Sedimentology (1996) **43**, 631–646

Transition from foreland- to piggyback-basin deposition, Plio-Pleistocene Upper Siwalik Group, Shinghar Range, NW Pakistan

DAVID A. PIVNIK* and M. JAVED KHAN†
Amoco Production Company, 1670 Broadway, Denver, CO 80201, USA
†Department of Geology, University of Peshawar, Peshawar, Pakistan

ABSTRACT

Plio-Pleistocene synorogenic deposits of the Upper Siwalik Group in the Shinghar Range (Trans-Indus Salt Ranges) of north-western Pakistan record the transition from foreland-basin to piggyback-basin deposition on the hangingwall of the Salt Range thrust. The Siwalik and Upper Siwalik Groups are over 4 km thick in the Shinghar Range. The lower 3 km consists of the Miocene Siwalik Group, which was deposited by a south-flowing foreland trunk stream, the palaeo-Indus River. The upper 1·5 km consists of the Upper Siwalik Group, which is herein divided into three members. The lowest member includes deposits of the south-flowing palaeo-Indus River and is distinguished from the underlying Siwalik Group by the first appearance of conglomerate. The transition from the lower member to the middle member is interpreted as recording uplift on the Salt Range thrust. As the Salt Range thrust was active, the palaeo-Indus River was bifurcated to the east and west around the embryonic Shinghar Range and overbank and lacustrine deposition occurred, represented by the middle member. When the Shinghar Range achieved significant topography, the upper member was deposited by streams transporting gravel and sand that flowed north and west out of the range and into a piggyback basin that formed on the hangingwall of the Salt Range thrust. New and previously published palaeomagnetic stratigraphy and fission-track ages from volcaniclastic deposits within the Upper Siwalik Group provide tight constraints on the chronology of sedimentary-facies transitions and timing of uplift of the Shinghar Range. The integration of sedimentological and geochronological data indicates that motion on the Salt Range thrust and repositioning of the Indus River began at $\sim$1·0 Ma.

INTRODUCTION

The use of foreland-basin synorogenic deposits in dating tectonic episodes within compressional mountain belts has achieved new status as an effective and quantitative approach to understanding styles of deformation and resultant sedimentation within foreland basins (e.g. Johnson *et al.*, 1986; Jordan *et al.*, 1988; Steidtmann & Schmitt, 1988; Pivnik, 1990; DeCelles *et al.*, 1991; Burbank *et al.*, 1992; Lageson & Schmitt, 1994; Pivnik & Johnson, 1995). Despite this, many issues concerning what kinds of sedimentological facies result from tectonic events, particularly foreland thrusting, remain in debate (e.g. Burbank *et al.*, 1988; Heller *et al.*, 1988; Paola *et al.*, 1992) and the danger of using circuitous reasoning in assigning ages to tectonic events by using what may be tectonically unrelated strata still persists. We present a straightforward, chronologically, sedimentologically and structurally well-constrained example of the disruption of a major foreland fluvial system, the Indus River, in response to a foreland deformational event. This study also provides an important data point for the determination of the chronology of Himalayan-foreland deformational episodes.

The Miocene through Recent synorogenic deposits of the Pakistani foreland, the Siwalik and Upper Siwalik Groups, have been the topic of intensive sedimentological and stratigraphical studies since the mid-1970s (e.g. G. D. Johnson *et al.*, 1979, 1986; N. M. Johnson *et al.*, 1985; Burbank *et al.*, 1986; Willis, 1993; Pivnik & Johnson, 1995). These deposits have been used to determine uplift rates of the Himalayan hinterland (Cerveny *et al.*, 1988); to date the first exposure of specific terranes within the hinterland (Cerveny *et al.*, 1989); and to date motion on specific structures within the foreland (Burbank *et al.*, 1986; Johnson *et al.*, 1986; Pivnik & Johnson, 1995). Magnetostratigraphic and tephrachronological dating techniques have provided the framework for unprecedented precision in stratigraphic correlation and determination of the timing of deformational episodes within the Potwar Plateau, Peshawar Basin and Campbellpore Basin, all located within the deformed Himalayan foreland (Fig. 1; Burbank & Raynolds, 1984; Burbank *et al.*, 1986; Johnson *et al.*, 1986; Pivnik, 1992; Pivnik & Johnson, 1995). However, only limited studies have been conducted in the Trans-Indus region of the foreland, west of the Indus River (e.g. Khan, 1983; Khan & Opdyke, 1987; Khan *et al.*, 1988; McCormick, 1984). This paper presents new sedimentological and chronological data, integrated with previous work, to describe and date significant sedimentary-facies changes in the Upper Siwalik Group in the Shinghar Range, part of the Trans-Indus Salt Ranges (Fig. 2). These changes record the uplift of the Shinghar Range and the transition from deposition by the southward-flowing palaeo-Indus River, the main foreland trunk stream, to deposition of braided streams in a piggyback basin that formed on the hangingwall of the Salt Range thrust.

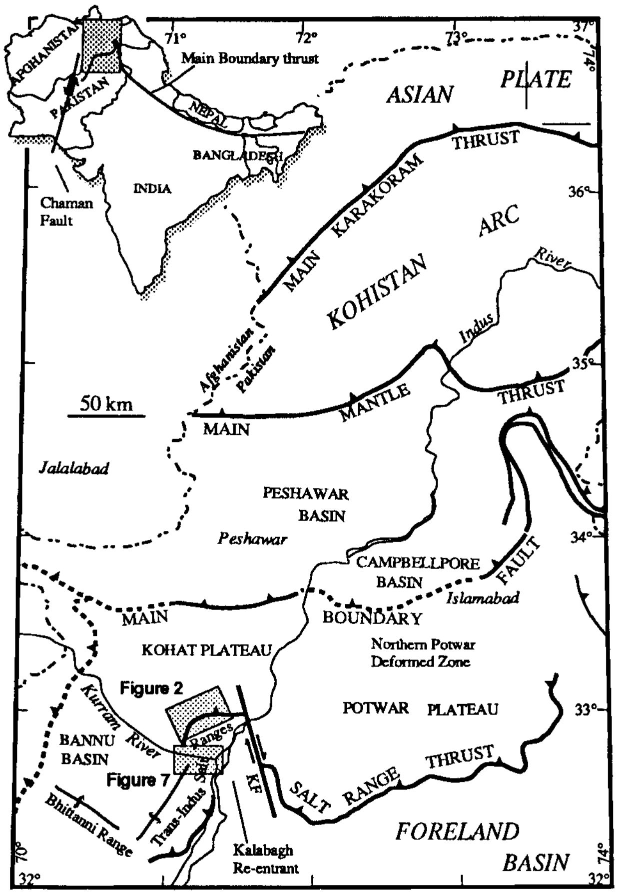


Fig. 1. Generalized tectonic map of northern Pakistan. Location of Fig. 2 shown as shaded box. KF – Kalabagh Fault. Modified from Lillie *et al.* (1987).

REGIONAL GEOLOGY

Ongoing collision between Eurasia and the Indian subcontinent has created distinctive tectonomorphic terrains (Fig. 1). The northernmost terrain is bounded to the south by the Main Karakoram thrust which places rocks of the Asian continental shelf and margin over the Kohistan Island Arc terrain (Tahirkheli, 1979). The Kohistan terrain is bounded to the south by the Main Mantle thrust, which places the ancient island arc over rocks of the northern continental shelf and slope of the Indian subcontinent. These shelf and slope sedimentary and metasedimentary rocks are complexly deformed and are juxtaposed with Miocene foreland-basin sedimentary rocks along the Main Boundary fault (Yeats & Hussain, 1987). Located to the south of the Main Boundary fault, the Northern Potwar deformation zone has been interpreted as a duplex that has propagated toward the foreland underneath a blind, passive roof-thrust (Jaumé & Lillie, 1987; Lillie *et al.*, 1987; Pennock *et al.*, 1989). The Kohat Plateau is the western structural equivalent of the Northern Potwar deformed zone. Although two recent papers have applied the duplex model to the Kohat Plateau (Abbasi & McElroy, 1991; McDougall & Hussain, 1991), Pivnik & Sercombe (1993) and Sercombe *et al.* (1994) have indicated that the Kohat Plateau (as well as the majority of the foreland region) is composed of high-angle, oblique reverse faults, strike-slip faults and pressure ridges. The southernmost exposed major

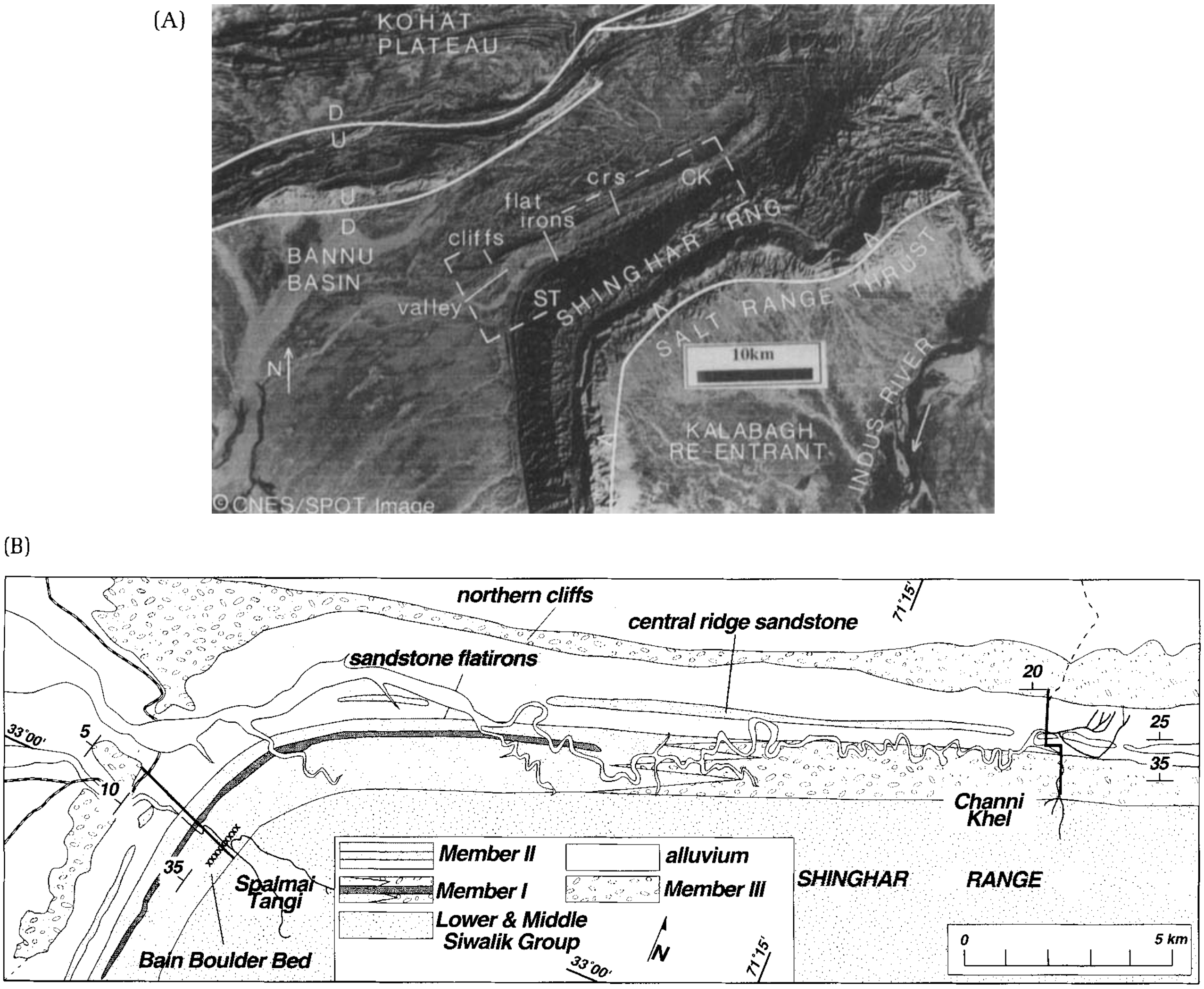


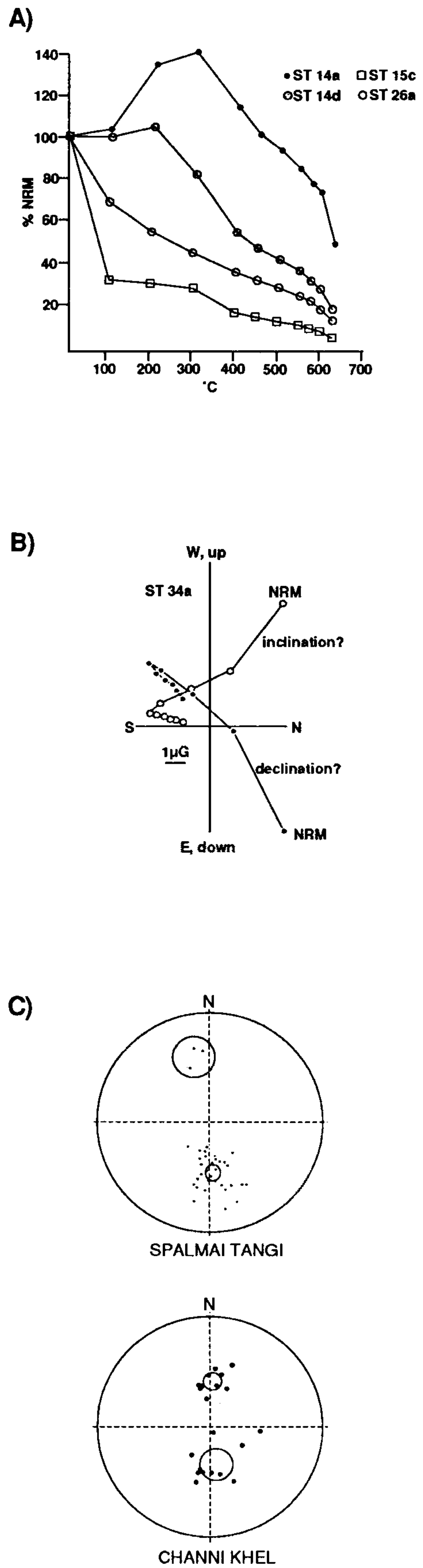
Fig. 2. (A) SPOT image of north-western corner of Shinghar Range, including the locations of the Spalmai Tangi (ST) and Channi Khel (CK) measured sections and the central ridge sandstone (crs). Location of (B) outlined as rectangle. (B) Geological map of northern and western flanks of the Shinghar Range showing correlation of members between the Spalmai Tangi and Channi Khel sections.

fault in the Pakistan foreland is the Salt Range thrust, although Yeats & Lillie (1991) reported a blind thrust fault south of the Salt Range. The Salt Range thrust places an Eocambrian through Pliocene stratigraphic section over undeformed Quaternary foreland deposits of the Indo-Gangetic Plain. West of the Indus River, the Trans-Indus Salt Ranges are composed of several NE–SW- and N–S-trending mountain ranges that rim the Kalabagh Re-entrant (Fig. 1). One of these ranges, the Shinghar Range, contains more than 4 km of N- and W-dipping, red and whitish-green sandstone, conglomerate and shale of the Siwalik and Upper Siwalik Groups. These lie unconformably on the Eocambrian–Eocene sedimentary sequence deposited on the northern Indian continental margin. We focus on the uppermost 1·5 km of the section, the Upper Siwalik Group, and describe how it relates to uplift on the Salt Range thrust (Fig. 2).

MAGNETOSTRATIGRAPHY

Methods

Palaeomagnetic-reversal data were collected from two stratigraphic sections; an ≈1100-m-thick section located near the village of Channi Khel; and a 1500-m-thick section along Spalmai Tangi, near the village of Thatti Nasratti, on the north-central and north-western flanks of the Shinghar Range, respectively (Fig. 2b). Palaeomagnetic-reversal data from these sections have been previously published (Khan & Opdyke, 1987), except for data



from the upper 200 m of the Channi Khel section, which were collected for this study. Twenty-two sites (minimum of three samples per site) were established at the Channi Khel section, and 41 sites at Spalmai Tangi. Samples were orientated in the field with a hand-rasp and Brunton compass, and were cut into 2·5-cm^2 cubes in the lab and spun in a Schondestat spinner magnetometer.

Natural remnant magnetization (NRM) intensities for the samples ranged from 1×10^{-6} to 8×10^{-5} Gauss. Some samples were subjected to stepwise thermal demagnetization from 100 to 660 °C, using intervals of 25–100 °C. Step-vs.-intensity and Zijderveld plots for several of these samples demonstrate the presence of a secondary component of magnetization carried by magnetic grains with blocking temperatures of 300–400 °C (Fig. 3A,B). The magnetization vectors on the Zijderveld plots decay linearly towards the origin from 400 to 660 °C. This implies that a temperature of 400 °C is required to isolate the primary component of magnetization. The remaining samples were subjected to blanket thermal demagnetization to 500 °C, and some were subjected to temperatures of 625 °C for further verification. No significant changes in direction were observed beyond the 500 °C step.

The stable directions of magnetization obtained after thermal demagnetization were corrected for bedding dip and these values were used to calculate the site-mean directions using Fisher's (1953) statistics. All site-mean directions were classified as class A or B. Class A sites consist of three (or four) samples with the same direction, and class B sites have one deviant sample (Khan *et al.*, 1988). From the Spalmai Tangi section 37 sites are class A and four are class B. All of the 22 sites at Channi Khel are class A (Table 1). The reversely and normally polarized site-mean directions are

Fig. 3. (A) Step intensity plot for four samples from the Spalmai Tangi section. Points show successive loss of intensity from original NRM intensity with increasing temperature. (B) Zijderveld plot for thermal demagnetization of a typical sample from Spalmai Tangi. Open circles (declination) are plotted on up-down plane, and closed circles (inclination) are plotted on E–W plane. Scale bar shows vector length (in micro-Gauss) from centre to each data point. Intensities approach zero in a linear fashion at temperatures higher than 400 °C (kink in each line), indicating the minimum temperature that is required to isolate the primary magnetization direction. (C) Stereo plots showing site-mean directions after thermal demagnetization and corrected for bedding dip for Spalmai Tangi and Channi Khel sections. Small circles are 95% confidence cones.

Table 1. Thermal demagnetization data for the Channi Khel section. Site locations are on Fig. 4(B). *N* is the number of samples at each site. NRM Dec. is the natural remnant magnetization declination, in degrees azimuth. NRM Incl. is the natural remnant magnetization inclination, in degrees azimuth. De-mag Dec. is the direction, in degrees azimuth, of declination after thermal demagnetization. De-mag Incl. is the direction, in degrees azimuth, of inclination after thermal demagnetization. *R* is a statistical parameter (Fisher, 1953) that relates the individual vectors for each sample to the mean vector. For values of *N* of 3, *R* should be greater than 2·62. For values of *N* of 4, *R* should be greater than 3·91. *K* is a precision parameter of Fisher (1953). Sites CK-1–11 were subjected to 500 °C thermal demagnetization, and sites CK-12–21 were subjected to 625 °C thermal demagnetization.

Site	*N*	Site mean NRM Dec.	Site mean NRM Incl.	Site mean De-mag Dec.	Site mean De-mag Incl.	*R*	*K*	Class
CK-1	3	190·4	−41·9	192·5	−46	2·99	232·8	A
CK-2	4	189·9	−44·3	188·7	−45·4	3·97	86·84	A
CK-3	3	173·4	−54·9	168	−42·1	2·97	78·25	A
CK-4	3	290·4	−21	121·1	−52·9	2·95	39·82	A
CK-5	3	1	−41	212·4	−56·1	2·92	23·84	A
CK-6	3	283·2	63·5	143·4	−82·6	2·83	11·85	A
CK-7	3	345·1	−10·6	177·7	−44	2·96	45·22	A
CK-8	3	228·9	−32·9	194·3	−42·8	2·99	1079·8	A
CK-9	3	160·3	−33·4	157	−33·1	2·99	302·56	A
CK-10	3	42·7	−20·1	94·6	−41·3	2·96	47·65	A
CK-11	3	207·5	−33·7	193·8	−35·1	2·99	145·01	A
CK-12	3	341·7	50·2	344·7	46·3	2·98	127·2	A
CK-13	4	343	49·2	350·4	48	3·92	37·83	A
CK-14	3	9·8	40	11·8	37	2·98	83·29	A
CK-15	3	352·5	48·8	347·3	48·8	2·99	226·18	A
CK-16	3	352·9	49·4	352·7	60	2·97	72·69	A
CK-17	3	8·5	48·7	7·6	46·8	2·99	135·13	A
CK-18	3	357·7	43·4	358·1	38·3	2·98	107·99	A
CK-19	3	0·3	46·4	18·7	27·5	2·99	324·65	A
CK-20	3	13·7	57·9	23	48·9	2·97	57·57	A
CK-21	3	356	37·9	4·5	33·1	2·97	60·34	A

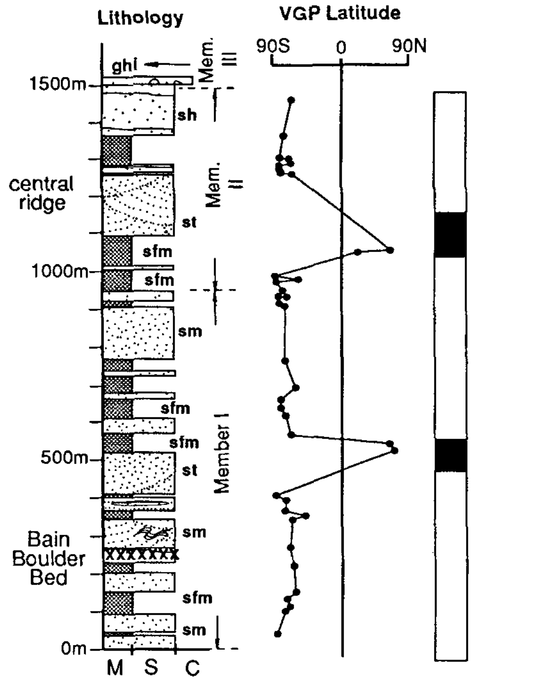
antipolar, suggesting that the stable magnetization was acquired under the influence of the Earth's magnetic field (Fig. 3C).

Spalmai Tangi

Five magnetozones were recognized at Spalmai Tangi (Fig. 4A). Although the section is dominated by reversed polarity, there are two short, normally polarized zones. The correlation of these polarity zones to the magnetic polarity timescale of Cande & Kent (1992) is based upon several pieces of data. First, a diamictite unit which has been correlated to the Bain Boulder Bed in the Bhittanni Range (Fig. 1; Morris, 1938) is located within the lowest reversed magnetozone (Khan, 1983; Khan *et al.*, 1988). Zircon crystals from pumice fragments within this diamictite at Spalmai Tangi were dated using the fission track method (Naeser, 1978) and yielded an age of 2·89 ± 0·6 Ma (Pivnik, 1992). Poage (1991) dated the Bain Boulder Bed in the Bhittanni Range using the same methods and calculated an age of 2·16 ± 0·4 Ma, and these two dates fall within each other's errors. This suggests that the lowest reversed magnetozone lies below the Olduvai subchron and above the Gauss chron (Fig. 5). Second, a jaw of *Elephas* was collected from the lower part of the measured section (Khan & Opdyke, 1987), indicating the presence of Pinjor stage fauna which, in the Potwar Plateau, are found in rocks younger than 3·0 Ma (Opdyke *et al.*, 1979). Third, the dominance of reversed magnetic polarity in the Spalmai Tangi section points to it being correlated with the Matuyama chron. The two short, normal-polarity zones are correlated with the Olduvai and Jaramillo subchrons, respectively (C2n and C1r.1n chrons of Cande & Kent, 1992). Because the top of the section has reversed polarity, it is assumed that the Brunhes chron was not encountered. Thus, the sampled portion of the Upper Siwalik Group at Spalmai Tangi ranges in age from no older than 2·6 Ma to no younger than 0·78 Ma.

Previous to Khan (1983) and subsequent papers by Khan and other authors, the Upper Siwalik sequences exposed in the Shinghar Range were correlated with the Dhok Pathan Formation of the

(A)



(B)

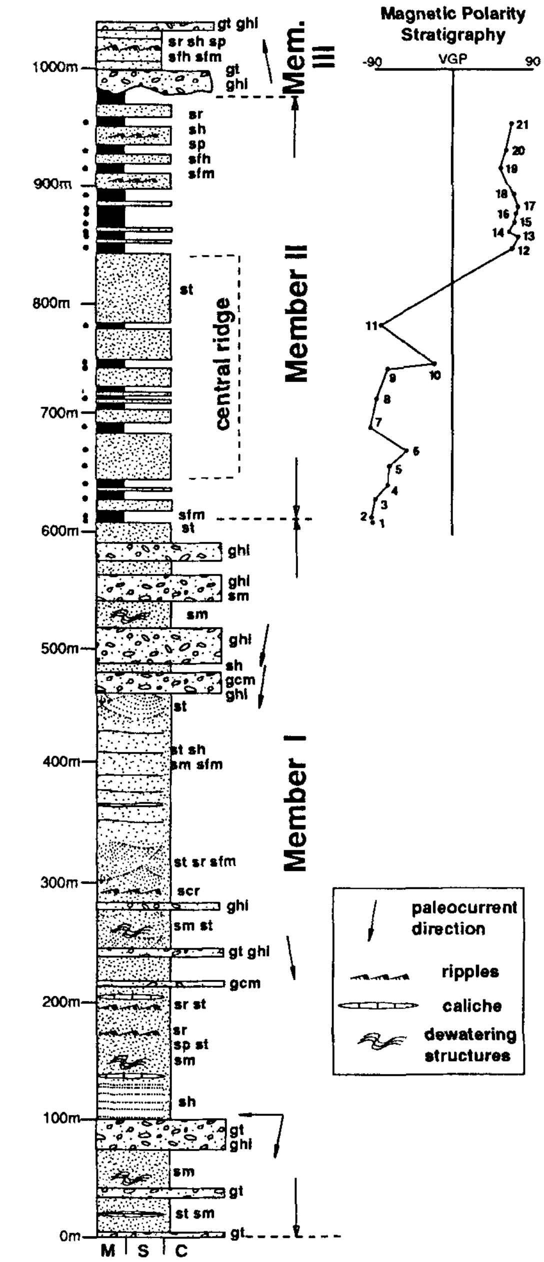


Fig. 4. (A) Log of measured section at Spalmai Tangi. Lithology and magnetic stratigraphy from Khan & Opdyke (1987). VGP – virtual geomagnetic pole, M – mudstone, S – sandstone, C – conglomerate. See (B) for key to symbols and Table 2 for facies codes. (B) Log of measured section at Channi Khel. Palaeomagnetic stratigraphy for 600–800-m interval from Khan & Opdyke (1987). Palaeomagnetic stratigraphy for 800–1000-m interval, and lithological and facies data from this study.

Potwar Plateau (Meissner *et al.*, 1974) which has been dated as being 7·9–5·1 Ma (Johnson *et al.*, 1982). Clearly, the Upper Siwalik sequence in the Shinghar Range is younger than the Dhok Pathan Formation and is instead chronostratigraphically equivalent to the Soan Formation and Lei Conglomerate in the Potwar Plateau (e.g. Pivnik & Johnson, 1995).

Channi Khel

Two magnetozones were identified at Channi Khel (Fig. 4B). Topographic maps and SPOT colour satellite images were used to correlate between the Spalmai Tangi and Channi Khel sections. Correlatable geomorphological features include the stratigraphic position of the Bain Boulder Bed, the topographic break from sandstone flatirons to a major shale-floored valley, a sandstone ridge located in the centre of the valley, and the cliffs on the northern and western edges of the valley (Figs 2 and 5). The Bain Boulder Bed is present only at Spalmai Tangi, but its stratigraphic position correlates to below the base of the Channi Khel section. The lower, reversed-polarity interval at Channi Khel is correlated

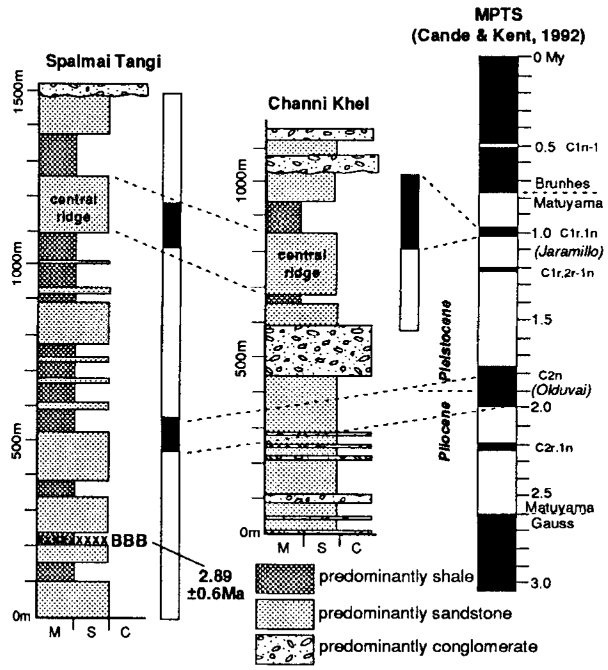


Fig. 5. Correlation of Spalmai Tangi and Channi Khel sections to magnetic polarity time-scale (MPTS) of Cande & Kent (1992). Lithologies are generalized from Fig. 4. Standard names for subchrons given in abbreviations. BBB=Bain Boulder Bed.

with the reversed-polarity interval between the Olduvai and Jaramillo subchrons (Fig. 5; Khan & Opdyke, 1987). The normally polarized interval at Channi Khel is correlated with the Jaramillo subchron. The sampled portion of the Channi Khel section spans from no older than 1·76 Ma to no younger than 0·78 Ma.

SEDIMENTOLOGY

We divide the Upper Siwalik Group of the Shinghar Range into three members based on major lithofacies assemblages. Sedimentological facies are coded according to Miall (1978) and modified by Pivnik (1990). Sedimentary facies codes, descriptions and interpretations are summarized in Table 2. Additional information on sedimentological facies is from McCormick (1984).

Member I: palaeo-Indus River

Description

Member I is over 600 m thick at Channi Khel (Fig. 4B). The lowest major conglomeratic unit in the Siwalik Group sequence was used to locally define the base of Member I. The Siwalik Group below Member I is predominantly sandstone, with only minor lenses of conglomerate (Khan & Opdyke, 1987). The top of the member occurs at a major break in lithology, from dominantly sandstone and conglomerate to dominantly shale and sandstone, and is easily identified on satellite images as the topographic break between flatirons and a shale-floored valley (Figs 2 and 5). Member I at Channi Khel predominantly consists of multistoried, white to green-grey sandstone; conglomerate units that range in thickness from less than 1 m to 25 m; and minor shale horizons.

The majority of sandstone units are generally massive and are either thick bedded (tens of metres) or occur as thin beds and lenses above and within conglomerate facies. Generally massive sandstone units contain dewatering structures such as flame structures and convoluted bedding; isolated, pebble- to cobble-sized clasts similar to glacial dropstones; discontinuous pebble 'stringers'; thin (1–2 cm) calcified horizons which are most likely caliches; concretions; carbonaceous laminations; burrows; and root traces. Other sandstone facies include trough cross-stratified sandstone which contains cross-beds that are defined by heavy minerals or that are lined with pebbles or intraformational rip-up clasts of shale or siltstone. Cross-bed sets are commonly less than 1 m thick, commonly have planar upper bounding surfaces, and dip predominantly to the south. Horizontally laminated sandstone is laterally continuous in outcrop and is defined by alternating layers of well-sorted, dark and light minerals. Ripple-laminated sandstone occurs as thin horizons not more than 0·5 m thick. It is present either above trough cross-stratified sandstone or is closely associated with shaley horizons or caliches. Minor amounts of fine-grained facies such as shale and siltstone occur as massive or horizontally bedded units. Point counts of sandstone samples indicate an average of 29% monocrystalline quartz, 16% feldspar and 54% lithic fragments. Approximately half of the lithic fragments are of igneous or metamorphic rocks, indicating a northern, Himalayan source. Due to the coarse grain size of the samples, sandstone composition was calculated using the 'traditional' method, in which polymineralic lithic grains are counted rather than the mineral constituents in them (Suttner & Basu, 1985).

Conglomerate is clast supported and ranges in size from pebbles to 60-cm boulders. There are three main conglomerate facies. The predominant

Table 2. Sedimentary facies codes, descriptions and interpretations. Based on Miall (1978).

Code	Description	Sedimentary structures	Interpretation
gcm	clast-supported, poorly to well-sorted, tabular or lenticular, pebble-boulder conglomerate	mostly massive, some imbrication and inverse or normal grading	longitudinal gravel bars, dilute sediment-gravity flows, scour fill
gt	clast-supported, poorly to well-sorted, pebble-boulder conglomerate	small- and large-scale trough cross-stratification	small and large 3D ripples, small-channel fill
ghi	clast-supported, moderately to well-sorted, tabular cobble-boulder conglomerate	imbrication, beds often one clast-size in thickness	longitudinal gravel bars, overbank splay deposits
st	moderately to well-sorted, fine- to coarse-grained and pebbly sandstone	small- and large-scale trough cross-stratification	small and large 3D ripples
sp	moderately to well-sorted, fine- to coarse-grained and pebbly sandstone	small- and large-scale planar cross-stratification	small and large 2D ripples, delta foresets, point-bar deposits
sh	moderately to well-sorted, fine- to coarse-grained and pebbly sandstone	horizontal stratification	upper-flow-regime plane beds, subcritically climbing ripples (reworked by wind)
sm	poorly to moderately sorted, fine- to coarse-grained and pebbly sandstone	mostly massive, bioturbation, mottling, vague horizontal stratification, concretions, pebble-clusters	reworked overbank deposits
sr,scr	fine- to medium-grained, well-sorted sandstone	asymmetrical ripple marks, climbing ripplemarks	overbank-splay deposits (when ripplemarks associated with overbank facies)
sfh	clay, silt and very fine-grained sandstone	horizontal stratification	overbank deposits
sfm	clay, silt and very fine-grained sandstone	massive, bioturbation, mottling, concretions	overbank deposits

facies is imbricated conglomerate, which is interbedded with trough cross-stratified conglomerate and massive conglomerate. Thicknesses of imbricated-conglomerate units range from one-clast-thick beds to 25-m-thick units which contain several amalgamated fining-upward sequences. Fining-upward sequences are defined by erosive lower bounding surfaces and concentrations of the coarsest boulders in the lower portion of the sequences. In some cases, lenticular sandstone beds define upper surfaces of sequences. Individual fining-upward sequences are up to 5 m thick. The conglomerate units are laterally continuous for hundreds of metres and interfinger with sandstone units. Conglomerate also occurs as pebble- or cobble-lined troughs and stringers within otherwise sandstone-dominated units. Palaeoflow directions determined from imbricated clasts located at the bases of fining-upward sequences in Member I are toward the south (Fig. 6).

The majority of conglomerate clasts (>95%) were derived from areas to the north, in the Karakoram, Hindu Kush and Himalayan highlands. The predominant lithology is quartzite of varying colours and fabrics, with pyroxene–plagioclase amphibolite, garnet granulite, red and green porphyritic andesite, diorite, metavolcanic rocks with black or green matrices, chert and mylonite. Minor amounts (<5%) of clasts derived from local sources are also present and include grey limestone; grey to tan nummulitic limestone; and hard, white quartz arenite. These were most likely derived from Jurassic–Eocene limestone and sandstone exposed in the nearby Kohat Plateau and on the hangingwall of the Main Boundary fault. No up-section changes in conglomerate-clast composition were observed.

Member I is ~950 m thick at Spalmai Tangi (Fig. 4A). At Spalmai Tangi, there are no major conglomeratic facies to distinguish the Upper Siwalik Group from the underlying Siwalik

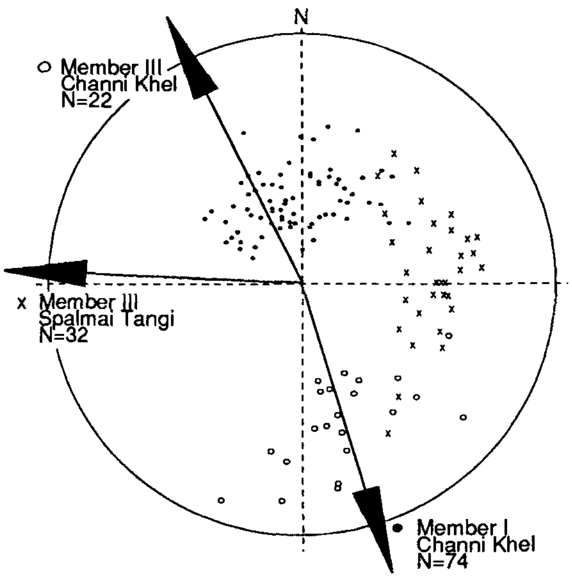


Fig. 6. Equal-angle stereonet showing three populations of palaeocurrent directions, determined from imbricated conglomerate clasts. Dip and dip direction of clasts are shown as points and are corrected for bedding dip. Palaeocurrent directions are 180° from dip directions of clasts. Conglomerate of Member I at Channi Khel shows consistent southward palaeoflow; those of Member III at Channi Khel show northward palaeoflow; and those of Member III at Spalmai Tangi show westward palaeoflow.

Group. Member I is thicker at Spalmai Tangi than at Channi Khel because the base of the member was chosen at the stratigraphically lowest fine-grained lithology suitable for palaeomagnetic-reversal analysis, and does not correspond to the first appearance of conglomeratic facies.

The top of the member is defined the same way as at Channi Khel, by the topographic break between sandstone flatirons and the shale-floored valley. In general, the Spalmai Tangi section contains more shale than the Channi Khel section. Member I is dominated by thick-bedded (several tens of metres), massive sandstone that contains dewatering structures, concretions, hardened calcareous horizons, pebble- to cobble-sized 'dropstones' (as described for Channi Khel) and clast-thick lenses of cobble conglomerate. Trough cross-stratified sandstone is poorly developed, and trough limbs dip consistently to the south. Shale horizons can be up to several tens of metres thick. Shale is orange-red in colour and is generally massive with root traces and burrows. The Bain Boulder Bed is ~300 m above the base of the section and is ~5 m thick. It is tabular with a flat, nonerosive lower bounding surface. Directly below this surface is a 25–50-cm-thick layer of mudstone. Clasts in the Bain Boulder Bed are as large as 25 cm and consist of pumice, gabbro and basalt, dark-grey andesite, gneiss, amphibolite, phyllite, granodiorite, marbled and banded quartzite, dark micritic limestone, white limestone, nummulitic limestone, hard red sandstone and chert. All of these lithologies were derived from western Pakistan and Afghanistan. The Bain Boulder is sedimentologically unlike conglomerate found in other parts of the Upper Siwaliḳ Group because the clasts are poorly sorted, angular, have no depositional fabric and float in a grey, glassy matrix, as identified in thin section.

Interpretation

Member I was deposited within a braided or anastamosing fluvial system that encompassed a wide floodplain with stable interchannel areas. Because of the thickness of the deposits, southward palaeocurrent directions and the presence of clasts that were derived from the Himalayas, we interpret that this was the palaeo-Indus River. Large-scale, epsilon cross-beds, typical of deposits of meandering rivers (e.g. Allen, 1963), are absent in the Channi Khel and Spalmai Tangi sections. Sandstone bodies are tens of metres thick, with little evidence of scouring or amalgamation, suggesting that channels were wide and stable. Imbricated conglomerate was deposited as large, longitudinal barforms located within a wide channel complex. Massive and horizontally laminated sandstone overlying gravel barforms represents upper plane-beds deposited during waning periods of high-flow events, or aeolian-reworked sands that were deposited on top of barforms (Allen, 1965). Trough cross-stratified sandstone was deposited as small-scale, three-dimensional bedforms located within channels during normal flow conditions or on top of longitudinal bars during waning flood conditions. Dewatering structures resulted from rapid changes in water depth during high-flow events, and are similar to Brahmaputra River deposits described by Coleman (1969).

The predominance of massive sandstone, caliche horizons, rootlets, burrows, ripples and horizontal bedding implies that an extensive and stable interchannel deposystem existed between major channels, a characteristic of anastamosing fluvial systems. Sand in the interchannel areas was reworked by aeolian, biological and fluvial processes. Horizontally laminated sandstone closely resembles sand-sheet deposits produced

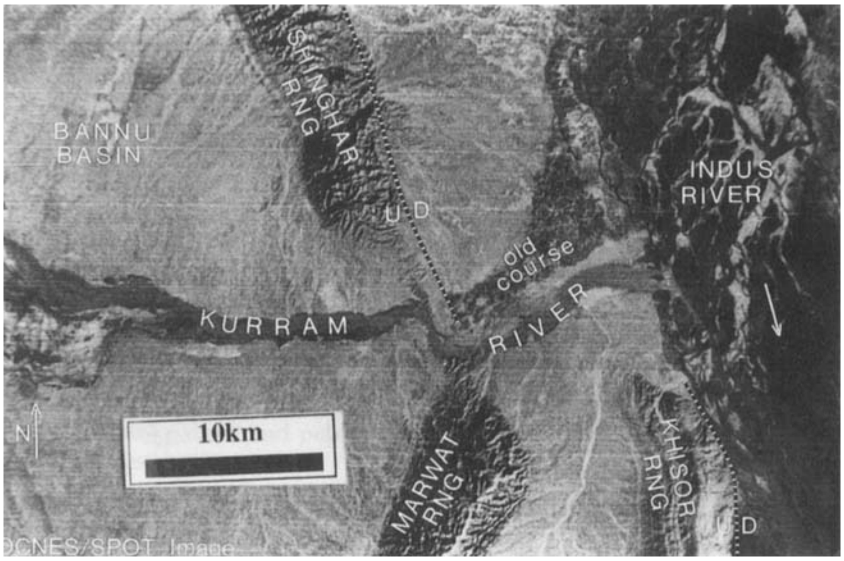


Fig. 7. The modern Kurram and Indus Rivers at the north end of the Marwat Range (see Fig. 1 for location). The Indus River serves as an analogue for Member I, and consists of a braided-channel network with large, longitudinal, gravelly and sandy bars that separate active channels. The deflection of the Kurram River around the uplifted southern end of the Shinghar Range serves as an analogue for the deflection of the Indus River around the northern Shinghar Range during deposition of Member II (central ridge sandstone).

by subcritically climbing wind ripples (Ahlbrandt & Fryberger, 1981; Allen, 1965). Root traces, burrows and dropstone-like solitary clasts attest to the influence of biological reworking; single pebbles were dropped into burrows or depressions during high-flow events, not unlike post-storm lags in the nearshore environment (Clifton, 1981; Pivnik, 1990). Ripple-laminated sandstone was deposited by splays that moved across interchannel bars during flood conditions, or may represent supercritically climbing wind ripples.

Conglomerate facies are rare at Spalmai Tangi, and shale is more common, compared with the Channi Khel section. At Spalmai Tangi, the main fluvial channels carried sand as bedload with very minor gravel. Thus, it is envisaged that while sandy channel facies were being deposited at Spalmai Tangi, the main channels of the palaeo-Indus River system in which large, gravelly bars were being deposited existed to the east near Channi Khel. The width of the palaeo-Indus River floodplain, including main gravelly channels, minor sandy channels, interchannel and over-bank areas, was 25 km or more, based on the distance between Channi Khel and Spalmai Tangi. Nio & Hussain (1984) suggested a similar width of the palaeo-Indus River from equivalent deposits in the Bhittanni Range (Fig. 1).

The modern Indus River south of the Salt Range thrust presents a depositional environment that is analogous to Member I (Fig. 7). In this area, the Indus has a main braided-channel network with large, longitudinal gravelly bars separating active channels. Separating the main channels are large bars or islands that are covered by wind-rippled sand. Between these islands are small channels or ponds. During high flood stages these islands are completely covered by water. Further still from the main channel, these islands are vegetated. Although the Indus cuts a narrow gorge through Palaeozoic bedrock of the Shinghar Range, it is aggrading and actively depositing sand and gravel in the Kalabagh Re-entrant (Fig. 1). The modern Indus River in the Kalabagh Re-entrant has a floodplain width as great as 25 km.

The Bain Boulder Bed has historically been considered a deposit of glacial till (Morris, 1938), but recent workers have described it as the deposit of a volcanic debris-flow, or lahar (Nio & Hussain, 1984; Khan *et al.*, 1985). We agree with the latter interpretation because the unit is matrix-supported, has no internal structure, does not appear to have an erosional lower bounding surface, carries volcanic clasts including pumice and is associated with bentonized volcanic ash at other localities (Johnson *et al.*, 1982). Khan *et al.* (1985) interpreted the Bain Boulder Bed as a channel-fill lahar which flowed east through existing river channels (perhaps the palaeo-Kurram River; Fig. 1) possibly from as far away as the Dasht-i-Nawar volcanic complex in eastern Afghanistan (Bordet, 1975). The horizon of mud-stone below the boulder bed may have served as a glide horizon for the generally cohesive plug of volcanic debris above it. A zircon morphology study by Poage (1991) of a suite of Plio-Pleistocene bentonized ash from throughout the foreland suggested that the zircon crystals, including ones from pumice clasts within the

Bain Boulder Bed, had a singular source. Present knowledge of the ashes within the foreland and of the Dasht-i-Nawar complex indicates that the ashes and the Bain Boulder Bed most likely were derived from eastern Afghanistan (Poage, 1991).

Member II: overbank

Description

Member II is ~475 m thick at Channi Khel and 550 m thick at Spalmai Tangi (Fig. 4). It predominantly consists of poorly exposed, sandy and silty mudstone and forms the strike-parallel valley that can be traced across the northern and western flanks of the Shinghar Range (Fig. 2). Member II is generally poorly exposed; however, McCormick (1984) described exposures east of Channi Khel. Member II contains orange-red, brown and grey mudstone which is locally deformed into tight, small-scale folds; sandstone units arranged in fining-upward sequences; thick-bedded sandstone; minor conglomerate lenses; and clastic dykes.

Sandstone facies are organized in thin, commonly less than 1-m-thick, fining-upward sequences. These sequences have sharp, erosive lower bounding surfaces and grade upward into small-scale trough cross-beds with intraformational rip-up clasts up to 1 m in diameter (McCormick, 1984). Horizontally laminated sandstone is commonly above trough cross-stratified sandstone and some sequences contain ripple-laminated sandstone which grades into massive, fine-grained facies which contain root traces and burrows. A thick-bedded sandstone unit occurs in the middle of Member II, here called the 'central ridge sandstone' because it forms a ridge that runs through the centre of the shale-floored valley (Fig. 2). The sandstone contains similar facies as in Member I. The upper part of Member II forms a set of cliffs on the north and west sides of the shale-floored valley. It predominantly consists of well-bedded, tabular, 1–3-m-thick, fining-upward sequences similar to those in the lower portion of Member II. In general, sandstone is dark grey but washed to a light brown colour by siltstone that is located above the cliffs. Lenses of boulders derived from the north are locally present in the upper part of Member II.

Interpretation

It is evident from the change in lithofacies that there was a dramatic change in depositional processes from Member I to Member II. As opposed to the thick, coarse-grained sandstone and conglomerate units of Member I which represent wide and stable fluvial channels, Member II is dominated by thin, finer-grained fining-upward sequences deposited by floodplain splays and minor channels distal to the main channel of the palaeo-Indus River. The folds and dykes reported by McCormick (1984) reflect influence of seismic activity and active faulting. The cessation of deposition of major fluvial channels indicates that the palaeo-Indus River was deflected from this area during deposition of Member II. We hypothesize that the palaeo-Indus bifurcated around the uplifting Shinghar Range (Fig. 8). The main branch flowed to the east, where it presently cuts a narrow gorge that separates the Salt Range and the Trans-Indus Salt Ranges. The central ridge sandstone represents a west branch that must have flowed around the west end of the Shinghar Range and then south to meet the palaeo-Indus. The modern Kurram River, south of the Shinghar Range, is an excellent modern analogue for this fluvial configuration (Fig. 7). The Kurram has been deflected south, around the southern end of the Shinghar Range. The southern end of the range is a south-plunging anticline, very similar to what the west end of the Shinghar Range must have looked like during deposition of the central ridge sandstone. Unfortunately, no facies are exposed well enough to allow palaeocurrent determination, so we have no quantifiable evidence to support this fluvial model.

Member III: bajada or braidplain

Description

Member III at Channi Khel consists of greater than 100 m of interbedded sandstone and conglomerate that dip gently (20° and less) north and grade into the present alluvial-fan surfaces. The basal conglomerate has a channel-form, erosional lower bounding surface and caps the cliffs to the north of Channi Khel. Facies include massive, clast-supported conglomerate and imbricated conglomerate. Palaeocurrent directions determined from imbricated clasts are toward the north-north-west (Figs 4B and 6). The thickness of conglomerate beds varies from less than 3 m to greater than 25 m. Conglomerate-clast composition is identical to conglomerate in Member I, except that Member III includes clasts of intraformational, grey sandstone which are not in Member I. Interbedded with conglomerate is unconsolidated sandstone

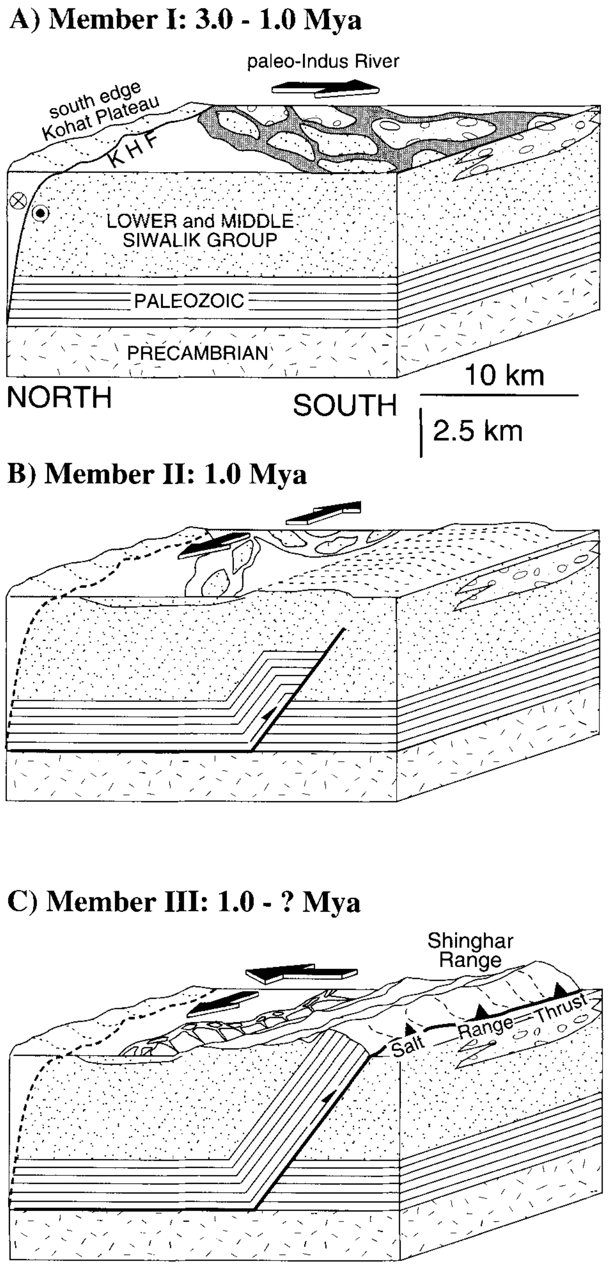


Fig. 8. Depositional model for Upper Siwalik Group in the Shinghar Range. (A) Uplift in the foreland to the north created a proximal source for gravel and the deposition of conglomerate by the south-flowing palaeo-Indus River. (B) Initial uplift along the Salt Range thrust resulted in bifurcation of the Indus around the rising Shinghar Range. The main channel of the river was deflected east, where it exists today, and the other was deflected west. The two branches must have formed a junction to the south, but as the Indus was deflected further east, the west channel was abandoned. (C) Uplift of the Shinghar Range as a major topographic feature created a proximal source for gravel and sand. Braided steams emanated from the mountains and coalesced to form a bajada between the Shinghar Range and the Kohat Plateau.

and siltstone that contain weak, normal grading and ripple laminations. Bed thicknesses are of the order of tens of centimetres and are stacked in sequences tens of metres thick.

Member III at Spalmai Tangi consists of ~50 m of imbricated conglomerate that dips gently (10° and less) to the west and disappears underneath the modern, gravelly alluvium of the Bannu Basin. It caps the low hills that form a discontinuous ridge that can be traced from south of Spalmai Tangi to Member III at Channi Khel and east (Fig. 2). These low hills are presently being dissected by modern streams that drain the Shinghar Range and eventually meet the Kurram River in the central Bannu Basin (Figs 1 and 2). The basal bounding surface of the conglomerate is sharp, planar and erosional, cutting down into poorly exposed sandstone and siltstone of the upper part of Member II. Conglomerate-clast composition is the same as at Channi Khel. Palaeoflow directions determined from conglomerate clast imbrications are to the west (Figs 4A and 6).

Interpretation

Member III is interpreted as the deposits of gravelly streams that emanated from the Shinghar Range. Because no classical, proximal alluvial-fan facies such as mud-supported debris-flow deposits are contained within Member III, and because there is no evidence that meandering streams existed, a gravelly braidplain with local apices at the mountain front is envisaged (see Nemec & Steel, 1988, for alluvial-fan nomenclature). Because Member III can be traced along the entire length of the north flank of the range, and southward to Thatti Nasratti and beyond, it can be surmised that this gravelly braidplain was a continuous bajada.

In comparison with the braidplain deposits of Member III at Channi Khel, those at Spalmai Tangi transported very little gravel and as a result deposited a smaller amount of conglomerate near the mountain front. Because Member I of the underlying Siwalik Group in the western portion of the Shinghar Range served as a source for Member III and does not contain any significant conglomeratic facies, it follows that rivers that had their sources in this part of the range did not transport large amounts of gravel. The present-day divide between streams that flow south into the Kalabagh Re-entrant and those that flow north and west into the Bannu Basin is in the centre of the range, stratigraphically above

Precambrian–Eocene sedimentary rocks. Streams that flow into the Bannu Basin do not contain first cycle gravel derived from Eocene and older rocks of the Shinghar Range, and probably did not during deposition of Member III.

TRANSITION FROM FORELAND TO PIGGYBACK BASIN

Piggyback basins are defined as intermontane basins that form on the hangingwall of an active thrust sheet and that can contain sediments shed dorsally from that thrust sheet (Ori & Friend, 1984). The sedimentological facies and chronostratigraphic analyses presented above define a well-constrained interpretation of the tectonic influences that controlled deposition of the Upper Siwalik Group exposed in the Shinghar Range. In our interpretation, a major, south-flowing fluvial system, the palaeo-Indus River, was displaced and locally replaced by overbank and then north- and west-flowing rivers deposited in a braidplain in a piggyback basin on the hangingwall of the Salt Range thrust (Fig. 8). The geometry of the uppermost braidplain deposits of the two sections and the palaeocurrent directions determined from them leave little doubt that the streams flowed away from the Shinghar Range. The fission-track ages and palaeomagnetic-reversal stratigraphy from each section define a narrow time-window during which thrusting and uplift of the Shinghar Range could have taken place.

During deposition of Member I, a south-flowing palaeo-Indus River with a floodplain that spanned over 25 km in width was positioned with its main channels in the Channi Khel area (Fig. 8a). This configuration of the palaeo-Indus could have existed from as early as 12 Ma (Khan & Opdyke, 1987) and continued until the end of Member I deposition, at $\sim$1·0 Ma (Jaramillo subchron or C1r.1n of Cande & Kent, 1992). The Siwalik Group is over 4 km thick in the Shinghar Range, but thins to the west and east, and contains consistent southward-directed palaeocurrent indicators from the base of the section to Channi Khel (Bonis, 1985; Khan, 1987). This indicates that the channels of the Indus were positioned in this region during the Miocene and Pliocene. The influx of gravels at the Channi Khel section at $\sim$2·5 Ma is interpreted as reflecting uplift of the Kohat and Potwar Plateaux and the ranges associated with the Main Boundary fault, and other studies have also documented uplift of these regions during this time (Burbank & Tahirkheli, 1985; Pivnik & Johnson, 1995). Gravel that was carried by the palaeo-Indus River and formerly deposited in the proximal footwall of the Main Boundary fault was reworked and transported to the south of the uplifting Kohat Plateau and deposited in the vicinity of the Shinghar Range, immediately south of the deformed zone (Fig. 8A). The Bain Boulder Bed records intense volcanism in the hinterland, also a reflection of tectonism and uplift.

During deposition of Member II, only minor channels and overbank splays were being deposited in the Channi Khel and Spalmai Tangi areas. These areas were most likely part of a floodplain between major channels (Fig. 8B). The central ridge sandstone records the last phase of deposition by the palaeo-Indus River in the Channi Khel area (Figs 2, 4 and 5). The central ridge sandstone is time-transgressive and is younger at Spalmai Tangi than at Channi Khel (Fig. 5). We interpret this to reflect westward migration and bifurcation of a part of the palaeo-Indus fluvial system around the rising Shinghar Range (Fig. 8B). Also during deposition of Member II, the major channels of the palaeo-Indus River were deflected eastward, around the rising Shinghar Range and towards the present-day position of the Indus River, where it has eroded a steep gorge through the eastern Trans-Indus Salt Ranges. McDougall (1989, 1990) observed Upper Siwalik Group conglomerate east of Channi Khel that record similar eastward deflection and related it to motion on the Kalabagh Fault which forms the eastern border of the Trans-Indus Salt Ranges. Clastic dykes and soft-sediment slumps within fine-grained units of Member II could be related to tectonic activity on the Salt Range thrust and Kalabagh fault.

Member III represents deposition by braided rivers that emanated from the rising Shinghar Range and flowed northward and westward into a piggyback basin located on the hangingwall of the Salt Range thrust (Fig. 8C). Deposition within this basin, the Bannu Basin, began at some point after the Jaramillo subchronon. Thus, uplift of the Shinghar Range and the transition from deposition by a foreland fluvial system to that within a piggyback basin located on the hangingwall of the Salt Range thrust must have occurred between $\sim$1·0 and 0·78 Ma (0·78 Ma being the age of the base of the Brunhes Chron, which was not observed in either of the sections). Yeats *et al.* (1984) showed that the Salt Range thrust near Jhelum deforms alluvial-fan deposits that are $\sim$0·4 Ma. These deposits could be equivalent in age to the upper part of Member III, which could have been deposited during the Brunhes chron, but for which there is no magnetostratigraphic control because of the coarseness of the facies.

Facies sequences similar to that described above for the Upper Siwalik Group in the Shinghar Range occur throughout the Trans-Indus Salt Ranges. For example, Nio & Hussain (1984) described deposits of the age-equivalent Marwat Formation (correlation by Khan *et al.*, 1988) in the Bhittanni Range (Fig. 1). They concluded that the Marwat Formation consisted of a lower, thick-bedded unit representing deposition in a braided, fluvial system and an upper, thin-bedded and shale-rich unit (which contains two thick sandstone units, interpreted as channel deposits, similar to the central ridge sandstone) that represents deposition in a fluvial system with a lower rate of aggradation. The sequence is capped by conglomerate of the Malaghan Formation. We have observed a similar sequence within the Upper Siwalik Group in the northernmost Marwat Range east of the junction of the Kurram and Indus Rivers, central to the sections presented in this paper and those of Nio & Hussain (1984; Figs 1 and 7). At this locality, thick-bedded, whitish-green sandstone containing minor conglomeratic facies and south-directed palaeocurrent indicators is capped by reddish-orange shale and siltstone. No conglomerate is present in the uppermost part of the section because, like at Spalmai Tangi, the underlying members of the Upper Siwalik Group do not contain significant amounts of conglomerate. We interpret these sequences to record the same phases of syntectonic deposition as the Upper Siwalik Group in the Shinghar Range. Thus, a history of deposition by the palaeo-Indus River, followed by a stage of waning fluvial deposition, and culminating in deposition of locally derived conglomerate is consistent throughout the Trans-Indus Salt Ranges, and records the repositioning of the Indus River and the development of a piggyback basin in response to uplift of the Trans-Indus Salt Ranges.

ACKNOWLEDGMENTS

We thank SPOT Image Corporation for allowing us to use satellite imagery of the Shinghar Range in this paper. Zircon fission tracks were counted by E. Heady at Dartmouth College. Fieldwork was supported from grants to D.A.P. from the National Science Foundation, the Geological Society of America, the American Association of Petroleum Geologists, Sigma Xi, the Albert Cass Fellowship and the Stoiber Field Fund of Dartmouth College. Versions of the manuscript were reviewed by R. G. Raynolds, B. G. Jones, G. D. Johnson, P. G. DeCelles, T. E. Jordan and P. L. Heller. This paper is dedicated to Malik Aleem Hassan of Channi Khel village, who provided gracious hospitality to us and to previous students of Dartmouth College. Mr Hassan died tragically in 1990.

REFERENCES

Abbasi, I.A. and McElroy, R. (1991) Thrust kinematics of the Kohat Plateau, Trans Indus Salt Range, Pakistan. *J. Struct. Geol.*, **13**, 319–327.

Ahlbrandt, T.S. and Fryberger, S.G. (1981) Introduction to eolian deposits. In: *Sandstone Depositional Environments* (Ed. by P. Scholle and D. Spearing), *Mem. Am. Ass. petrol. Geol.*, **31**, 11–47.

Allen, J.R.L. (1963) The classification of cross-stratified units with notes on their origin. *Sediment. Geol.*, **2**, 93–114.

Allen, J.R.L. (1965) A review of the origin and classification of recent alluvial sediments. *Sedimentology*, **5**, 89–191.

Bonis, N.R. (1985) *Paleocurrent Analysis of Siwalik Strata in the Trans-Indus region, northwestern Pakistan.* Senior thesis, Hanover, Dartmouth College.

Bordet, P. (1975) Les volcans récents du Dacht-e-Nawar (Afghanistan central). *Ann. Sci. University of Clermont, Geol. Mineral. Ser.*, **26**, 1–86.

Burbank, D.W., Beck, R.A., Raynolds, R.G.H., Hobbs, R. and Tahirkheli, R.A.K. (1988) Thrusting and gravel progradation in foreland basins: a test of post-thrusting gravel dispersal. *Geology*, **16**, 1143–1146.

Burbank, D.W., Puigdefabregas, C. and Munoz, J.A. (1992) The chronology of the Eocene tectonic and stratigraphic development of the eastern Pyrenean foreland basin, northeast Spain. *Bull. geol. Soc. Am.*, **104**, 1101–1120.

Burbank, D.W. and Raynolds, R.G.H. (1984) Sequential late Cenozoic structural disruption of the northern Himalayan foredeep. *Nature*, **311**, 114–118.

Burbank, D.W., Raynolds, R.G. and Johnson, G.D. (1986) Late Cenozoic tectonics and sedimentation in the northwestern Himalayan foredeep: II. Eastern limb of the Northwest Syntaxis and regional synthesis. In: *Foreland Basins* (Ed. by P. Allen & P. Homewood), *Spec. Publ. int. Ass. Sediment.*, **8**, 222–240.

Burbank, D.W. and Tahirkheli, R.A.K. (1985) The magnetostratigraphy, fission track dating and stratigraphic evolution of the Peshawar intermontane basin, northern Pakistan. *Bull. geol. Soc. Am.*, **96**, 539–552.

Cande, S.C. and Kent, D.V. (1992) A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *J. geophys. Res.*, **97**, 13917–13951.

Cerveny, P., Naeser, N., Zeitler, P., Naeser, C. and Johnson, N. (1988) History of uplift and relief of the Himalaya during the past 18 million years: Evidence from fission-track ages of detrital zircons from the sandstonesof the Siwalik Group. In: *New Perspectives in Basin Analysis* (Ed. by K. Kleinsphen & C. Paola), pp. 43–61. Springer-Verlag, New York.

Cerveny, P.F., Johnson, N.M., Tahirkheli, R.A.K. and Bonis, N.R. (1989) Tectonic and geomorphic implications of Siwalik Group heavy minerals, Potwar Plateau, Pakistan. In: *Tectonics of the Western Himalayas* (Ed. by L. L. Malinconico & R. J. Lillie), *Spec. Pap. geol. Soc. Am.*, **232,** 129–136.

Clifton, H.E. (1981) Progradational sequences in Miocene shoreline deposits, southeastern Caliente Range, California. *J. sedim. Petrol.*, **51,** 165–184.

Coleman, J.M. (1969) Brahmaputra river: channel processes and sedimentation. *Sediment. Geol.*, **3,** 131–239.

DeCelles, P.G., Gray, M.B., Ridgway, K., D., Cole, R., B., Srivastava, P., Pequera, N. and Pivnik, D.A. (1991) History and kinematics of foreland uplift from synorogenic conglomerate, Beartooth Range, Wyoming and Montana. *Bull. geol. Soc. Am.*, **103,** 1458–1475.

Fisher, R.S. (1953) Dispersion on a sphere. *Proc. R. Soc. Lond.*, **217,** 295–303.

Heller, P., Angevine, C., Winslow, N. and Paola, C. (1988) Two-phase stratigraphic model of foreland basin sequences. *Geology*, 16, 501–504.

Jaumé, S. and Lillie, R. (1987) Mechanics of the Salt Range – Potwar Plateau, Pakistan: a fold and thrust belt underlain by evaporites. *Tectonics,* **5,** 57–71.

Johnson, G.D., Johnson, N.M., Opdyke, N.D. and Tahirkheli, R.A.K. (1979) Magnetic reversal stratigraphy and sedimentary tectonic history of the upper Siwalik Group eastern Salt Range and southwestern Kashmir. In: *Geodynamics of Pakistan* (Ed. by A. Farah & K. DeJong), pp. 149–165. Geological Survey of Pakistan.

Johnson, G.D., Raynolds, R. and Burbank, D. (1986) Late Cenozoic tectonics and sedimentation in the northwestern Himalayan foredeep: I. Thrust ramping and associated deformation in the Potwar region. In: *Foreland Basins* (Ed. by P. Allen & P. Homewood), *Spec. Publ. int. Ass. Sediment.*, **8,** 273–291.

Johnson, G.D., Zeitler, P.K., Naeser, C.W., Johnson, N.M., Summers, D.M., Frost, C.D., Opdyke, N.D. and Tahirkheli, R.A.K. (1982) Fission-track ages of late Neogene and Quaternary volcanic sediments, Siwalik Group, northern Pakistan. *Palaeogeol. Palaeoclim. Palaeoecol.*, **37,** 63–93.

Johnson, N.M., Stix, J., Tauxe, L., Cerveny, P.F. and Tahirkheli, R.A.K. (1985) Paleomagnetic chronology, fluvial processes, and tectonic implications of the Siwalik deposits near Chinji village, Pakistan. *J. Geol.*, **93,** 27–40.

Jordan, T., Flemings, P. and Beer, J. (1988) Dating thrust-fault activity by use of foreland-basin strata. In: *New Perspectives in Basin Analysis* (Ed. by K. Kleinsphen & C. Paola), pp. 307–330. Springer-Verlag, New York.

Khan, M.J. (1983) *Magnetostratigraphy of Neogene and Quaternary Siwalik Group of the Trans-Indus Salt Range, Northwestern Pakistan.* PhD dissertation, Columbia University, New York.

Khan, M.J. (1987) Sedimentation and tectonics of the Siwalik Group of the Trans-Indus Salt Range, Northwestern Pakistan. *Geol. Bull. Univ. Peshawar,* **20,** 129–141.

Khan, M.J. and Opdyke, N.O. (1987) Magnetic-polarity stratigraphy of the Siwalik Group of the Shinghar and Surghar Ranges, Pakistan. *Geol. Bull. Univ. Peshawar,* **20,** 111–127.

Khan, M.J., Opdyke, N.D. and Shroder, J.F., Jr. (1985) Bain Diamictite: lithology, age and origin. *Geol. Bull. Univ. Peshawar,* **18,** 53–64.

Khan, M.J., Opdyke, N. and Tahirkheli, R. (1988) Magnetic stratigraphy of the Siwalik Group, Bhittanni, Marwat and Khisor Ranges, northwestern Pakistan and the timing of Neogene tectonics of the Trans-Indus. *J. geophys. Res.*, **93,** 11773–11790.

Lageson, D.R. and Schmitt, J.G. (1994) The Sevier orogenic belt of the western United States: Recent advances in understanding its structural and sedimentologic framework. In: *Mesozoic Systems of the Rocky Mountain Region, USA* (Ed. by M. Caputo, J. Peterson & K. Franczyk), pp. 27–64. Rocky Mountain Association of Geologists, Denver.

Lillie, R., Johnson, G., Yousuf, M., Zamin, A. and Yeats, R. (1987) Structural development within the Himalyan foreland fold-and-thrust belt of Pakistan. In: *Sedimentary Basins* and *Basin-Forming Mechanisms* (Ed. by C. Beaumont & A. Tankard), *Mem. Can. Soc. petrol. Geol.*, **12,** 379–392.

McCormick, D.S. (1984) *The Physical and Magnetic Polarity Stratigraphy of the Upper Siwalik Group, Eastern Shinghar Range, Channi Khel, Pakistan.* Senior thesis, Hanover, Dartmouth College.

McDougall, J.W. (1989) Tectonically induced diversion of the Indus River west of the Salt Range, Pakistan. *Palaeogeol. Palaeoclim. Palaeoecol.* **71,** 301–307.

McDougall, J.W. (1990) Strike-slip faulting in a foreland fold-thrust belt: the Kalabagh Fault and western Salt Range, Pakistan. *Tectonics,* **9,** 1061–1075.

McDougall, J.W. and Hussain, A. (1991) Fold and thrust propagation in the western Himalaya based on a balanced cross section of the Surghar Range and Kohat Plateau, Pakistan. *Bull. Am. Ass. petrol. Geol.*, **75,** 463–478.

Meissner, C.R., Master, J.M., Rashid, M.A. and Hussain, M. (1974) Stratigraphy of the Kohat Quadrangle, Pakistan. *Prof. Pap. US geol. Surv.*, **716-D.**

Miall, A.D. (1978) Lithofacies types and vertical profile models in braided river deposits: a summary. In: *Fluvial Sedimentology* (Ed. by A. Miall), *Mem. Can. Soc. petrol. Geol.*, **5,** 597–604.

Morris, T.O. (1938) The Bain Boulder Bed: A glacial episode in the Siwalik series of the Marwat Kundi Range and Shekh Budin, Northwest Frontier Province, India. *Q. J. geol. Soc. Lond.*, **49,** 385–421.

Naeser, C.W. (1978) Fission-track dating. *US geol. Surv. Open File Report,* **76–190.**

Nemec, W. and Steele, R.J. (1988) What is a fan delta and how do we recognize it? In: *Fan Deltas: Sedimentology* and *Tectonic Settings* (Ed. by W. Nemec & R. Steele), pp. 3–13. Blackie, London.

Nio, S.D. and Hussain, S.T. (1984) Sedimentological framework of Late Pliocene and Pleistocene alluvial deposits in the Bhittanni Range, Pakistan. *Geol. Mijnb.*, **63**, 55–70.

Opdyke, N.D., Lindsay, E.H., Johnson, G.D., Johnson, N.M., Tahirkheli, R.A.K. and Mirza, M.A. (1979) Magnetic polarity stratigraphy and vertebrate paleontology of the Upper Siwalik subgroup of northern Pakistan. *Palaeogeol. Palaeoclim. Palaeoecol.*, **27**, 1–34.

Ori, G.G. and Friend, P.F. (1984) Sedimentary basins formed and carried piggyback on active thrust sheets. *Geology*, **12**, 475–478.

Paola, C., Heller, P.L. and Angevine, C.L. (1992) The large-scale dynamics of grain-size variation in alluvial basins, 2: Theory. *Basin Res.*, **4**, 73–90.

Pennock, E., Lillie, R., Zaman, A. and Yousaf, M. (1989) Structural interpretation of seismic reflection data from the eastern Salt Range and Potwar Plateau, Pakistan. *Bull. Am. Ass. petrol. Geol.*, **73**, 841–857.

Pivnik, D.A. (1990) Thrust-generated fan-delta deposition, Little Muddy Creek conglomerate, SW Wyoming. *J. sedim. Petrol.*, **60**, 489–503.

Pivnik, D.A., 1992, *Depositional Response to the Encroachment of Himalayan Compressional and Transpressional Deformation on the Northern Pakistan Foreland.* PhD thesis, Hanover, Dartmouth College.

Pivnik, D.A. and Johnson, G.D. (1995) Depositional response to Plio-Pleistocene foreland deformation in NW Pakistan. *Bull. geol. Soc. Am.*, **107**, 895–922.

Pivnik, D.A & Sercombe, W.J. (1993) Transpression- and compression-related, evaporite-controlled faulting and folding in the Kohat Plateau, NW Pakistan. In: *Himalayan Tectonics* (Ed. by M. Searle & P. Treloar), *Spec. Publ. geol. Soc. Lond.*, **44**, 559–580.

Poage, M.A. (1991) *Fission-track Ages, Stratigraphic Correlation, and Zircon Morphology of Plio-Pleistocene Volcanic Ashes, Northern Pakistan.* Senior thesis, Hanover, Dartmouth College.

Sercombe, W.J., Pivnik, D.A., Stratton, M.A., Albertin, M., Beck, R.A., Wilson, W.P. and Roth, B.L. (1994) Wrench faulting in the northern Pakistan foreland region. *The Leading Edge*, **13**, 1107–1110.

Steidtmann, J.R. and Schmitt, J.G. (1988) Provenance and dispersal of tectogenic sediments in thin-skinned, thrusted terranes. In: *New Perspectives in Basin Analysis* (Ed. by K. Kleinsphen & C. Paola), pp. 353–366. Springer-Verlag, New York.

Suttner, L.J. and Basu, A. (1985) The effect of grain size on detrital modes: a test of the Gazzi-Dickinson point-counting method–Discussion. *J. sedim. Petrol.*, **55**, 616–617.

Tahirkheli, R.A.K. (1979) Geology of Kohistan and adjoining Eurasian and Indo-Pakistan continents. *Geol. Bull. Univ. Peshawar*, **11**, 1–30.

Willis, B. (1993) Evolution of Miocene fluvial systems in the Himalayan foredeep through a two kilometer-thick succession in northern Pakistan. *Sediment. Geol.*, **88**, 77–121.

Yeats, R.S. and Hussain, A. (1987) Timing of structural events in the Himalayan foothills of northern Pakistan. *Bull. geol. Soc. Am.*, **99**, 161–176.

Yeats, R.S., Khan, S.H. and Akhtar, M. (1984) Late Quaternary deformation of the Salt Range of Pakistan. *Bull. geol. Soc. Am.*, **95**, 958–966.

Yeats, R.S. and Lillie, R.J. (1991) Contemporary tectonics of the Himalayan frontal fault system: folds, blind thrusts and the 1905 Kangra earthquake. *J. Struct. Geol.*, **13**, 215–225.

Manuscript received 23 June 1995; revision accepted 12 December 1995.