unconformity spanning at least late Eocene to early Oligocene time, may reflect the change from low strength collision (when thinned Indian continental margin crust was subducting) to high strength collision (when unstretched Indian continental crust of normal thickness entered the subduction zone; Guillot et al., 1997). The significant increase of metamorphic grade in the Kasauli Formation source rocks suggests the beginning of rapid tectonic exhumation in early Miocene time, likely the result of movement along the Main Central thrust, which was active at this time. Subsequently, the foreland basin sediments of the Siwalik Group record erosion from progressively deeper seated metamorphic rocks at the core of the growing orogen.

Evolution of detrital modes following initial India-Asia collision has similarities with that recorded by Pliocene-Pleistocene sandstones in Taiwan, which testify to unroofing of an accretionary prism in the very first stages of arc-continent collision (Dorsey, 1988). The Taiwan sandstones first document early collisional recycling of unlithified quartz-rich sediments from the highest part of the accretionary prism, shortly followed by erosion of very low (slate) to low-grade (phyllite) metapelites during progressive uplift of the newly formed fold-thrust belt. Such evolution in Taiwan, however, required a time period an order of magnitude less than for the Himalaya, where there is a >25 m.y. time gap between collision onset and initial unroofing of metamorphic rocks as recorded in the foreland basin. A significant part of this time period is condensed in the Subathu-Dagshai unconformity, a major feature of the Himalayan foreland basin that may be related to choking of the continental subduction zone due to arrival of thicker Indian continental crust, or movement of a peripheral forebulge, either toward (e.g., Beaumont, 1981; Beaumont et al., 1988) or away from (DeCelles et al., 1998a) the orogen. The corresponding missing sediments were probably deposited in the Katawaz remnant ocean basin to the west, which represents an Eocene-Oligocene analogue of the Neogene to Holocene Indus delta and turbidite fan siliciclastic system (Qayyum et al., 1997).

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