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A reinterpretation of the Balakot Formation: Implications for the tectonics of the NW Himalaya, Pakistan

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[1] The Balakot Formation of the Himalayan foreland basin in Pakistan was originally described as a >8 km thick clastic red bed succession within which are stratigraphically intercalated four gray marl bands containing fossils dated at 55–50 Ma. On this basis, and the reported conformable contact with the underlying Paleocene Patala Formation, the Balakot Formation red beds were interpreted as tidal facies dated at 55–50 Ma, by >20 Myr the oldest foreland basin sediments eroded from the metamorphic orogen. However, our new detailed structural mapping shows the Balakot Formation to be in tectonic contact with the underlying Patala Formation, and the marl bands to be structurally intercalated with the red beds. Hence neither the nature of the Balakot Formation lower contact nor the intercalated marl bands can be used to date the red beds. Our Ar/Ar dating of 257 individual detrital white micas from the Balakot Formation red bed sandstones shows that the red bed succession must be younger than 37 Ma, and we thus conclude that the first exposed foreland basin continental sediments eroded from the metamorphic mountain belt were deposited after 37 Ma, at least 15 Myr later than previously believed. These new structural, stratigraphic, and isotopic data from the Balakot Formation provide new constraints to the early tectonic evolution of the mountain belt, result in reassessment of the facies and provenance of the Balakot Formation, and force reconsideration of models of orogenesis, basin evolution, and the timing and diachroneity of India-Asia collision that are based on the original documentation of the Balakot Formation. *INDEX TERMS:* 1040 Geochemistry: Isotopic composition/chemistry; 8099 Structural Geology: General or miscellaneous; 8102 Tectonophysics: Continental contractional orogenic belts; 9320 Information Related to Geographic Region: Asia; *KEYWORDS:* Himalaya, Pakistan, Balakot Formation, Murree Formation, foreland basin, orogenesis. **Citation:** Najman, Y., M. Pringle, L. Godin, and G. Oliver, A reinterpretation of the Balakot Formation: Implications for the tectonics of the NW Himalaya, Pakistan, *Tectonics*, *21*(5), 1045, doi:10.1029/2001TC001337, 2002.

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1. Introduction

[2] Material eroded from mountain belts and preserved in foreland basins can provide a record of the orogen's evolution through time. Study of these sediments therefore provides a complementary approach to traditional methods that focus on the rocks of the mountain belt itself but which can often only provide a snapshot in time, with earlier information often overprinted by later metamorphism or removed by tectonism or erosion.

[3] The Balakot Formation foreland basin sediments, located in the Hazara-Kashmir Syntaxis in N. Pakistan (Figure 1) consist of a more than 8 km thick sandstone, mudstone, and caliche red bed succession of mixed metamorphic and igneous provenance [*Critelli and Garzanti*, 1994]. *Bossart and Ottiger* [1989] dated these sediments at 55–50 Ma. Thus the Balakot Formation was determined to be the oldest Himalayan foreland basin sediments eroded from the metamorphic mountain belt, and influenced models on the timing and diachroneity of collision [*Rowley*, 1996, 1998; *Uddin and Lundberg*, 1998], timing and mechanisms of exhumation [*Treloar et al.*, 1991; *Treloar*, 1999], the palaeogeography and palaeotectonics of the mountain belt [*Critelli and Garzanti*, 1994; *Pivnik and Wells*, 1996], and foreland basin dynamics and sedimentology [*Burbank et al.*, 1996].

[4] In this paper, we provide new data that show the Balakot Formation red beds to be younger than 37 Ma, and we put forward new interpretations on the provenance and facies of the sediments. We consider the implications for Himalayan evolution in Pakistan in the light of these findings.

2. Geological Background of the Himalaya

2.1. Rock Units of the Pakistan Himalaya

[5] In northern Pakistan the orogen is composed of three main tectonostratigraphic terranes (see *Chamberlain and Zeitler* [1996] and references therein for a comprehensive review) (Figure 1): the Asian plate to the north, the Indian plate to the south, and the Kohistan island arc sandwiched

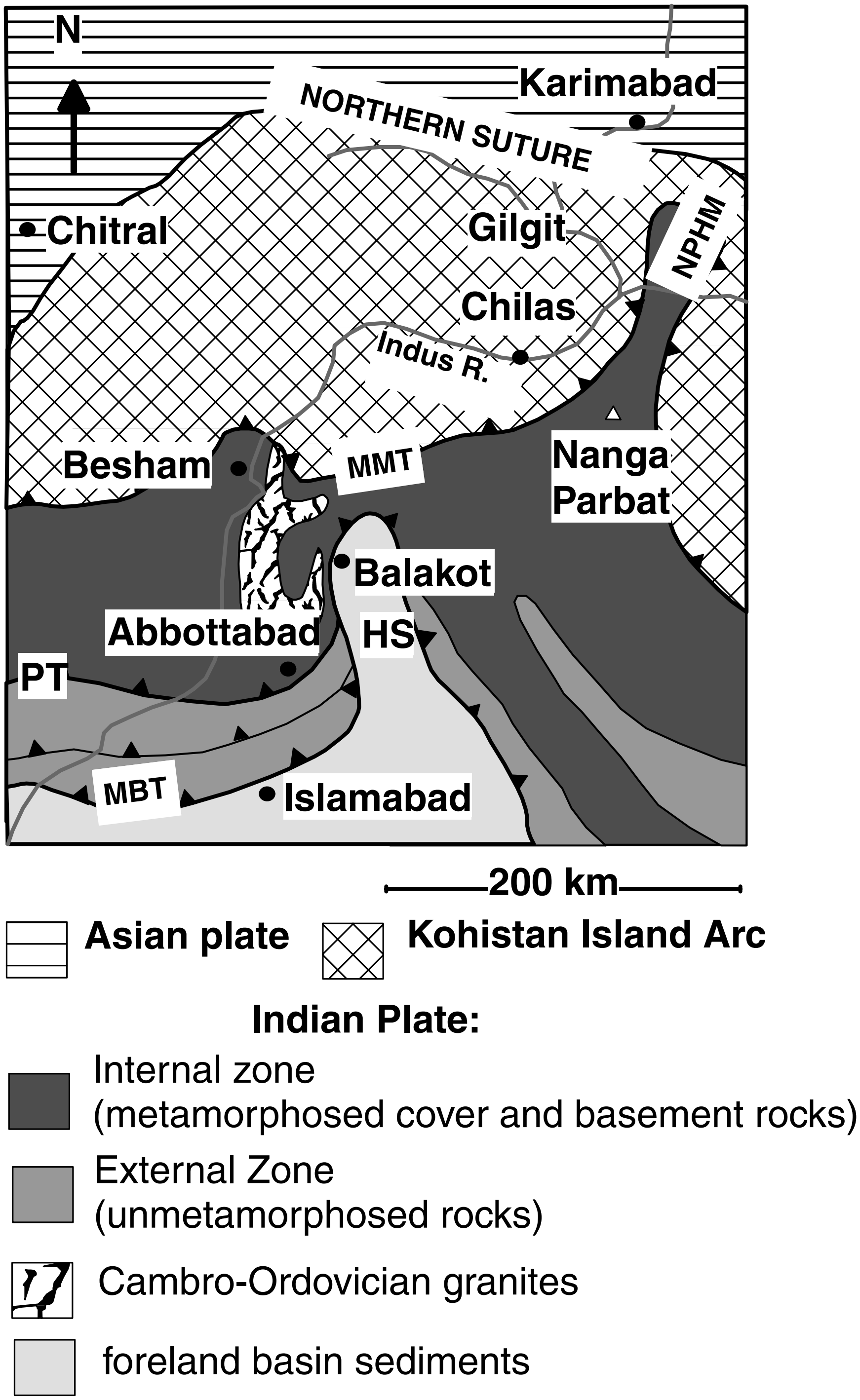


Figure 1. Regional geological map of the Pakistan Himalaya showing the location of the Hazara-Kashmir Syntaxis where the Balakot Formation sediments are exposed. For location of the Hazara-Kashmir syntaxis in its wider Himalayan context, this region corresponds to the area marked as location 2 on Figure 2. Abbreviations are as follows: MMT, Main Mantle Thrust; PT, Panjal Thrust; MBT, Main Boundary Thrust; NPHM, Nanga Parbat-Haramosh Massif; HS, Hazara-Kashmir Syntaxis.

between. The Kohistan arc is separated from the Asian plate by the Northern or Shyok Suture, and from the Indian plate by the Main Mantle Thrust (MMT). The Asian plate Karakoram can be divided into the Northern Sedimentary terrane of Palaeozoic and Mesozoic Formations, the Karakoram Batholith of Cretaceous to Miocene age, and the Southern Metamorphic Complex consisting of rocks subjected to precollisional and postcollisional metamorphism prior to 37 Ma [e.g., *Le Fort et al.*, 1983; *Searle and Tirrul*, 1991; *Fraser et al.*, 2001]. The Kohistan arc consists of Late Cretaceous and Eocene plutonic belts, and pyroxene granulites, calc-alkaline volcanics, amphibolites, and minor metasediments [e.g., *Coward et al.*, 1984]. The Indian plate can be subdivided into three tectonic units: From north to south these are (1) an internal metamorphosed unit, (2) an external unmetamorphosed or low-grade metamorphic unit, and (3) the foreland basin sediments [*Treloar et al.*, 1991]. The internal unit consists of cover and basement rocks. The basement rocks are predominantly high-grade gneisses, in some areas unaffected by the Himalayan metamorphism; the cover rocks are predominantly greenschist- to amphibolite-grade metapelites and metapsammites metamorphosed during the Himalayan orogeny [e.g., *Butler and Prior*, 1988; *Treloar et al.*, 1989a; *Argles*, 2000]. Other important components are eclogites [e.g., *Pognante and Spencer*, 1991; *Lombardo et al.*, 2000, and references therein], and Cambro-Ordovician granitoid intrusions [e.g., *Le Fort et al.*, 1979]. The internal zone is separated from the external zone unmetamorphosed to low-grade metamorphic Precambrian sediments and dominantly Mesozoic to Eocene Tethyan shelf sediments by the Panjal Thrust (PT). Farther to the south, the Main Boundary Thrust (MBT) separates these rocks from the Tertiary foreland basin deposits. The Main Frontal Thrust (MFT) delineates the southernmost extent of the foreland basin fold and thrust belt.

2.2. Tectonic History of the Pakistan Himalaya

[6] The Kohistan Island arc was initiated in Early Cretaceous times. It collided with the Asian plate sometime between 70 and 100 Ma [e.g., *Coward et al.*, 1986], from which time on it acted as an Andean-type margin until final closure of Tethys and India-Asia/Kohistan collision at sometime between 65 and 50 Ma [e.g., *Maluski and Matte*, 1984; *Tonarini et al.*, 1993; *Smith et al.*, 1994] (also see review by *Chamberlain and Zeitler* [1996]). In the hanging wall of the MMT, most deformation and metamorphism of the arc postdated suturing with Asia but predated collision with India; although younger, Himalayan cooling ages become more prevalent eastward, toward the margin of the Nanga Parbat syntaxis [*Zeitler*, 1985; *Treloar et al.*, 1989a; *George et al.*, 1995; *Krol et al.*, 1996]. In the footwall of the MMT, many of the Indian plate rocks attest to a polymetamorphic and deformational pre-Himalayan history. Granulite facies metamorphism and migmatisation affected the Indian plate basement gneisses at circa 1850 Ma [*Treloar et al.*, 2000], reflected in the cooling ages of a variety of minerals [*Chamberlain et al.*, 1989; *Zeitler et al.*, 1989; *Treloar et al.*, 1989b; *Treloar and Rex*, 1990; *Schneider et al.*, 1999] A mafic dyke intrusion event crosscuts the metamorphic fabric at circa 1600 Ma [*Treloar et al.*, 2000]. Dating of a series of granitoids suggests a period of magmatism, probably related to the Pan-African orogeny, in the Cambro-Ordovician, circa 400–500 Ma, with a cluster of ages at circa 470 Ma [*Le Fort et al.*, 1979; *Zeitler et al.*, 1989; *Chamberlain et al.*, 1989; *Treloar et al.*, 1991, 2000; *Foster et al.*, 1999; *Lombardo et al.*, 2000]. Carboniferous plutons are also in existence [*Smith et al.*, 1994]. The youngest Pre-Himalayan event recorded in the Indian plate basement is described by *Treloar et al.* [1989b], who consider 176–194 Ma biotite and muscovite K-Ar ages to represent a real thermal event, possibly continental extension or large-scale continental inversion in the early Jurassic.

[7] Himalayan-aged evolution of the Indian plate began at circa 50 Ma, when the northern margin of the Indian plate underwent initial tectonic thickening to peak metamorphic conditions, following collision with the Kohistan arc [*Tonarini et al.*, 1993; *Treloar et al.*, 1989b; *Treloar and Rex*, 1990; *Chamberlain et al.*, 1991; *Smith et al.*, 1994; *Foster et al.*, 1998]. Subsequent to metamorphism, the Indian plate and Kohistan rocks were thrust southward. *Treloar et al.* [1989a] consider this thrusting to have reimbricated the previously decoupled basement sequences unaffected by Himalayan metamorphism with cover sequences metamorphosed during the Himalayan orogeny. The timing and duration of this thrusting is not well established. The sharp metamorphic discontinuities within the imbricate thrust stack beneath the MMT indicate that thrusting was postmetamorphic. According to *Chamberlain and Zeitler* [1996], best estimates come from the cooling ages of metamorphic minerals in the cover sequence. Data from a number of sources [*Maluski and Matte*, 1984; *Zeitler*, 1985; *Treloar et al.*, 1989a; *Treloar and Rex*, 1990; *Chamberlain et al.*, 1991; *Smith*, 1993] provide hornblende ages ranging from 28 to 45 Ma, with a peak at 40 Ma, and mica cooling ages between 23 and 30 Ma. Thrust stacking occurred prior to cooling through the muscovite blocking temperature, as the ages of micas from within the shear zones and from the thrust pile are indistinguishable [*Treloar et al.*, 1991]. Decreasing pressure-temperature paths are interpreted by *Chamberlain and Zeitler* [1996] as presumably the result of tectonic unroofing as thrusts were stacked onto the Indian plate. Possibly this tectonic unroofing was achieved by extension within the upper parts of the overlying Kohistan arc as proposed by *Treloar* [1999], who considers there to be a short period of rapid cooling of the Indian plate between 43 and 40 Ma or early extensional movement on the MMT [*Burg et al.*, 1996; *Argles et al.*, 2000; *Argles and Edwards*, 2002]. Following thrusting, the Indian plate margin underwent a period of rapid cooling during the interval 25–20 Ma, possibly because of crustal extension as Kohistan moved north along normal faults, perhaps including the MMT [*Chamberlain et al.*, 1991; *Treloar et al.*, 1989a, 1991; *Burg et al.*, 1996].

2.3. Geological Background of the Himalayan Foreland Basin

[8] Throughout the foreland basin, from Pakistan [*Pivnik and Wells*, 1996] through India [*Najman et al.*, 1997] to Nepal [*DeCelles et al.*, 1998], a major unconformity is thought to separate rocks representing the last marine facies in Eocene times [*Mathur*, 1978, 1979; *Sakai*, 1989; *Pivnik and Wells*, 1996, and references therein], and the start of continental sedimentation eroded from the metamorphic rocks of the Himalayan orogen, dated in India at younger than mid-Oligocene [*Najman et al.*, 1997] and in Nepal at younger than earliest Miocene [*DeCelles et al.*, 2001]

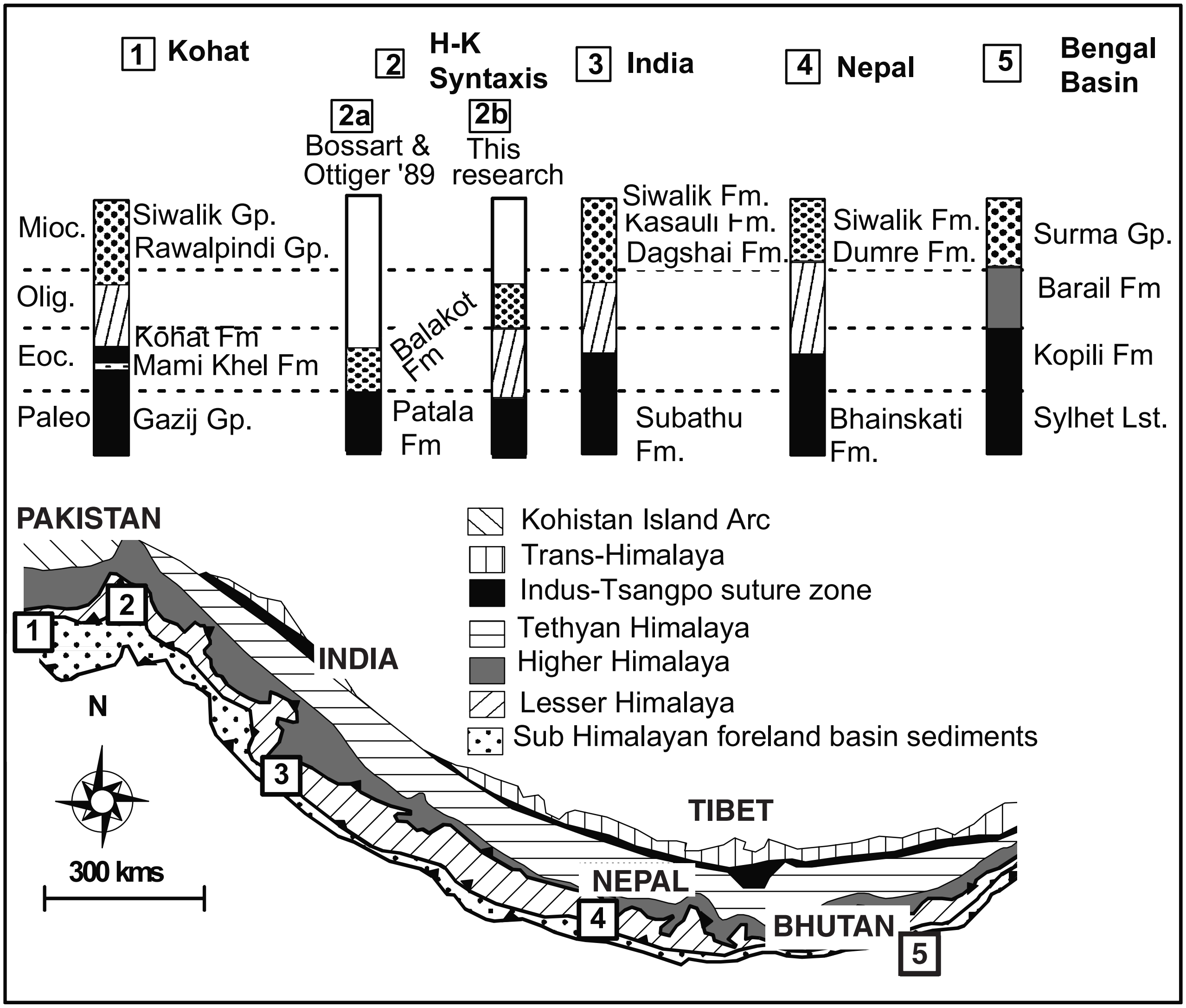


Figure 2. Comparison of the stratigraphy of the Himalayan foreland basin, from Kohat, Pakistan (location and stratigraphic summary 1) [*Pivnik and Wells*, 1996] through the study area of the Hazara-Kashmir Syntaxis Pakistan (location and stratigraphic summary 2; 2a, previously accepted stratigraphy after *Bossart and Ottiger* [1989]; 2b, current study), India (location and stratigraphic summary 3) [*Najman et al.*, 1997], Nepal (location and stratigraphic summary 4) [*DeCelles et al.*, 1998], to the Bengal Basin (location and stratigraphic summary 5) [*Uddin and Lundberg*, 1998]. Region 2, the Hazara-Kashmir Syntaxis, can be located on Figure 1. The "Internal" and "External" zones of Figure 1 correspond broadly with the Higher and Lesser Himalaya of the Indian and Nepal Himalaya. Legend patterns for the foreland basin stratigraphic columns are as follows: solid, shallow marine sediments; shaded, deltaic Indian craton-derived sediments; stippled, continental orogen-derived sediments; hatched, no sediments preserved. Note that the new stratigraphy for the Balakot Formation (stratigraphic column 2b) (1) removes the Hazara-Kashmir syntaxis region from its previously anomalous position as the only region in the foreland basin which displays a conformable marine-continental facies transition and (2) significantly decreases the timing of the start and degree of diachroneity of initiation of continental deposition. From *Najman et al.* [2001] (Reprinted with permission from *Nature*).

(Figure 2). These earliest continental sediments are called the Murree Formation in Pakistan [*Shah*, 1977], the Dagshai Formation in India [*Bhatia*, 1982], and the Dumre Formation in Nepal [*Sakai*, 1989]. Farther east, in the Bengal Basin, the shallow marine estuarine and deltaic Barail Formation was deposited during the Oligocene period. These sediments may be of southerly cratonic origin, with the first arrival of orogen-derived material in the Miocene Surma Group [*Uddin and Lundberg*, 1998] approximately at the same time as in the foreland basin to the west.

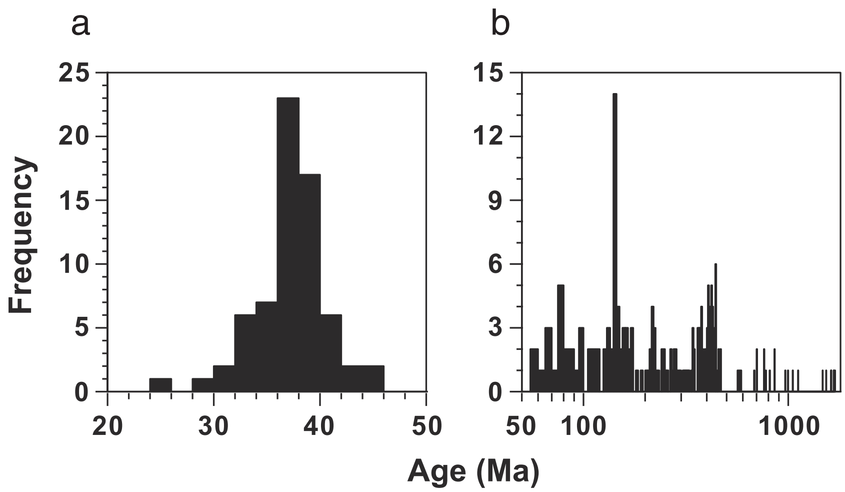


Figure 3. Distribution of Ar/Ar laser-fusion and step-heating analyses of 257 single-crystal detrital white mica grains from the Balakot Formation red bed sediments, Pakistan. (a) Grains 20–50 Ma were sorted in 2-Myr wide intervals. (b) Grains 50–2000 Ma (190 crystals) were sorted in 5-Myr intervals. The analytical error is typically less than the bin width.

[9] In Pakistan, in the Kohat region, the Eocene marine phase is briefly interrupted during the late Early Eocene by the 100–150m thick orogen-derived red beds of the Mami Khel Formation [*Pivnik and Wells*, 1996]. To the North, in the Hazara-Kashmir Syntaxis, the orogen-derived Balakot Formation red beds were interpreted by *Bossart and Ottiger* [1989] as tidal facies resting conformably on the shallow marine Paleocene Patala Formation and Lockhart Limestone. The red beds that were dated by these authors at 55–50 Ma on that basis are considered to be the oldest continental Himalayan-derived material, and the only known example in the Himalayan foreland basin where the marine to continental transition is conformable.

3. Balakot Formation

3.1. Summary of Previous Work

[10] *Bossart and Ottiger* [1989] mapped the >8 km thick red bed Balakot Formation in the Hazara-Kashmir Syntaxis as a steeply north dipping, normal homoclinal stratigraphic succession, conformably overlying the Paleocene-aged shallow marine Patala Formation and Lockhart Limestone (see their Figure 8). They therefore interpreted the four discrete 20–60 m thick dark gray fossiliferous marl bands found within the red bed succession as stratigraphic intercalations and took the age of these bands, determined at 55–50 Ma on the basis of nummulites and assilines, to represent the age of the entire Balakot red bed Formation. They noted the presence of sandstone channel facies, thinly interbedded sandstones and mudstones, and caliche, with fining up cycles, ripple marks, and flaser bedding. From this, and the presence of the marine marl bands, Bossart and Ottiger interpreted a tidal facies for the Balakot Formation red bed sediments. *Critelli and Garzanti* [1994] studied the petrography of the red bed sandstones and determined a mixed very low-grade metamorphic, arc, and suture zone provenance. They noted an increase in the igneous component up section which, in view of the prevailing view that the sequence was a normal stratigraphic succession, they interpreted as increased arc input with time.

3.2. New Constraints to the Age and Structure of the Balakot Formation

3.2.1. New Age Dating of the Balakot Formation

[11] We have dated 257 individual detrital white micas from the Balakot Formation red bed sandstones using total-fusion (Table A1) and step-heating (Table A2) Ar/Ar techniques similar to those used by *Richards et al.* [1999] (Figure 3; Tables A1 and A2 are available as electronic supporting material[1]). The results show over 20% of the crystals are <40 Ma, with 40 crystals 36–40 Ma, 13 crystals 32–36 Ma, and four crystals <32 Ma. This is incompatible with the 55–50 Ma biostratigraphic age determined by *Bossart and Ottiger* [1989], since the host sediment age must be younger than the detrital mineral age, unless the mineral has been reset by later metamorphism or suffered alteration. We describe in sections 3.2.1.1 to 3.2.1.4 four methods that were used to determine that alteration or resetting of the micas was insignificant. Step-heating experiments and electron microprobe traverses across micas from the Balakot Formation were carried out to determine if the grains were likely to have undergone significant resetting or alteration. A study of the petrography and illite crystallinity of the Balakot Formation rocks was carried out to determine if the rocks had been subjected to postdepositional metamorphic temperatures sufficient to reset micas.

[1]Auxiliary material (Tables A1 and A2) is available via Web browser or via Anonymous FTP from ftp://kosmos.agu.org, directory "append" (Username = "anonymous", Password="guest"); subdirectories in the ftp site are arranged by paper number. Information on searching and submitting electronic supplements is found at http://www.agu.org/pubs/esupp_about. html.

3.2.1.1. Ar/Ar Step-Heating Experiments

[12] Nineteen individual mica grains were analyzed using laser step-heating techniques. All of the micas from the young population (eight in total) yielded concordant plateaux ranging from 37.1 ± 0.4 to 41.0 ± 0.1 Ma, indicating that low-temperature alteration is not significant and that total-fusion analyses from the younger population are a reliable and robust estimate of the respective mica age (Figure 4). The weighted mean average of the four youngest step-heated grains is 37.6 ± 0.1 Ma. Thus, although it is possible that at least some of the apparently youngest grains analyzed by total-fusion techniques, i.e., the four grains <32 Ma in Figure 3, have been altered, we would suggest that at least some of the 13 total-fusion ages between 32 and 36 Ma are also reliable and robust age estimates. Alteration is more significant for the older population with only five out of eleven grains revealing concordant plateaux, suggesting that total-fusion ages of the older population may not represent the true mica age.

3.2.1.2. Compositional Profiles of Mica Grains

[13] Alkali loss is indicative of alteration in white micas. Electron microprobe traverses were carried out across 23 detrital white micas from the Balakot Formation red beds (Figure 5). Of these traverses, over half the micas showed no indication of alkali loss, as illustrated by the representative traverse shown as a line marked by circles on Figure 5. Of the micas that did show alteration, in every case, alteration was confined to the edge of the grains, as shown by the representative traverse marked by triangles in Figure 5, and in only one grain was this edge alteration severe (traverse marked by squares in Figure 5).

3.2.1.3. Petrography of the Balakot Formation

[14] Thin section petrographic studies by *Bossart* [1986] of the Balakot Formation red bed sandstones show the presence of pumpellyite, chlorite, and sericite, indicating prehnite-pumpellyite grade of metamorphism. At the base of the red bed succession, *Bossart* [1986] records the presence of stilpnomelane facies that he ascribed to increased burial depth rather than due to proximity to thrusts. These metamorphic facies, indicative of burial metamorphism, are of insufficient grade to reset detrital muscovite or provide conditions suitable for growth of new muscovite. Additionally, we note that the detrital quartz grains show no evidence of internal strain by dislocation creep, a mechanism which occurs above 350°C in quartz, a similar temperature to that required to reset white mica grains.

3.2.1.4. Illite Crystallinity Studies

[15] The degree of crystallinity of illite in a rock, measured in Hb_{rel} values [*Weber*, 1972], provides an indication of the degree of metamorphism that the rock has been subjected to. According to *Blenkinsop* [1988], Hb_{rel} values of below 147 represent metamorphic conditions equivalent to the epizone, values between 147 and 278 equate to the anchizone, and values above 278 indicate that conditions were never greater than diagenetic facies. Epizone conditions are required to reset K-Ar and $^{40}Ar/^{39}Ar$ age patterns in detrital illite-white mica [*Clauer and Chaudhuri*, 1999]. Detrital illite is thought to be concentrated in the >2 μm fraction of the rock. Therefore the <2 μm fraction was separated from red mudstone and red siltstone samples in order to gain information on the diagenetic component. Figure 6 shows that the Hb_{rel} values are concentrated in the lower anchizone and diagenetic zones, implying that these rocks have not been subjected to metamorphic conditions sufficient to reset the $^{40}Ar/^{39}Ar$ ages in coarser detrital white mica.

[16] The above four studies allow us to be confident that the mica ages represent the timing of cooling in the source region rather than postdepositional alteration or resetting. Since the host sediment must be younger than the detrital age, the age of the Balakot Formation red beds can therefore be taken as no older than 37.6 ± 0.1 Ma, and they could be younger than 32 Ma. Although this is incompatible with the 55–50 Ma biostratigraphic ages determined by *Bossart and Ottiger* [1989], the two data sets can be reconciled as described below.

3.2.2. Structure of the Balakot Formation

[17] Our structural investigation focused on the nature of the presumed stratigraphic contact between the marl bands and the red beds, and on the nature of the contact between the Balakot Formation and the underlying Paleocene Patala Formation and Lockhart Limestone. We will demonstrate in this section that these two contacts, which were used by *Bossart et al.* [1988] and *Bossart and Ottiger* [1989] to deduce a 55–50 Ma age for the Balakot Formation, failed crucial testing during detailed field investigation (Figure 7).

3.2.2.1. Intercalation of the Marl Bands

[18] Although previously described as a regular north dipping homocline with no structural discontinuities [*Bossart et al.*, 1988], the Balakot Formation is actually variably deformed and folded by a series of tight folds (wavelength and amplitude of ~ 1 km) (Figures 7b and 8). From Balakot to Paras, the beds of the Balakot Formation follow a series of anticlines and synclines that intensify in tightness toward the middle of the section. The surface distribution of the marl bands coincides with high-strain zones localized in the hinge zones of F_1 folds (Figure 7b).

[19] Throughout the studied area, we observed two generations of cleavages. The oldest one is the most penetrative (S_1). It consists of a near vertical, NW-SE trending slaty cleavage (average N293°/84°NE; Figure 8) that cuts the bedding (S_0) at a generally very small angle. The S_1 cleavage is axial planar to tight F_1 folds. The S_0–S_1 angle increases in the hinge zones of F_1 folds, where both S_0 and S_1 are well differentiated. The limbs of F_1 folds display a near parallelism between S_0 and the S_1 cleavage (Figure 9). The hinge zones are readily interpreted in the field by an almost orthogonal relationship between S_0 and S_1, as well as reversals of S_0–S_1 angles on either limbs. The younger cleavage (S_2) is a southeast

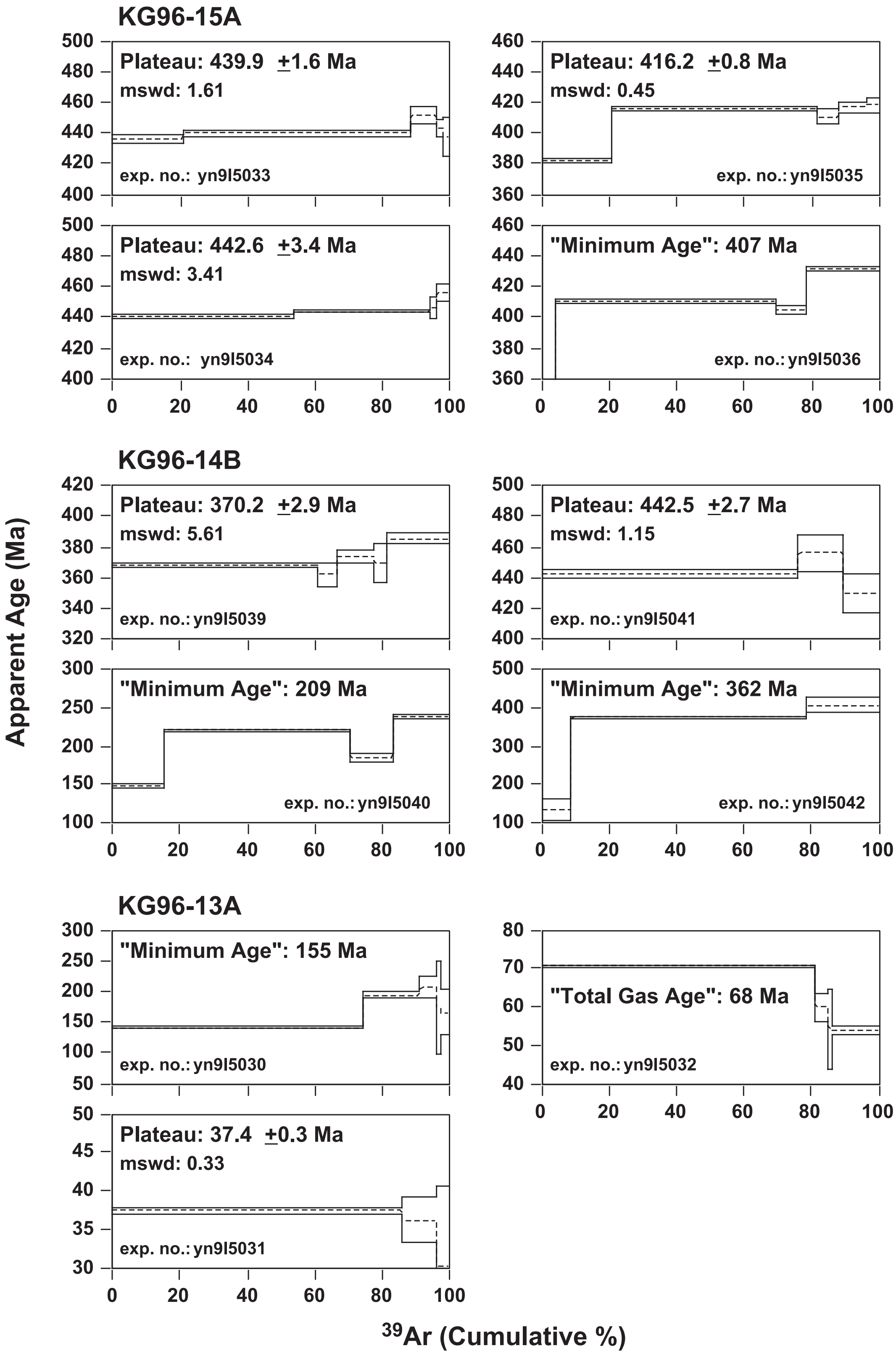


Figure 4. Step-heating experiments: single crystal Ar/Ar age spectra for 19 individual detrital white micas from the Balakot Formation red beds. Each step is drawn 2 standard deviations tall.

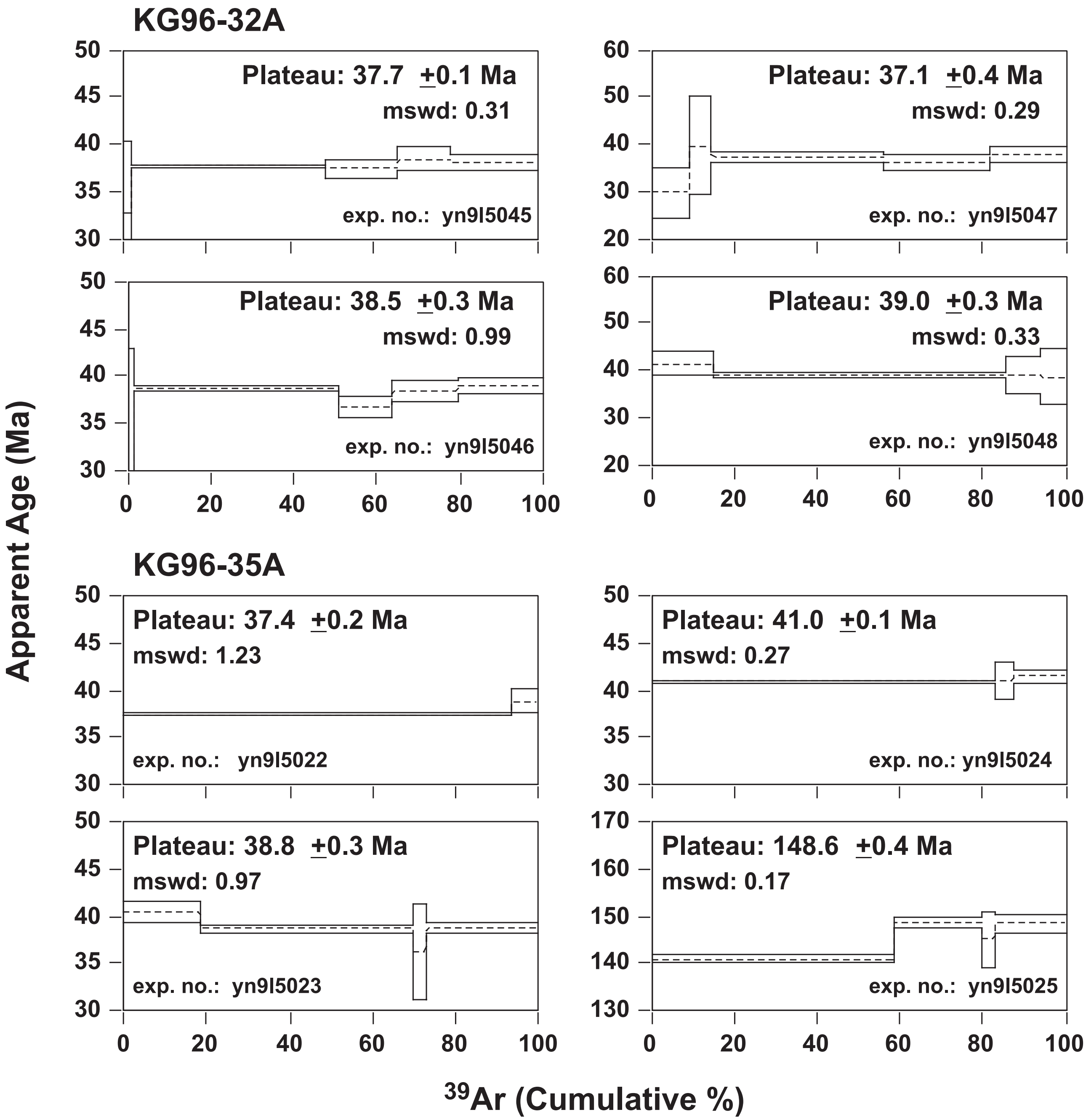


Figure 4. (continued)

trending, shallow southwest dipping spaced cleavage (average is N131°/11°; Figure 8). S_2 is regularly spaced every 10 cm and is associated with fine crenulations, asymmetrical southwest verging kink folds, and calcite-filled tensional veins subparallel to S_2.

[20] In thin section, quartz grains in the Balakot Formation display nonfibrous strain shadows and caps, with marked dissolved edges parallel to the penetrative cleavage, indicative of pressure solution deformation mechanism (Figure 9a). Furthermore, quartz strain fringes are visible on angular pyrite cores and are interpreted to be the result of displacement-controlled growth due to noncoaxial progressive strain [*Passchier and Trouw*, 1996]. Highly deformed bedding indicates intense transposition along the S_1 cleavage planes (Figure 9b). All this evidence suggests that the S_1 cleavage planes were the locus of transposition and noncoaxial strain, assisted by pressure solution.

[21] Elongation lineations defined by strain fringes around ilmenite and pyrite grains, partly dissolved quartz grains, and long axis of deformed green reduction spots are often visible on cleavage planes. These lineations tend to be steeply plunging to the northeast and are more or less downdip of

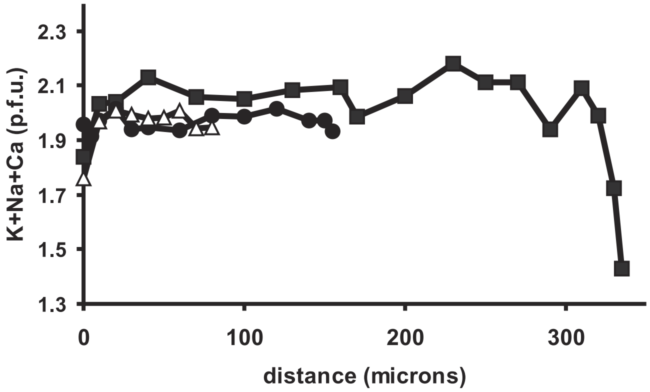


Figure 5. Electron microprobe traverses were carried out on a total of 23 detrital mica grains from the Balakot Formation red beds. In this diagram, only three representative traverses, which span the degree of compositional variation, are shown for clarity. Alkali loss is indicative of alteration. The traverse line marked by circles shows no alkali loss, the traverse line marked by triangles shows a small amount of alkali loss at the grain edge, and the traverse line marked by squares shows more significant alkali loss but confined to the grain edge only.

S_1 cleavage planes. Intersection lineations between bedding and S_1 cleavage are subhorizontal, parallel to F_1 fold hinges, which are shallowly plunging to the ESE (average 23° toward N105°; Figure 8).

[22] The marl bands coincide in the field with chlorite-grade high-strain zones. These zones are characterized by highly discontinuous and transposed bedding, similar to the ones displayed in Figure 9b. Because of the high chlorite content and fissile nature of the rock in these zones, the sense of motion within these zones is not well constrained. Nevertheless, the highly discontinuous and folded nature of preserved beds in these zones as well as pervasive downdip elongation lineations strongly suggest that they are the product of localized strain with a significant vertical motion.

[23] On the basis of the above mentioned observations, we suggest a different interpretation of the structural style of the Balakot Formation, in which the marl units are part of an underlying formation, exposed by subsequent deformation related to shear folding and associated faulting. It is argued that shortening of the highly incompetent mudstone beds of the Balakot Formation produced passive-flow F_1 folds where deformation was localized along cleavage planes that acted as flow planes (Figure 10). These flow planes are highlighted in thin section by cleavages intensely transposing bedding (Figure 9b). In areas of concentrated strain, this flow folding process brought underlying Early Eocene marl bands next to Oligocene mudstones of the Balakot Formation red beds.

3.2.2.2. Contact Between the Balakot and Patala Formations

[24] Previous interpretations concerning the lower contact of the Balakot Formation imply that it conformably overlies the Paleocene deposits consisting mainly of the Lockhart limestone and the shales and marls of the Patala Formation [*Bossart et al.*, 1988; *Bossart and Ottiger*, 1989]. The same workers also interpret the Patala and Lockhart Formations to unconformably overlie the Late Precambrian to Cambrian Abbotabad Formation, which forms the core of the Muzaffarabad anticline [*Calkins et al.*, 1975].

[25] Inspection of the site (Behrin Katha, N34° 32.925′ E073° 22.369′ and surrounding region) described by *Bossart and Ottiger* [1989] revealed that exposure is insufficient to be confident of a sedimentary conformable contact between the Balakot Formation and underlying formations. New exposure <1 km north of Balakot, along the Balakot-Paras road (Figure 7a), reveals an imbricated thrust zone involving the Balakot, Patala, and Abbotabad Formations (Figure 11). At this locality, the three rock units are highly strained, with discontinuous and dislocated bedding. The lower part the Balakot Formation is structurally imbricated and isoclinally folded with the Patala Formation, which in turn is in thrust contact with the overlying Abbotabad limestones. Primary bedding features have not been observed within the Balakot Formation; instead, the beds are completely transposed and contain a penetrative cleavage with a pervasive downdip elongation lineation. The entire package is complexly faulted, with systematic top to the southwest thrust shear sense (Figure 11b). These data do not support the conformable interpretation of *Bossart et al.* [1988] and *Bossart and Ottiger* [1989]. Instead, they demonstrate that the base of the Balakot Formation is in fault contact with underlying formations.

[26] Therefore, in summary, the Balakot Formation red beds are younger than 37 Ma, lie in thrust contact with the Paleocene aged shallow marine Patala Formation and Lockhart Limestone below, and are tectonically intercalated with an underlying dark gray marl formation which contains fossils aged 55–50 Ma.

3.3. Sedimentology of the Balakot Formation: Tidal or Alluvial Facies?

[27] *Bossart and Ottiger* [1989] interpreted the red bed succession as tidal facies on the basis of the occurrence of

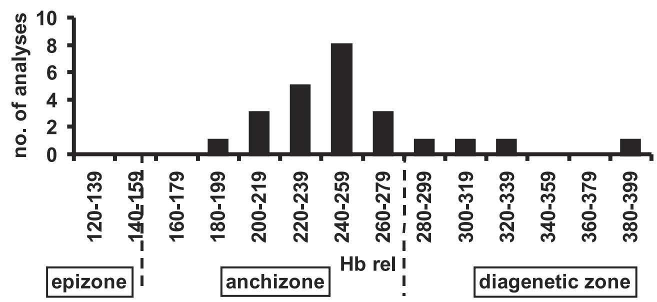
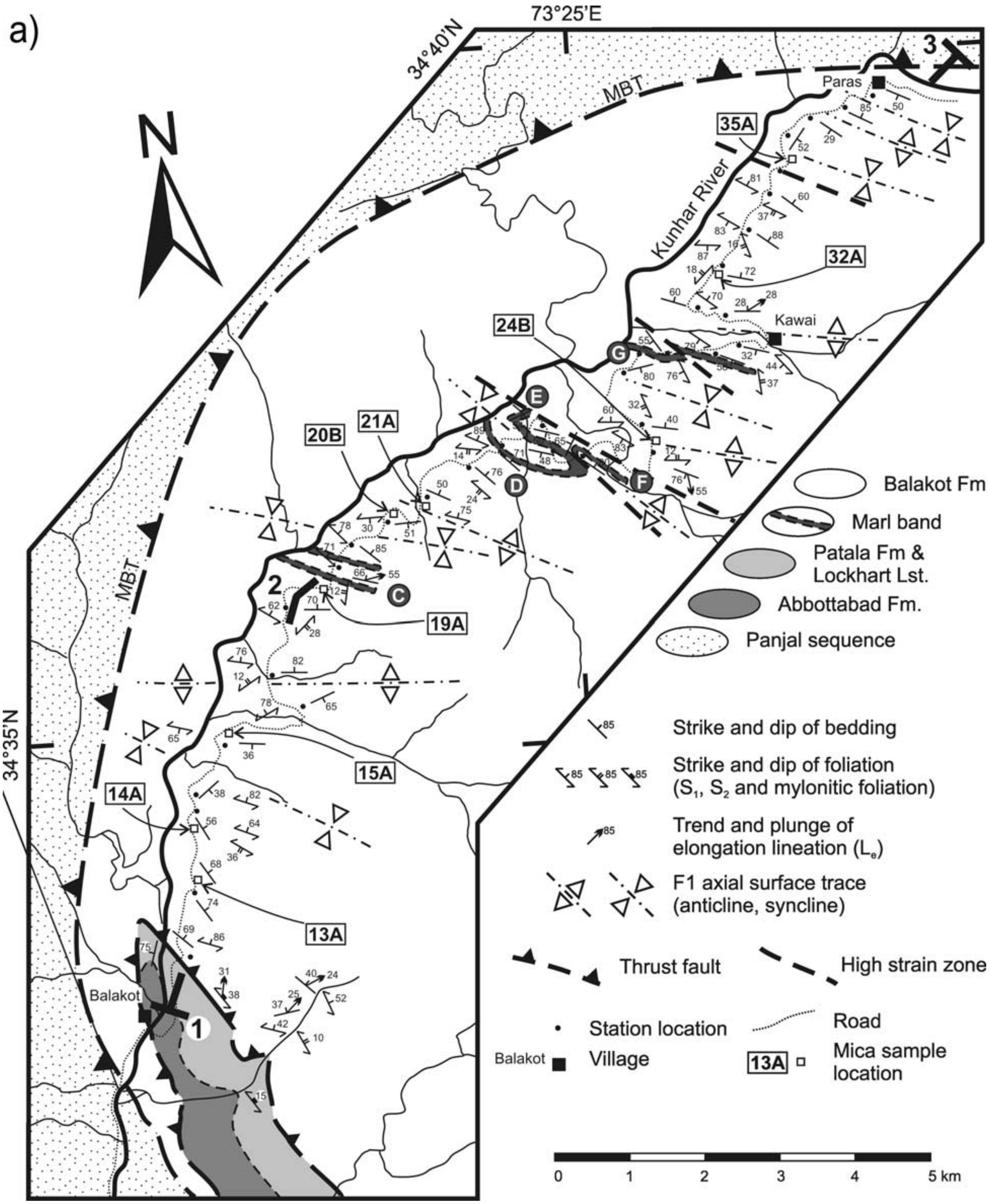


Figure 6. Histogram showing illite crystallinity analyses (measured as Hb_{rel} values) from the diagenetic (<2 μm) component of mudstones and siltstones from the Balakot Formation red beds. Analyses show that burial metamorphism never attained epizone conditions required to reset white micas.



a)
73°25'E
34°40'N
34°35'N
N
MBT
Paras
Kawai
Balakot
Kunhar River
35A
32A
24B
21A
20B
19A
15A
14A
13A
1
2
3
Balakot Fm
Marl band
Patala Fm & Lockhart Lst.
Abbottabad Fm.
Panjal sequence
Strike and dip of bedding
Strike and dip of foliation (S1, S2 and mylonitic foliation)
Trend and plunge of elongation lineation (Le)
F1 axial surface trace (anticline, syncline)
Thrust fault
High strain zone
Station location
Road
Village
Mica sample location
0 1 2 3 4 5 km

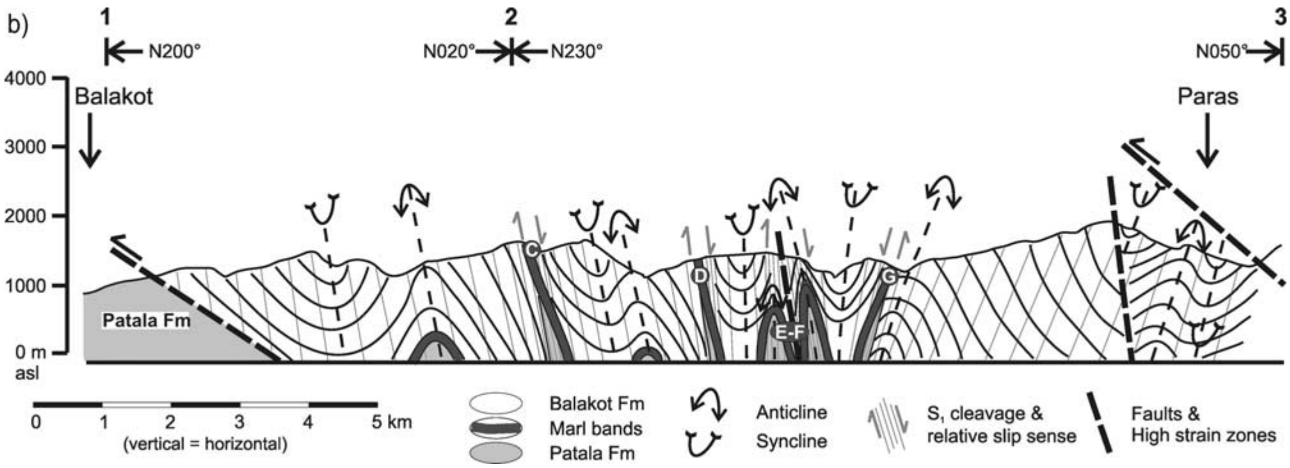


Figure 7. (a , opposite) Geological map and (b , above) cross section of the Balakot Formation, Kaghan Valley, Hazara-Kashmir Syntaxis, Pakistan. These new data contrast with mapping undertaken by *Bossart and Ottiger* [1989] (compare with their Figure 8), who interpreted the Balakot Formation as a steeply north dipping normal stratigraphic succession, with intercalated fossiliferous marl bands, labeled C–G. Here we show the presence of south dipping strata, folds, faults, and high-strain zones. The fossiliferous marl bands labeled C–G, the same annotations used by *Bossart and Ottiger* [1989] in their Figure 8 for easy comparison, outcrop in the core of anticlines or at high-strain zones. We therefore interpret the marl bands as part of an underlying formation, now structurally intercalated with the Balakot Formation red beds and exposed by subsequent deformation. The upper marl band contacts, when not highly strained, most probably are unconformable. Note also that the southern Patala-Balakot Formation boundary, interpreted by *Bossart and Ottiger* [1989] as a conformable contact, is here interpreted as a thrust contact on the basis of its tectonized appearance and shear sense indicators. The cross section was drawn from point 1, through 2, to 3. Note that this section is located west of marl bands sites E and F. Since the structures plunge moderately to the northwest, marl bands sites E and F are projected below the surface. Marl bands have been biostratigraphically dated by *Bossart and Ottiger* [1989] as follows: band C, mid-Late Ilerdian; band D, Ilerdian-Cuisian transition; bands E–F, Early to Middle Cuisian; and band G, Late Cuisian to Early Lutetian. From *Najman et al.* [2001] (Reprinted with permission from *Nature*).

(1) intercalated marine fossiliferous marl bands, interpreted as shallow marine subtidal lagoonal facies, and (2) cyclic sedimentation in the red bed succession. The cyclic sedimentation consists of fining up cycles composed of, from base to top, (1) erosively based, lens shaped, intraformational, and extraformational conglomerates, (2) coarse-grained cross-bedded, graded bioturbated sandstone, (3) ripple-marked and flaser-bedded sandstone, (4) thinly interlayered sand/mud lamination, often pervasively bioturbated, (5) caliche, and (6) siltstone, largely homogenous, with rare desiccation cracks. The conglomerates and cross-bedded sandstones are interpreted as tidal channels with rare fluvial channels deposited in the subtidal zone. Ripple-marked sandstone is interpreted as sand flats in the intertidal zone. The sand/mud lamination and caliche are interpreted as mudflat facies deposited in the intertidal and supratidal zones.

[28] With our new reinterpretation of the fossiliferous marl bands as a separate formation to that of the red bed succession, is the remaining evidence sufficient to retain a tidal facies interpretation? This question is an important one since, with the reinterpreted age of the red bed succession at younger than 37 Ma, it has implications for the timing of the cessation of marine conditions in the foreland basin.

[29] Figure 12 illustrates parts of the Balakot Formation sedimentary succession. The Balakot Formation red bed succession shows fining up sequences, often beginning with thick-bedded, medium-grained sandstones which are quite commonly erosively based and/or channel lagged, with rare groove and flute marks and cross beds. Overlying these sandstones, thinner-bedded and finer-grained sandstones are often found, sometimes separated by thin undulating mud-draped beds. Thick mudstones at the top of the cycle can be interbedded with thin or medium-bedded siltstones and sandstones. Caliche is also present. Sedimentary structures present in the sandstones include grading, asymmetrical ripple marks, flasers, climbing ripples, convolute bedding, load and flame and parallel laminations. Interlaminations of mudstone and sandstone on a fine scale are also present. It should be noted that it is unlikely that this list is representative off all sedimentary structures present. Sedimentary structures were infrequently visible, probably in part due to the relatively limited and weathered nature of the exposure prior to, and during the field season of, 1996, and due to major and extensive roadbuilding during the field season of 1999.

[30] In general, differentiation between alluvial strata and tidal strata is often subtle, and many units originally assigned

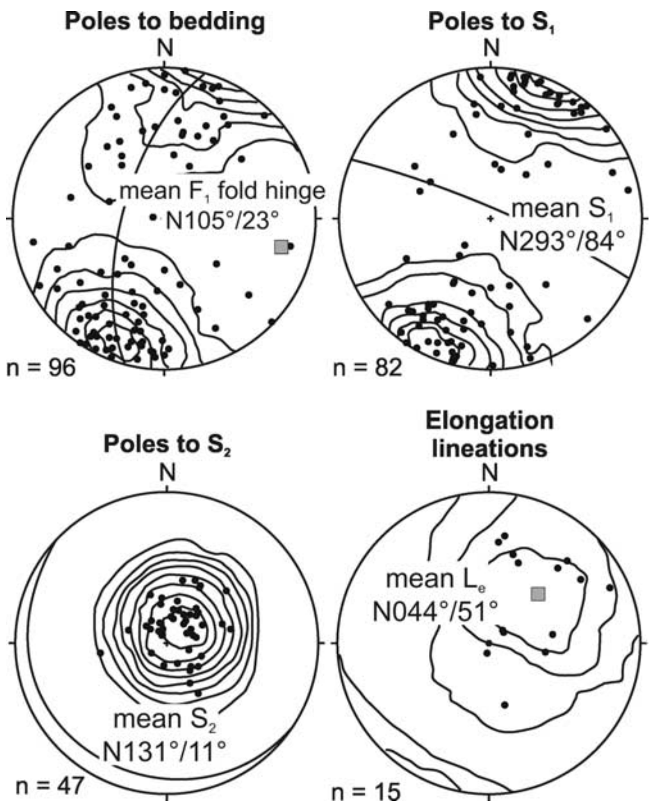


Figure 8. Equal-area lower hemisphere stereoplots of poles to bedding planes, S_1 foliation, S_2 crenulation cleavage, and L_e elongation lineations collected in the study area.

to fluvial facies have more recently been reinterpreted as tidal [e.g., *Kuecher et al.*, 1990]. *Stear* [1978, 1980], drew attention to the similarity in sedimentary structures produced during waning ephemeral sheetflow in shallow water and structures that form as a result of tidal processes on low-energy beaches. No structures are unique to tidal or alluvial facies: For example, climbing ripples, observed in the Balakot Formation, are extremely common in alluvial facies and rare in tidal facies [*McKee*, 1966; *Reineck and Singh*, 1980], but they do occur in the latter [e.g., see *Wunderlich*, 1969; *Yokokawa et al.*, 1995]. Likewise, flaser bedding is characteristic of tidal facies [*Reineck and Wunderlich*, 1968], but it has also been recorded in alluvial strata [e.g., *Parkash et al.*, 1983; *Bhattacharya*, 1997]. A preponderance of sedimentary structures common to tidal environments is required to obtain a reasonable degree of certainty in tidal facies interpretation [e.g., *Shanley et al.*, 1992; *Shanmugan et al.*, 2000].

[31] In the Balakot Formation, there is not a preponderance of sedimentary structures indicative of tidal activity. The shallowing up cycles and thinly interbedded sandstones and mudstones, interpreted by *Bossart and Ottiger* [1989] as evidence of tidal activity, and the sedimentary structures recorded in this study, can equally well be explained by channel and overbank flood facies in an alluvial setting. While flaser bedding is rare in an alluvial environment, in isolation it does not constitute a unique feature to tidally dominated systems [*Nio and Yang*, 1991]. For example, the ephemeral Markanda River and Markanda terminal fan in India consist of erosively based cross-bedded sandstone

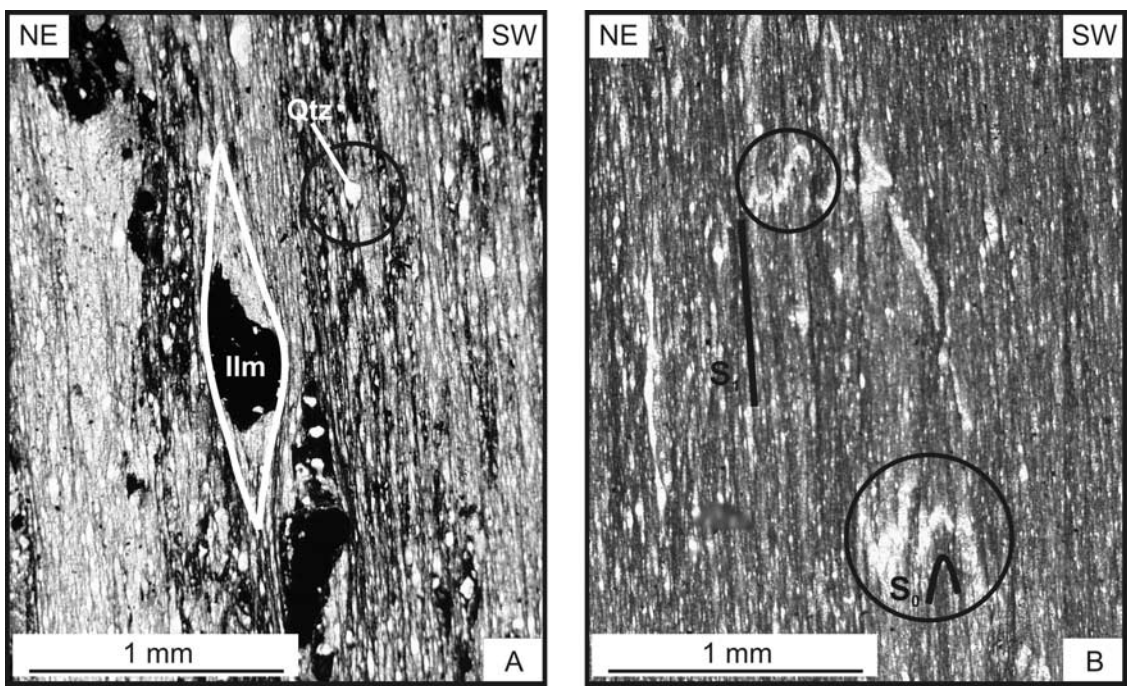


Figure 9. Photomicrographs showing microstructures developed in the Balakot Formation. (a) Pressure solution cleavage marked by dissolved edges of quartz grains parallel to the penetrative cleavage and by nonfibrous strain shadows and caps. (b) Highly deformed bedding (S_0) indicates intense transposition along the S_1 cleavage planes. Abbreviations are as follows: ilm, ilmenite; qtz, quartz. Both thin sections are seen in the vertical plane.

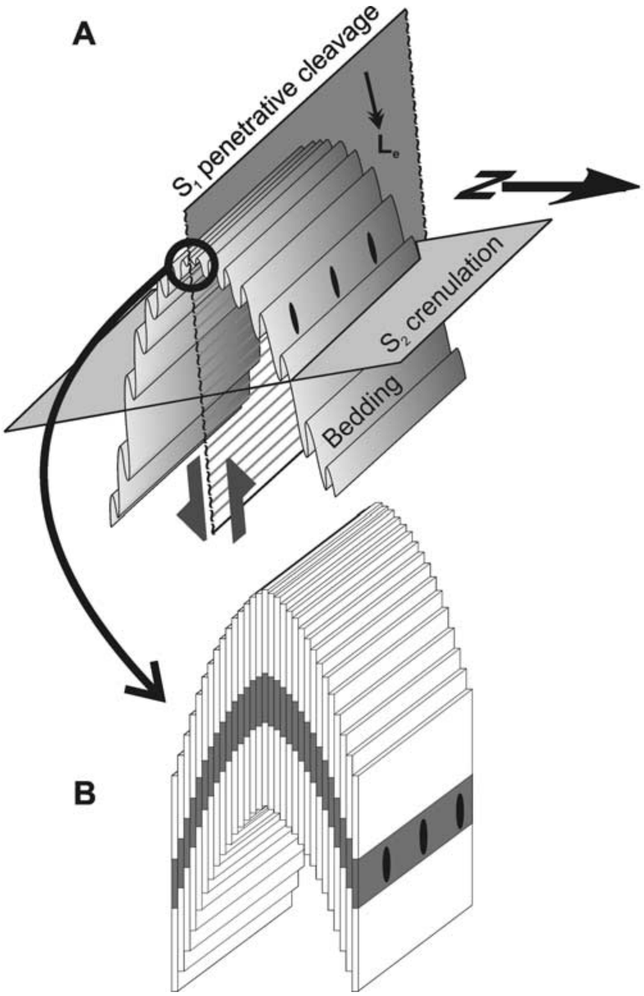


Figure 10. (a) Diagram showing the geometrical relationship between bedding planes, S_1 cleavage, elongation lineation, and S_2 crenulation. (b) Passive-shear folding model in which the layers are affected by shear planes at a high angle to the bedding orientation (modified after *Twiss and Moores* [1992]). Such shear planes are represented in the field by the penetrative S_1 cleavage. In intensely folded areas, this type of folding could have brought the underlying Patala Formation upward against the overlying Balakot Formation. Such a model implies that the Balakot Formation was highly incompetent during folding.

channel facies, thinly interbedded laminated sand, silt, and mud deposits from a levee environment and massive muds with minor cross-laminated siltstones deposited in a floodplain environment. Flaser bedding, reactivation surfaces, climbing ripples, mud drapes, and convolute bedding are all found [*Parkash et al.*, 1983].

[32] Therefore, while we do not rule out the possibility of tidal influence in the Balakot Formation red beds, we believe that at present there is insufficient evidence to state, with any degree of certainty, that a marine tidal influence was still prevalent in the foreland basin after 37 Ma. With the relatively limited level of good exposure previously and currently available to view, an alluvial facies environment is equally probable.

3.4. Provenance of the Balakot Formation

3.4.1. Previous Work

[33] Detrital material present in the Balakot Formation red beds, as documented by *Critelli and Garzanti* [1994], includes fine-grained lithic fragments, predominantly low-grade metapelites, volcanic material of andesitic-dacitic and subordinately rhyolitic composition, ophiolitic lithics including serpentine-schist, and sedimentary lithics (carbonate, shale, siltstone, sandstone, and chert). Coarse-grained lithic fragments are represented by quartz-mica schist and gneiss, plutonic rocks, sandstone, and metasandstone. Minerals include chromian spinel, muscovite, tourmaline, epidote, and amphibole. The predominant material is that of low-grade metapelites, with significant but subordinate igneous and sedimentary input which *Critelli and Garzanti* [1994] and *Bossart and Ottiger* [1989] interpreted as derived from the Indian plate, Kohistan arc, and suture zone ophiolites. Arc and ophiolitic material increases from south to north within the Balakot Formation section, which, on the assumption of an untectonized continuous sedimentary succession as described by *Bossart and Ottiger* [1989], was recorded as an up-section increased input from the arc-trench subduction complex with time.

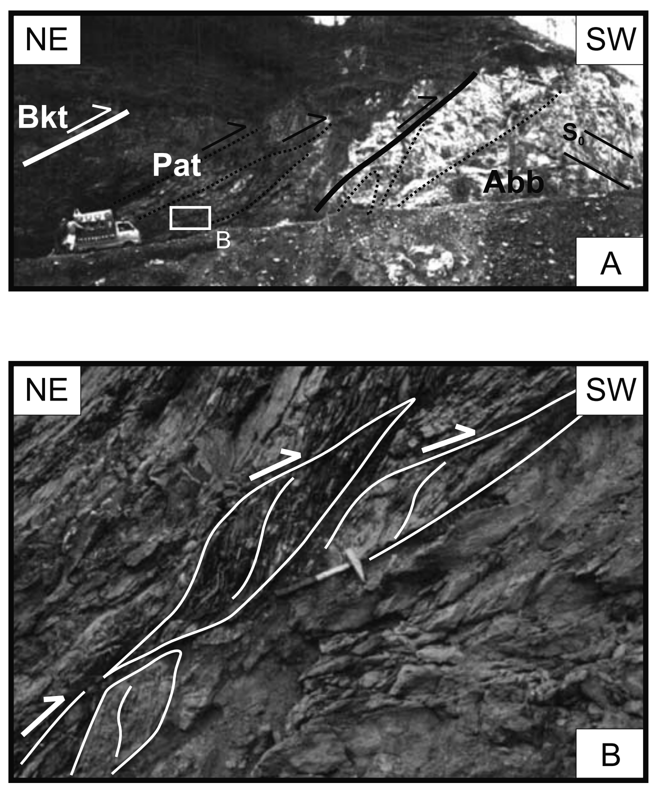


Figure 11. (a) Southwest verging thrust imbricate zone involving the Balakot (Bkt), Patala (Pat), and Abbotabad (Abb) Formations. S_0 marks the bedding orientation. (b) Detailed photograph of highly strained Patala Formation.

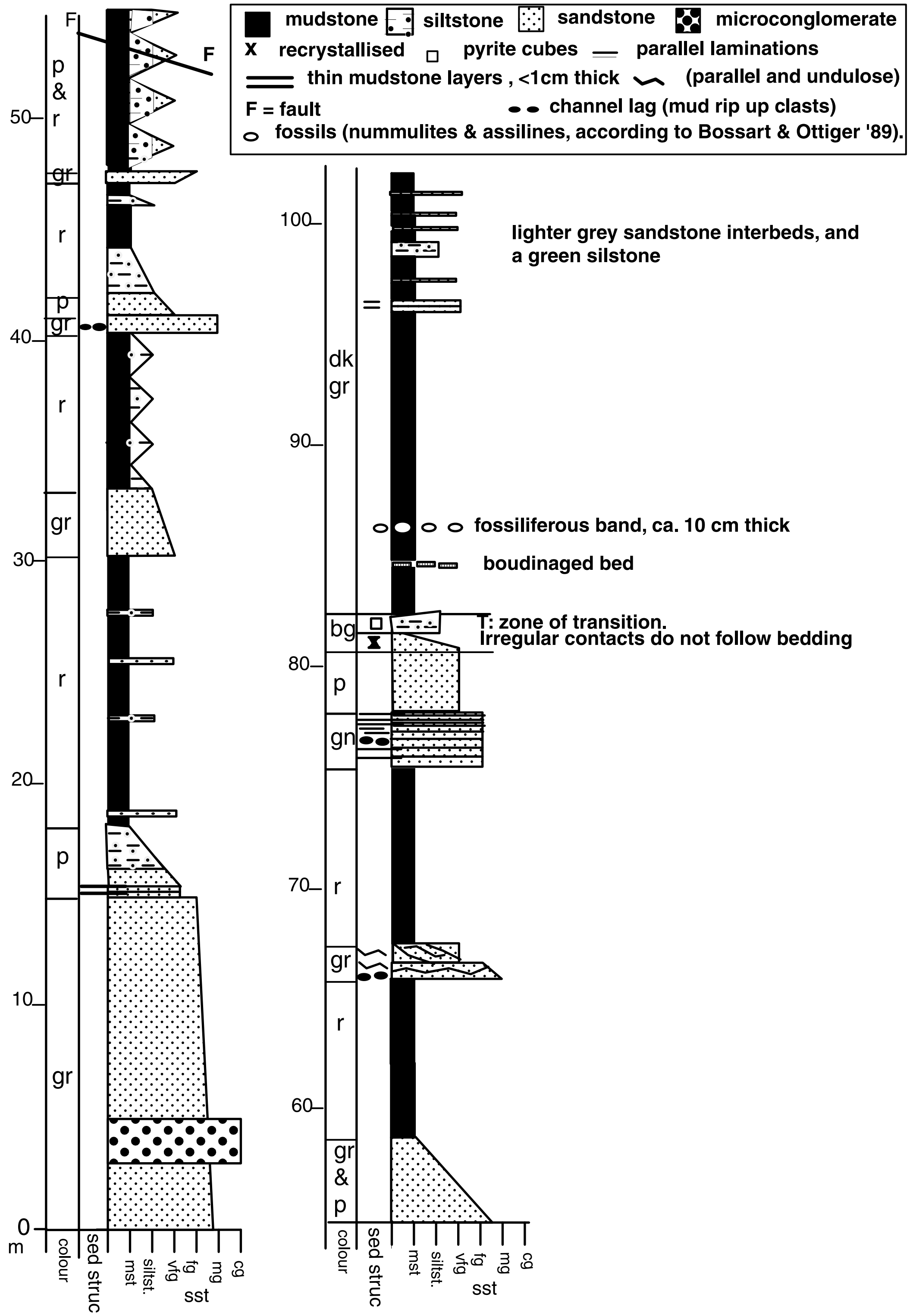


Figure 12. Sedimentary log showing the Balakot Formation red beds and marl band E (as located on Figure 7b). Log measured along the Balakot-Paras road at N34° 37.132′ E073° 24.486′. "T" marks the zone of transition between the red beds below (and to base of logged section) and marl band E above (and to top of logged section). In this transition zone, the color change is irregular and does not follow the bedding. The sandstone becomes very fine grained, recrystallized, and bright green in colour. It is overlain by a siltstone of the same color, containing pyrite cubes. Colors are labelled as follows: gr, gray; gn, green; p, purple; r, red; dk gr, dark gray; bg, bright green.

[34] *Critelli and Garzanti* [1994] described the source of the low-grade metamorphic Indian plate material as the "proto High Himalaya." Because of the improbability of Indian plate material being buried to sufficient depths for metamorphism, exhumed and eroded within the time frame between the time of collision and the then accepted time of Balakot Formation deposition, they considered the thrust belt to be material metamorphosed to low grade during the Pan-African orogeny and unaffected by Himalayan metamorphism.

3.4.2. New and Revised Provenance Data

[35] The mica ages presented in this research show peaks at circa 37 Ma, 140–150 Ma, and 400–450 Ma. There is a rapid drop to "background levels" after circa 470 Ma, falling further to zero by circa 1100 Ma, and a small cluster of ages at circa 1600 Ma (Figure 3a). Ar loss in older grains precludes accurate provenance analysis, but ages are consistent with known tectonothermal events affecting rocks of the Indian plate, including a Pre-Cambrian metamorphic event, Cambro-Ordovician and Carboniferous plutonism possibly associated with Pan-African orogenesis and Neo-Tethyan rifting, and Jurassic and Early Cretaceous thermal events [*Treloar et al.*, 1989b; *Treloar and Rex*, 1990; *Gaetani and Garzanti*, 1991; *Smith et al.*, 1994; *Garzanti et al.*, 1999; *Treloar et al.*, 2000] (see section 2.2). Some contribution from the Kohistan arc might also be expected. We consider any significant contribution from the Asian plate to be unlikely because Ar/Ar cooling ages of hornblendes in the Indian plate thrust stack (circa 40 Ma) indicate that the thrust belt would likely have provided a topographic barrier by this time. Only a large river either of antecedent character or capable of effecting river capture would be capable of breaching this barrier, and the deposits of the Balakot Formation show no evidence of deposition from such a major river.

[36] Therefore, in contrast to the interpretation of *Critelli and Garzanti* [1994] the Balakot Formation does contain a high proportion of material affected by Himalayan metamorphism, permissible within the new timescale of deposition for the Balakot Formation. We consider the provenance of the Balakot Formation red bed succession to be that of Indian plate material, including cover rocks affected by Himalayan metamorphism and basement that retained its Pre-Cambrian protolith ages, and Kohistan arc and ophiolitic material as evidenced by detrital modes analysis carried out by *Critelli and Garzanti* [1994]. Like *Critelli and Garzanti* [1994], who noted up-section increase in igneous input, we also note south to north variation in detritus, with our three most northern samples (KG96-32A, 35A, and 24B) containing a much higher proportion of Himalayan aged micas. This implies greater contribution from metamorphosed Indian plate cover rocks compared to basement which contains micas unreset by Himalayan metamorphism. However, with the removal of the biostratigraphic age constraints as supplied by *Bossart and Ottiger* [1989] it is no longer possible to relate these variations to time.

4. Implications for Himalayan and Basin Tectonics

4.1. Timing and Degree of Diachroneity of India-Asia Collision

[37] Stratigraphic data has been cited as one of the most compelling lines of evidence for the timing and degree of diachroneity of collision [*Butler*, 1995; *Rowley*, 1998]. Initiation of orogen-derived foreland basin sedimentation provides a minimum age for orogenic loading of the crust, and the timing of the marine-continental facies transition in the suture and foreland basin, and variation along strike, has been used to determine the timing and diachroneity of collision.

[38] *Rowley* [1996] considered that only in the NW Himalaya were data of sufficient quality to accurately determine the timing of the marine-continental facies transition. He cited the transition between the Late Paleocene marine Dibling Limestone to Early Eocene continental Chulung La sediments in the suture zone in Zanskar, India, and between the Paleocene-aged marine Patala Formation and the 55–50 Ma aged continental Balakot Formation in the Hazara-Kashmir syntaxis as evidence for the timing of India-Eurasia collision at 51 Ma in the northwest Himalaya. However, since the age of the unfossiliferous Chulung La Formation is poorly constrained, based only upon its stratigraphic position unconformably above the Dibling Limestone and its assumed but unproven correlation with the Kong Slates of that age [*Garzanti et al.*, 1987, 1996], the stratigraphic argument is confined to the Balakot Formation data. Hence this transition can now only be bracketed at sometime between 55–50 Ma and younger than 37 Ma for the northwest Himalaya. *Rowley* [1998] then compared this data with subsidence data from Eocene marine facies in Tibet which showed that collision must have postdated 45.8 Ma in that region. He therefore concluded that Himalayan collision was diachronous [*Rowley*, 1998, Figure 1]. *Uddin and Lundberg* [1998] came up with a similar conclusion, noting the eastward younging in the start of substantial Himalayan-derived material to the foreland (e.g., 55–50 Ma for the Balakot Formation in Pakistan compared to the Miocene Surma Group). Our new data which give a younger than 37 Ma age for the Balakot Formation red bed succession show that the degree of west to east younging is considerably reduced, if present at all, since detrital mineral ages can only provide a maximum age for the sediment.

4.2. Tectonic Evolution of the Thrust Belt

[39] Our new data can be used to refine the tectonic evolution of the Himalayan thrust belt in Pakistan as outlined in section 2.2. The petrography of the Balakot Formation shows that the Kohistan island arc, obducted onto the Indian plate along the MMT by circa 50 Ma, was an area of positive topographic relief subject to significant amounts of erosion by the time of deposition of the Balakot Formation sediments after 37 Ma. The timing of thrust stack cooling is constrained by hornblende cooling ages as old as 45 Ma (peak at 40 Ma) from Himalayan rocks at the surface today. The sedimentary record provides information further back in time, from rocks of the

Indian plate thrust stack since eroded from the mountain belt. The oldest Himalayan aged white micas in the Balakot Formation are 44 Ma, with a peak of ages at 37 Ma (those found in Himalayan rocks at the surface today are aged 23–30 Ma). If we assume that hornblendes eroded from the equivalent rock units were also correspondingly older than those at the surface today, we must conclude that cooling began earlier than previously believed (i.e. >40 Ma). This implies that cooling from peak metamorphic temperatures occurred at a faster rate. Alternatively, if hornblende ages are not correspondingly older, unlikely in view of the age difference between micas in the Balakot Formation and those at the surface today, rapid cooling between the hornblende and mica closure temperature would be required to explain the data. Overall, cooling from peak metamorphic temperatures (500°–600°C) [*Chamberlain and Zeitler*, 1996] at circa 50 Ma to the mica closure temperature of 350°C at 37 Ma, indicates an averaged cooling of circa 20°C/Myr during this period. The mix of Himalayan aged and pre-Himalayan aged detrital micas in the Balakot Formation suggests that exhumation of both basement and cover rocks to the surface occurred early in the thrusting event.

[40] Because of the previously assigned age of the Balakot Formation, *Treloar* [1999] acknowledged that some contribution to an early period of rapid cooling and exhumation at 43–40 Ma could have been made by erosional processes, although he considered tectonic exhumation to be prevalent. The revised age for the Balakot Formation now removes existing evidence for an erosional contribution, although that need not necessarily mean that such a contribution did not exist. Tectonic exhumation during these early stages of orogenic development may have been achieved by early movement along the MMT which *Argles and Edwards* [2002] have demonstrated to have occurred in the ductile regime and therefore likely not long after peak metamorphism which occurred at 44–38 Ma in their area of study [*Foster et al.*, 2000]. This is in accord with the Balakot Formation detrital muscovite cooling age peak at 37 Ma.

[41] *Critelli and Garzanti* [1994] were forced to reconstruct an Early Eocene thrust barrier south of the suture, consisting of material metamorphosed during a Pan-African event, in order to explain the difference in petrography between supposedly coeval sediments of the more northerly located Chulung La Formation and the Balakot Formation, and the presence of metamorphic detritus in the latter. The reinterpretation of the Balakot Formation now renders it noncoeval with the Chulung La red beds, and thus the interpreted development of a substantial topographic thrust barrier by this early stage of orogenesis is not required.

4.3. Basin Tectonics and Stratigraphy

[42] Our revision of the age, structure, and facies of the Balakot Formation affects models of foreland basin geometry and evolution. The new age for the Balakot Formation removes it from its previous anomalous position to the otherwise basinwide unconformity that separates marine sediments of nonmetamorphic provenance from continental sediments of metamorphic provenance over a hiatus of circa 15 My during Late Eocene-Oligocene times. Therefore it is now consistent with the model of hiatus formation as the result of cratonward movement of a peripheral forebulge over a backbulge depozone as proposed by *DeCelles et al.* [1998] but inconsistent with models of hinterlandward movement of the forebulge due to crustal thickening during the phase 2 thrusting event [*Treloar et al.*, 1991]. The thickness and age of the Balakot Formation were also used by *Burbank et al.* [1996] to support the contention that basin geometry was influenced by changes in the rigidity of the underthrust plate with time. Our reinterpretation of the structure of the Balakot Formation not only substantially reduces the stratigraphic thickness and hence estimates of the depth of the basin at this time, but also shows that the marl bands cannot be used to determine sedimentation rates of the clastic deposits, and therefore there is no constraint on the early sedimentation and subsidence history of the basin.

[43] The Balakot Formation is officially termed part of the Murree Formation (see review by *Bossart and Ottiger* [1989]). Bossart and Ottiger informally named it the Balakot Formation and requested to the Stratigraphic Committee of Pakistan that this name be adopted officially in view of the older age and facies of the red beds in the Hazara-Kashmir syntaxis compared with the continental facies further south. In view of the reinterpretation of the age and facies of the red beds in the Hazara-Kashmir Syntaxis, this recommendation may now be disregarded.

5. Summary and Conclusions

[44] Our new structural mapping of the Balakot Formation shows that the discrete fossiliferous marl bands, previously used to date the red bed succession, are structurally rather than stratigraphically intercalated with the sediments and therefore cannot be used to date the formation or infer tidal facies. Likewise, we demonstrate that the base of the Balakot Formation lies in tectonic rather than sedimentary contact with the underlying Paleocene Patala Formation and also cannot be used to date the formation. New $^{40}Ar/^{39}Ar$ dating of detrital white micas from the Balakot Formation sandstones indicates that the sediments were deposited after 37 Ma, 15 Myr younger than previously believed.

[45] Our petrographic and isotopic data from the Balakot Formation place constraints on the early evolution of the orogen. The Kohistan arc, obducted onto the Indian plate along the MMT during the initial stages of collision, was a topographic high subject to erosion at the time of deposition of the Balakot Formation (after 37 Ma). Cooling of the postmetamorphic Indian plate thrust belt beneath the MMT probably occurred earlier than previously believed with faster cooling from peak metamorphic temperatures. Basement and cover sequences were unroofed to the surface early in this thrusting event. Tectonic exhumation may have been achieved by early extensional faulting along the MMT, in accord with the detrital mica cooling ages. Although there may have been an erosional contribution to exhuma-

tion during the earliest stages of the orogeny, the new data remove the previously cited existing evidence for such a contribution.

[46] The revised age for the Balakot Formation reduces the accuracy of the stratigraphically determined timing of collision to between 55–50 Ma and <37 Ma, and the degree of diachroneity determined from stratigraphic constraints is reduced, if present at all. Additionally, the new age for the Balakot Formation removes the Hazara-Kashmir Syntaxis from its previously anomalous position to the otherwise basinwide unconformity separating marine from continental facies. In conjunction with the considerably reduced thickness estimate of the sediments (due to previously unrecognized structural repetition), and negation of sedimentation rates based on the intercalated marl bands, this will allow clearer understanding of the influences on basin evolution.

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