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Early Pliocene uplift of the Salt Range; Temporal constraints on thrust wedge development, northwest Himalaya, Pakistan

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ABSTRACT

Recent chronologic and stratigraphic studies in the northwestern Himalayan foreland basin have led to better constrained deformational and depositional histories. In order to test the hypothesis that considerable pre-Pleistocene uplift occurred in the Salt Range of northern Pakistan, the stratigraphic record adjacent to the central and eastern Salt Range has been examined. Unconformities, paleomagnetically documented tectonic rotations across these unconformities, and changes in the paleocurrent directions, provenance, and rates of sediment accumulation serve to delineate an interval of early Pliocene uplift of the Salt Range, as well as several late Pliocene–Pleistocene uplift events in this range and adjacent structures. Stratigraphic, reflection seismic, and structural data indicate that these uplift events resulted from thrusting related to the salt-lubricated Potwar detachment. When considered in conjunction with the chronology of deformation in other parts of the foreland, these data clearly indicate that out-of-sequence thrusting has occurred on a large scale (>100 km) during the past 6 m.y. This pattern of deformation supports the concept that an irregular spatial and temporal distribution of shortening should be expected to occur within an advancing thrust wedge.

INTRODUCTION

Along the proximal margin of a foreland basin, the succession of thrusting events is usually envisioned to progress toward the basin in a sequential fashion (Jones, 1971; Allen and others, 1986). Where out-of-sequence thrusting has been documented in the past, it is typically seen near the basinward thrust front (e.g., Wiltschko and Dorr, 1983) and represents a temporary perturbation of the overall migrating pattern of structural disruption. Although out-of-sequence thrusting undoubtedly occurred previously on a large scale (tens to hundreds of kilometers), the structural and temporal relationships required to define unambiguously the sequence of thrusting frequently have been removed by subsequent erosion (Wiltschko and Dorr, 1983).

Recent studies in the Himalayan foreland basin of northern Pakistan (Fig. 1) have documented out-of-sequence thrusting events on structures as much as 30 km apart (Burbank and Raynolds, 1988; Johnson and others, 1986) and have suggested that such events may have occurred several million years and as much as 120 km apart. In particular, the Riwat fault, which truncates the southern limb of the Soan syncline about 25 km south of the Main Boundary Thrust (MBT), was active 3 to 3.5 m.y. ago, about a million years prior to major deformation along the MBT. Published reports from the southern edge of the Potwar Plateau along the flanks of the Salt Range (Opdyke and others, 1979; Johnson and others, 1982; Johnson and others, 1986) contain data that could be interpreted to represent an even earlier (4 to 5 m.y. ago) episode of uplift and thrusting in this region. We present here the results of our recent efforts to assess the stratigraphic evidence for the presence and timing of early Pliocene deformation of the Salt Range. Our results indicate that considerable uplift, most likely due to thrusting, occurred along at least the eastern Salt Range about 5 Ma. The implications of this event for the history of structural disruption of the Himalayan foreland basin and its relevance to other foreland basins are discussed.

GEOLOGIC SETTING

The ongoing collision of the Indian subcontinent with Eurasia has generated spectacular syntaxial bends at both the eastern

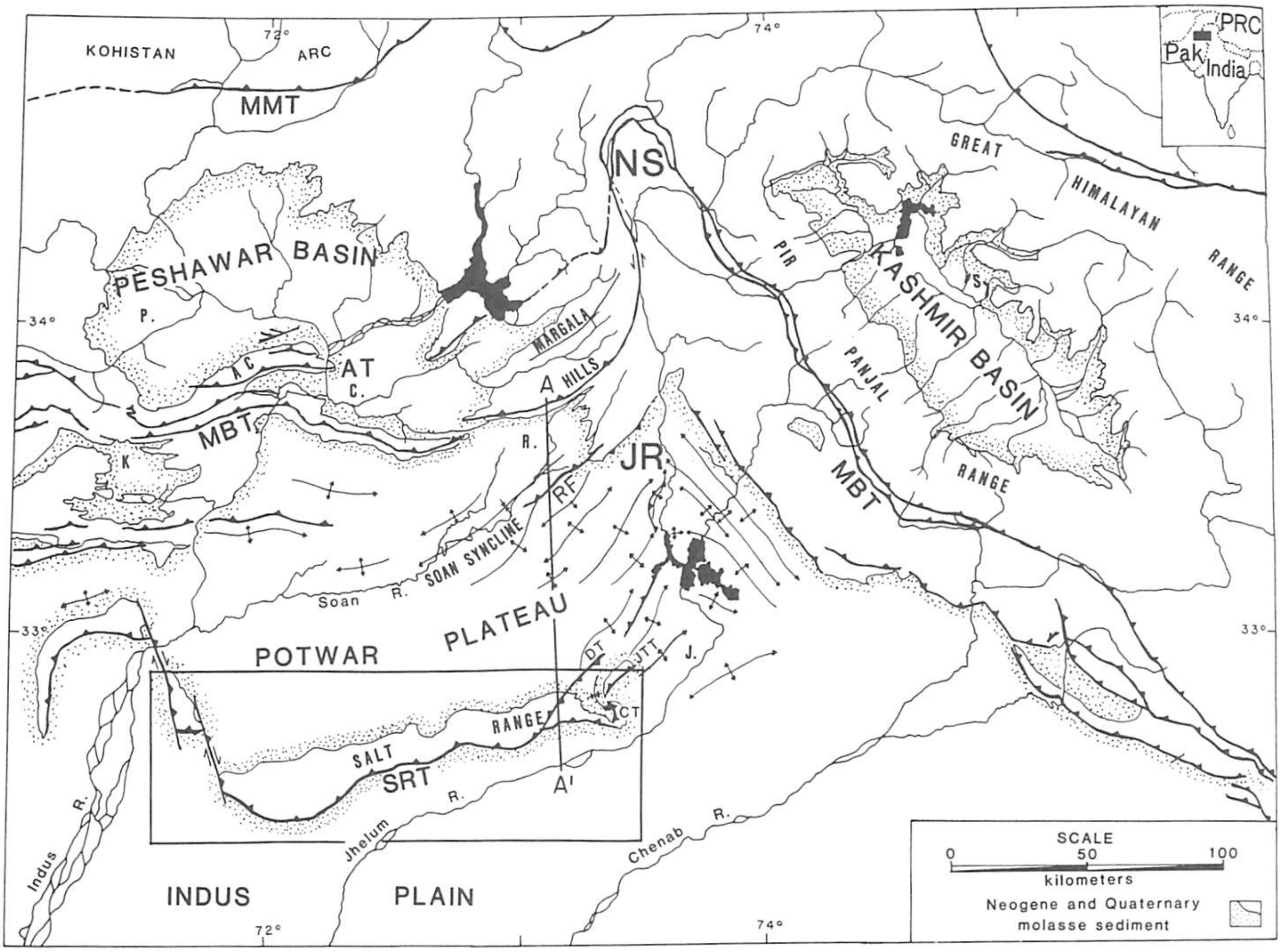

Figure 1. Map of the northwestern portion of the Indo-Gangetic foredeep and the southern margin of the Himalaya and the Hindu Kush in the vicinity of the Northwest Syntaxis (NS). The major anticlinal axes in the deformed molasse sediments, as well as major thrust faults (barbed lines) and strike-slip faults in the region surrounding the Jhelum Reentrant (JR), are delineated. Line A-A′ indicates the position of the cross section in Figure 2. The box surrounding the Salt Range indicates the area covered by the map in Figure 3. Major thrust faults: AT = Attock Thrust; CT = Chambal Thrust; DT = Domeli Thrust; JTT = Jogi Tilla Thrust; MBT = Main Boundary Thrust; MMT = Main Mantle Thrust; RF = Riwat Fault; SRT = Salt Range Thrust. Geographic locations: C = Campbellpore; J = Jhelum; K = Kohat; PRC = People's Republic of China; R = Rawalpindi; P = Peshawar; S = Srinagar. Irregular black areas represent water.

and western terminations of the Himalayan Range. Sharp structural contrasts exist across the axis of the Northwest Syntaxis of northern Pakistan (Fig. 1). The Himalayan Range crest, thrust traces, and associated folds to the east of the syntaxis trend northwest-southeast. West of the syntaxis, these features trend east-west or east-northeast–west-southwest, both in the Hindu Kush and in deformational structures bounding the proximal foreland basin. Lying along the interface between these contrasting provinces, the Jhelum Reentrant displays an intriguing array of interfering structures (Fig. 1). Located to the west of the reentrant and between the Kala Chitta–Margala Hills to the north and the Salt Range to the south, the Potwar Plateau is an allochthonous basin, gliding southward above a low-angle, salt-lubricated detachment, as suggested by Seeber and Armbruster (1979). Apparently situated near the base of the entire Phanerozoic succession beneath the Potwar, this detachment ramps upward beneath the northern Salt Range and breaks the surface along the southern margin of the range (Fig. 2).

The Salt Range itself marks the approximate southern limit of active deformation in this region. The eastern termination of the Salt Range is defined by the WSW–verging Chambal thrust, and the SSE–verging Jogi Tilla structure. Both of these ridges consist of imbricated thrust folds (Fig. 3) (Gee, 1980; Yeats and others, 1984). Between these two structures and the Salt Range proper is the Kotal Kund syncline that preserves a thick succession of syntectonic sediments. Along the axis and southern flank

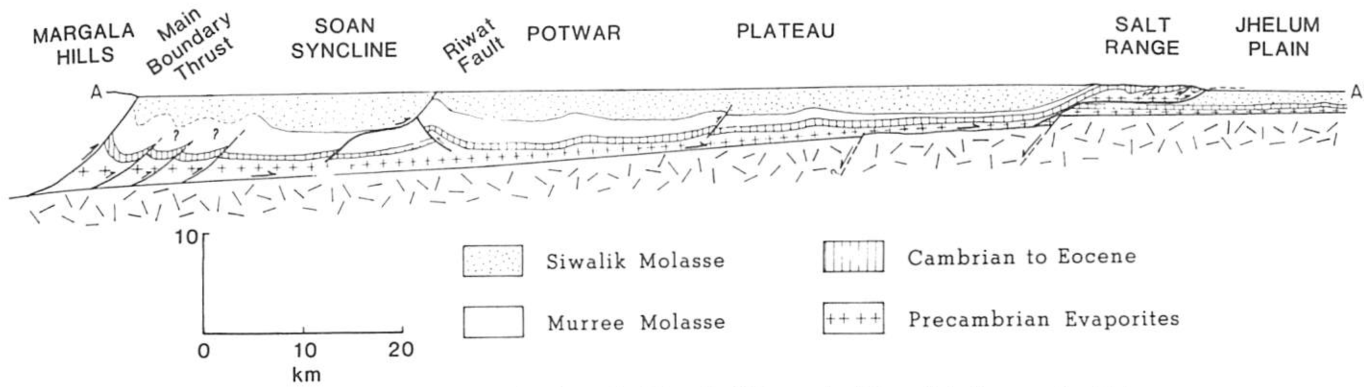

Figure 2. North-south cross section from the Margala Hills north of Rawalpindi across the Potwar Plateau and Salt Range to the Indus Plain. The location of the section is shown by line A-A′ in Figure 1. Control for the southern half of the section comes from seismic data (Lillie and others, 1987) and bedrock mapping (Gee, 1980). The northern third is less tightly constrained, but is based on interpretations of Coward and Butler (1985) and on mapping by Gill (1952) and Raynolds (1980). Deformation within the Potwar Plateau is moderate to slight. There is considerable variation in the style of deformation along the length of the Salt Range (e.g., Butler and others, 1987). In the vicinity of this section, bedrock mapping and seismic and drillhole data indicate that, at the site of the down-to-the-north basement fault, the sole thrust ramped upward to a new detachment level at the base of the molasse. Above this detachment, considerable thickening of the evaporitic beds and stacking of imbricated thrust slices took place. Modified after Lillie and others (1987) and Coward and Butler (1985).

of the Salt Range, most structures verge to the south, although there is considerable evidence for backthrusting in some areas (Gee, 1980; Butler and others, 1987). Several geographically extensive lineaments oriented obliquely to the range and clearly visible in satellite images suggest the presence of major tear faults. The displacement along these features, however, is poorly constrained. The western termination of the Salt Range is defined both by strike-slip faults oriented north-northwest–south-southeast and by southwesterly directed thrust faults (Gee, 1980; Burbank, 1983; Yeats and others, 1984; McDougall, 1985; Butler and others, 1987) related to the lateral ramp that delineates the western boundary of the Potwar detachment.

The Jhelum River skirts the outer eastern margin of the Salt Range and flows parallel to the range front (Fig. 1) before joining the Indus River. Although crustal loading due to thrusting (Beaumont, 1981; Jordan, 1981; Karner and Watts, 1983) has generated a new foredeep axis south of the thrust front, the arid climate and limited catchment areas in the Salt Range, combined with continued subsidence, have restricted the development of extensive alluvial fans. Because the rate of infilling with sediments eroded from the Salt Range is not overwhelming the rate of basin subsidence, fan sediments have not prograded extensively into the foreland. Similar relationships are frequently observed along the faulted margins of rapidly subsiding basins, particularly under arid climatic conditions (e.g., Fraser and Suttner, 1986). In Pakistan this causes the course of the Jhelum River to flow close to the range front, in sharp contrast to the Ganges River to the east, which typically flows more than 100 km south of the Himalayan deformational front.

Whereas extensive molasse sediments accumulated along the northern flank of the Salt Range during Miocene time (Fig. 2), there is little preserved evidence there for deposition during the past 4 m.y. With the exception of the southern portion of Kotal Kund syncline, molasse strata have been gently to moderately tilted and extensively beveled by late Cenozoic erosion. In most areas, only a thin veneer of Plio-Pleistocene sediment caps the truncated strata.

A typical crustal section in the vicinity of the Salt Range (Gee, 1980) consists of: (1) beveled Precambrian basement complex capped by Eocambrian evaporites (Salt Range Formation); (2) Cambrian carbonates and clastics overlain unconformably by Gondwana marine and nonmarine strata, including the Talchir boulder bed; (3) Mesozoic strata that accumulated in large part along the rifted northern margin of Indian Gondwanaland; (4) Paleogene shallow-water carbonates; and (5) a thick succession of mid- to late Cenozoic molasse sediments encompassed by the Rawalpindi and Siwalik Groups (Table 1). The unconformity at the base of the Paleogene gradually cuts down section to the east, such that the Mesozoic succession is absent in the eastern half of the range, and in the Chambal–Jogi Tilla area, the Paleogene rests directly on the Cambrian.

A series of recent studies in the vicinity of the Salt Range delineates diverse structural, stratigraphic, and temporal relationships that provide critical ingredients in our analysis. The Salt Range map series (Gee, 1980) provides a detailed picture of the bedrock geology throughout the entire study area (Fig. 3). Based on these maps, the position of critical source areas, such as the Talchir boulder beds, can be precisely determined, and the thicknesses of overlying strata that have been stripped away to reveal the present bedrock can be estimated. Detailed studies along portions of the Salt Range (Gee, 1980; Yeats and others, 1984; Butler and others, 1987) have served to delineate the geometry

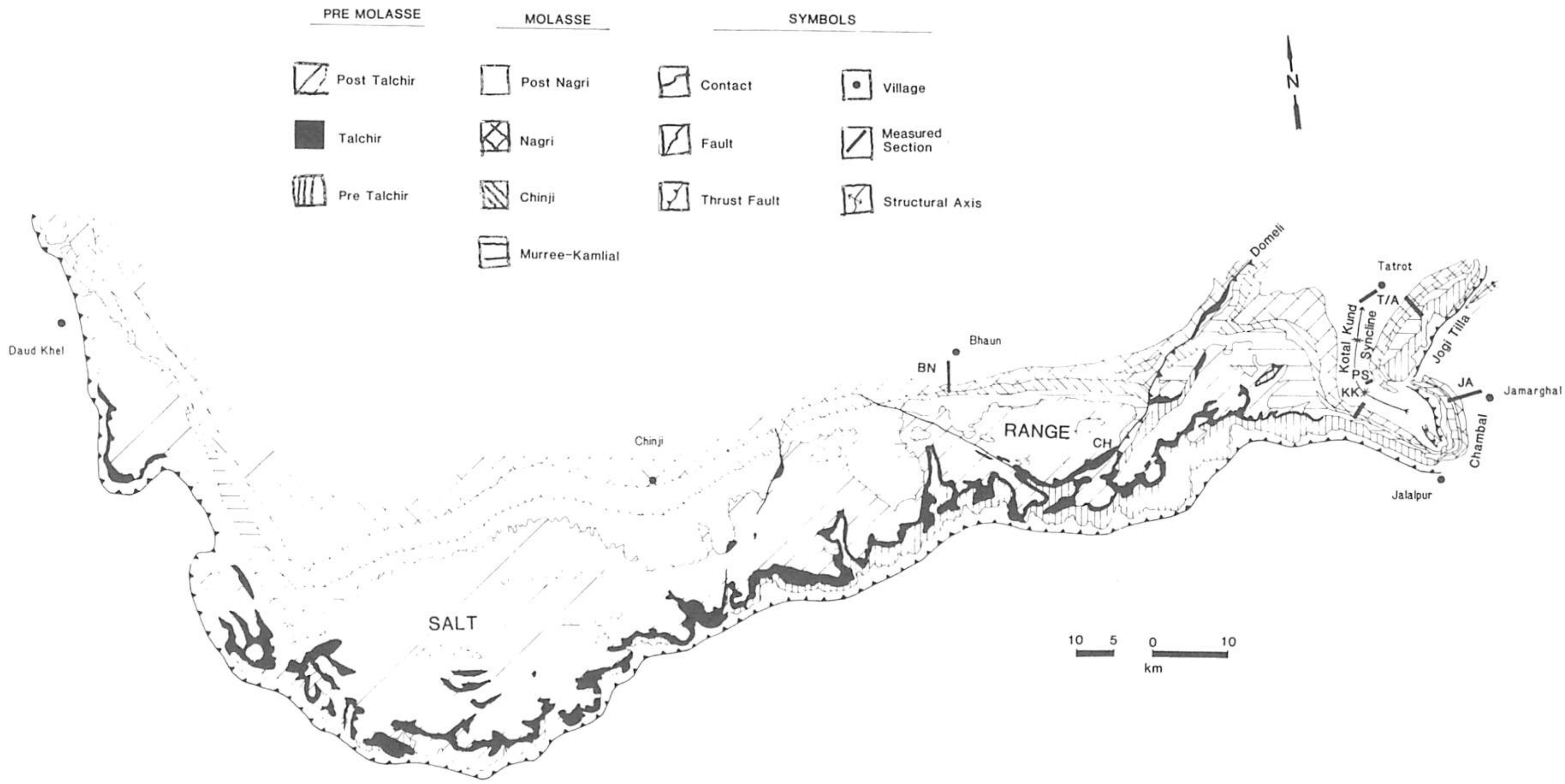

Figure 3. Simplified geologic map of the Salt Range indicating the outcrop patterns of the major stratigraphic units of importance to this study. Chronologic and stratigraphic data were gathered from the following locations: JA = Jalalpur; KK = Kotal Kund; PS = Pind Savikka; BN = Bhaun; T/A = Tatrot/Andar. A monoclinal flexure along the northern flank of the Salt Range exposes the pre-5-m.y.-old molasse sediments. Talchir beds were sampled near Choa Saidan Shah (CH). The absence of Talchir beds east of the Kotal Kund syncline in the Chambal and Jogi Tilla structures is of particular note. Modified from Gee (1980).

of numerous near-surface faults and to aid in structural reconstructions.

TABLE 1. STRATIGRAPHY OF THE HIMALAYAN MOLASSE, NORTHERN PAKISTAN[*]

Group	Subgroup	Formation	Age[†] (Ma)
Siwalik	Upper Siwalik	Soan	0 - 5
Siwalik	Middle Siwalik	Dhok Pathan	5 - 8.5
Siwalik	Middle Siwalik	Nagri	8.5 - 10.6
Siwalik	Lower Siwalik	Chinji	10.6 - 14.2
Siwalik	Lower Siwalik	Kamlial	14.2 - 18
Rawalpindi		Murree	>18

[*] Modified from Fatmai (1973).

[†] Ages from Johnson and others (1982, 1985).

In combination with drillhole data, recent reflection seismic studies (e.g., Lillie and others, 1987; Butler and others, 1987) have provided a three-dimensional perspective on portions of the Salt Range and the Potwar Plateau. These studies have confirmed the existence of the previously postulated (Seeber and others, 1979) low-angle surface that is believed to function as a salt-lubricated detachment surface, and they have delineated a zone of imbricate thrusts beneath the northern Potwar. Of equal significance, these seismic analyses have revealed the presence of at least two down-to-the-north normal basement faults, one with a throw of ~1 km beneath the northern flank of the Salt Range and a second of considerably lesser throw about 20 km farther north (Fig. 2).

Finally, a detailed chronology of molasse sedimentation has been developed during the past decade. Studies utilizing magnetic polarity stratigraphy in combination with fission-track dating of ashes (e.g., Opdyke and others, 1979; Johnson and others, 1982) have provided a remarkably well-constrained record of sedimentation over a broad region during the past 15 m.y. Although a primary focus of these studies was to develop chronologies for interpretation of the prolific faunal record preserved in the Siwaliks (e.g., Pilbeam and others, 1977; Barry and others, 1982), they have also yielded an excellent temporal framework within which to analyze the stratigraphic record.

In this chapter, we utilize the constraints provided by the distribution of bedrock thicknesses and source areas, the seismically determined subsurface geometry of the region, and the magnetostratigraphic chronologies of molasse sedimentation in order to develop a new interpretation of the uplift history of the Salt Range and to discuss its implications for the tectonic development of this region.

METHODOLOGY

Large-scale and rapid bedrock uplift, whether the result of folding or faulting, forces numerous changes to occur in the depositional environment adjacent to the uplift (e.g., Armstrong and Oriel, 1965; Burbank and Raynolds, 1988; Jordan and others, 1987). Although the direct structural evidence for uplift is often obscured or removed by subsequent erosion, the history of uplift can sometimes be reconstructed from the stratigraphic record. Because interpretations of previous studies by Opdyke and others (1979), Frost (1979), and Johnson and others (1986) suggested that uplift of the Salt Range could have occurred sometime between 5 and 2 Ma, we have focused our studies on sections with dated strata of this age.

Our overall strategy was to examine all available dated and measured sections adjacent to the Salt Range and of appropriate age in order to collect data on conglomerate compositions, clast morphologies, unconformities, paleocurrents, and rotations as derived from magnetic studies. Earlier chronologic studies indicate that the lower boundary of the interval of interest at 5 Ma approximately coincides with the Dhok Pathan/Tatrot faunal transition (Opdyke and others, 1979; Barry and others, 1982) and with the Dhok Pathan/Soan formational boundary (Shah, 1977). Consequently, we used magnetic chronologies and faunal and formational boundaries to guide us to the appropriate portions of previously studied sections. Conglomerate compositions and clast morphologies were studied in order to identify unique local source areas that may have been exposed during uplift. Typically, 100 to 200 clasts greater than 1 cm in diameter were counted. In particular, distinctive red porphyritic granitic clasts derived from the Permian Talchir boulder beds can be directly tied to sources in the Salt Range (Fig. 3). Because this represents their first introduction into the Potwar basin, even abundances of Talchir clasts of considerably less than 1 percent carry implications for the uplift and exposure of new source areas. The Talchir Formation includes Gondwanan tillites and associated glaciofluvial rocks. In places, faceted and striated clasts of glacial origin are preserved in a sandy and silty matrix. The red granitic clasts that constitute about 40 percent of the Talchir beds (Table 2) break into subangular to angular blocks when removed from the matrix. Over short transport distances, many of these clasts apparently undergo relatively little shape modification. Consequently, clast morphologies were also utilized to suggest the proximity of source areas.

Laterally extensive angular unconformities provide good evidence of uplift. Due to the nonplanar geometry of many fluvial deposits, however, subtle angular discordances are sometimes difficult to identify with confidence. Stratal truncations exceeding former paleochannel dimensions, rapid changes in bedding dip that persist along strike, and high relief on basal conglomeratic surfaces were utilized to define unconformities that could have resulted from uplift.

Although paleocurrents alone rarely provide incontrovertible evidence for uplift events, they can corroborate other indicators. Paleocurrent directions that diverge strongly from previously determined paleoflow directions for underlying strata and that are oriented away from potential uplifts or along troughs defined by them can reflect the influence of newly formed structural relief on the preexisting drainage network (Burbank and Raynolds, 1988).

TABLE 2. CONGLOMERATE CLAST COMPOSITIONS

Section	Level	Talchir Granites (%)	Lime-stone (%)	Volcanic-Metamorphic (%)	Quartzite (%)	Siwalik (%)	Others (%)
Choa Saidan Shah	Talchir Beds	38	1	19	14	0	18
Pind Savikka*	Soan Fm.	12	20	0	6	62	0
Kotal Kund	Soan Fm.	2	26	0	8	64	0
Jalalpur	Soan Fm.	0	45	0	0	54	1
Kotal Kund	Upper Nagri Fm.	0	14	14	6	63	0
Bhaun	Upper Nagri Fm.	0	3	47	25	13	12
Bhaun	Basal Nagri Fm.	0	2	42	30	14	12

*Data from Frost (1979).

The generally excellent exposures in the Siwalik molasse sediments of northern Pakistan permit ready collection of paleocurrent data. The axes of 15 to 50 large-scale trough cross-beds were recorded at each site where exposures permitted. After correcting for bedding tilt, plunging fold axes, and magnetically determined structural rotations, these directional data were statistically evaluated, and an analysis was made of directional changes within each section.

Differential rotations of strata separated by unconformities provide further evidence for tectonic activity. Because of the abundance of previously acquired magnetic data, considerable rotational information already exists (e.g., Opdyke and others, 1982). In some areas where the timing of rotation events was ambiguous, additional magnetic sites have been collected during this study. These specimens were subjected to step-wise thermal demagnetization up to 550°C, characteristic remanance directions were identified, and declination anomalies indicative of tectonic rotations were statistically defined.

Due both to localized uplift and to new crustal loads resulting from thrusting, the pattern of subsidence and rates of sediment accumulation may be modified adjacent to a new thrust. Within the newly created piggyback basin (Ori and Friend, 1984), rates of both subsidence and sediment accumulation are likely to diminish during thrust development (Burbank and Raynolds, 1988), whereas in the region ahead of the thrust, the newly imposed load should enhance the rates of subsidence and sediment accumulation (Beaumont, 1981). In order to more accurately estimate these rates during each interval of deposition, it is useful to decompact and backstrip the subsequently accumulated sediments, rather than using compacted sediment thicknesses, as has been done frequently in the past (e.g., Raynolds and Johnson, 1985). The decompaction methods described by Sclater and Christie (1980) were used in this study to estimate the appropriate rates for each depositional interval.

Whereas each type of observational data (clast composition and morphology, unconformities, paleocurrents, tectonic rotations, and rate changes) provides supportive evidence for tectonic interpretations, it is the conjunctive use of these observations that permits a strong case for Salt Range uplift to be solidified. A predictive model (Fig. 4) for the stratigraphically recorded changes that might be expected to result from extensive Salt Range uplift would have the following characteristics: (1) abrupt introduction of Talchir clasts and a probable increase in the abundance of Eocene limestone clasts; (2) increased angularity and mean size of clasts due to greatly shortened transport distances; (3) an angular unconformity separating the pre- and post-uplift deposits; (4) northerly oriented paleocurrents in positions close to the northern flanks of the uplift; (5) differential tectonic rotations across the unconformity, with the postuplift strata having experienced less rotation than older strata; and (6) accelerated rates of sediment accumulation in front of the thrust coupled with decreasing rates in the piggyback basin. Although not all of these indicators are observed at every site, many of them are present at several of the study localities.

RESULTS

Data collected during this and previous studies were evaluated at five localities (Fig. 3) adjacent to the central and eastern Salt Ranges: Bhaun, Tatrot/Andar, Kotal Kund, Pind Savikka, and Jalalpur. Analysis of earlier studies of these sections indicated that only data from Bhaun provided some support for an early Pliocene uplift of the Salt Range, whereas data from the other sections were interpreted to represent either early Pleistocene Salt Range uplift or early Pliocene uplift of the Jogi Tilla structure (see Burbank and Raynolds, 1988, for summary). Previously developed magnetic polarity stratigraphies (Opdyke and others, 1979; Frost, 1979; Johnson and others, 1982) provide the time control for each of these successions (Fig. 5). The data for each are summarized below.

Bhaun section

The 1,700-m-thick section measured along Sauj Kas in the south-central Potwar Plateau (Johnson and others, 1982) commences in the Nagri Formation where dips average >30°. Stratal dips shallow toward the north to <5° where the section terminates in the Soan Formation about 2 km from the village of Bhaun (for more precise locations, see Fig. 9 in Johnson and others, 1982). The magnetostratigraphy here (Fig. 5) is interpreted to span an interval from ~10 to 4 Ma. The Dhok Pathan/Tatrot faunal boundary occurs at the 1,500-m level (Johnson and others, 1982), which coincides with the Dhok Pathan/Soan formational boundary (Table 1). A potential unconformity had been previously identified at this boundary (Opdyke and others, 1979), and a differential tectonic rotation occurs across this boundary (Opdyke and others, 1982). The strata of Dhok Pathan and Nagri age (~10 to 5 Ma; Fig. 5) exhibit more than 30° of counterclockwise rotation, whereas the overlying Soan Formation strata are apparently unrotated. In addition, possible Talchir clasts had been reported from the unconformable Soan sequence (Johnson and others, 1986). These data suggest that uplift may have interrupted sedimentation at this site ~5 Ma.

Our results substantiate and expand the data described above. Although stratal dips change very gradually above and below the Dhok Pathan/Soan contact, a 10° shallowing is observable near the contact itself. Moreover, the basal Soan conglomerate locally truncates underlying strata. This conglomerate is dominated by pebble-sized carbonate nodules, Fe-Mn–coated mudstone rip-ups, and scattered Siwalik sandstone clasts. Subangular Talchir clasts up to 2 cm in diameter are present in low abundances (<0.5 percent). The preponderance of Siwalik-derived constituents (pedogenic carbonates, rip-ups, and sandstones), the angularity of the clasts, and the lack of extrabasinal bedrock clasts indicate a generally local source and short transport distances for these conglomerates. Paleocurrent measurements from the basal Soan Formation (Fig. 6) indicate deposition from primarily northward-flowing rivers.

These data strongly contrast with those collected from the underlying sequence at Bhaun. Because of the importance attached to the introduction of Talchir clasts as indicators of uplift, a concerted search was made for additional Talchir clasts in the strata greater than 5 Ma. None were found, and in fact, the conglomerate compositions (Table 1) and clast morphologies are distinctly different from those in the basal Soan Formation. The conglomerates in the older strata occur as channel lags at the base of thick (>5 m) sandstone units. The pebbles and cobbles scattered through the coarse-grained sandstone matrix are dominated by extrabasinal clasts (Fig. 7), primarily quartzites and volcanics. In addition, the clasts are very well rounded and polished, suggesting long distances of transport. Moreover, after the post-depositional counterclockwise tectonic rotation has been removed, paleocurrents in the Nagri Formation trend to the southeast (Fig. 6). This direction is regionally consistent with the essentially longitudinal (west-to-east) drainage system defined by a regional study of the Nagri Formation sites comprising more than 750 paleocurrent measurements at 16 localities (Beck and others, 1987). The mean Nagri-aged direction at Bhaun, however, differs by more than 90° from the mean direction found in the overlying Soan strata, suggesting that the younger system had a different orientation and is likely to have also had a different source area.

Tatrot/Andar section

The Andar section extends northward from the northern flank of the Jogi Tilla uplift (Fig. 3) near the eastern terminus of

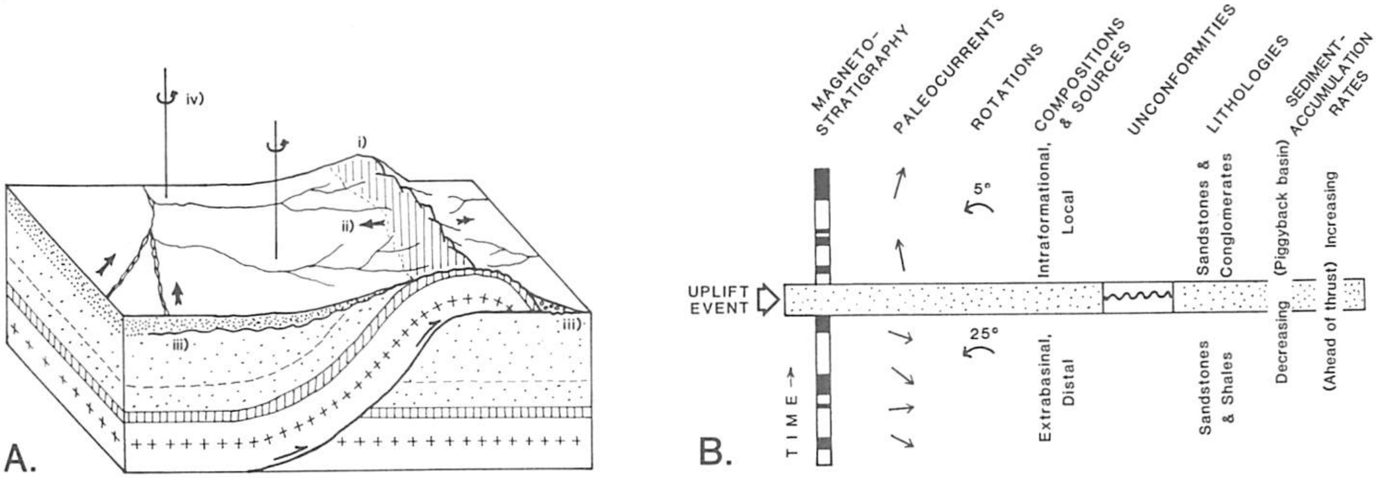

Figure 4. Idealized model of the structural and stratigraphic changes that might result from an interval of thrusting. A, Schematic block diagram in which thrusting has: (1) brought a new source terrain to the surface, (2) caused a change in the current directions on the back side of the uplifted thrust sheet, (3) generated unconformities and upward coarsening sequences resulting from nearby deformation, and (4) imposed a rotation to the upper plate. B, Hypothetical time-controlled stratigraphic data that could serve to constrain the thrusting event. These include temporal gaps in deposition as identified by magnetostratigraphic studies; changes in paleocurrents, provenance, and mean grain size; unconformities and differential rotations across unconformities; and opposing trends in sediment-accumulation rates ahead of and behind the new thrust.

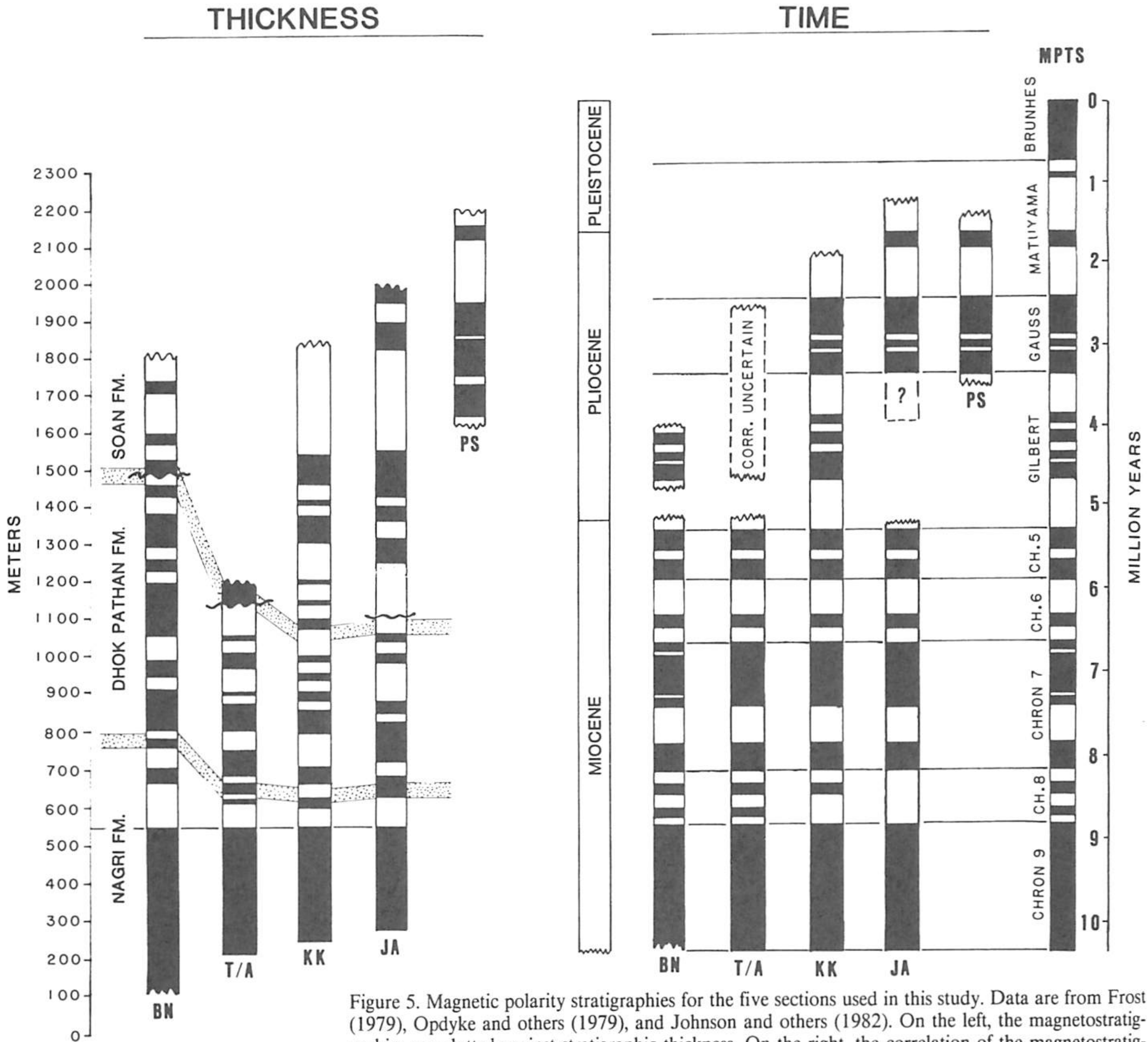

Figure 5. Magnetic polarity stratigraphies for the five sections used in this study. Data are from Frost (1979), Opdyke and others (1979), and Johnson and others (1982). On the left, the magnetostratigraphies are plotted against stratigraphic thickness. On the right, the correlation of the magnetostratigraphies with the magnetic polarity time scale (MPTS) for the past 10 m.y. (Mankinen and Dalrymple, 1979; Berggren and others, 1985) is shown. The correlations are aided by abundant faunal data (Barry and others, 1982) and the presence of volcanic ashes that bracket the Gauss-Matuyama boundary. Portions of these sections cannot be correlated with certainty, and their potential range of correlation is depicted (see text for discussion). BN = Bhaun; T/A = Tatrot/Andar; KK = Kotal Kund; JA = Jalalpur; PS = Pind Savikka.

the Salt Range; it has been successfully tied with correlative and younger strata near Tatrot village some 3 km farther north (Johnson and others, 1982). Although there is some ambiguity in the correlation with the global magnetic polarity time scale, the magnetostratigraphy at Tatrot/Andar (Johnson and others, 1982) is interpreted to span the interval from >10 to ~5 Ma (Fig. 5). The Tatrot biostratigraphic stage (Pilgrim, 1913) is defined at Tatrot village (Fig. 3), where Tatrot-age (Soan Formation) strata rest unconformably on the Dhok Pathan Formation (Opdyke and others, 1979). The age of the basal Soan Formation at Tatrot is uncertain. Due to the brevity of the sequence (<60 m), the magnetic stratigraphy is undiagnostic and could be correlated anywhere between the early Gilbert chron (~4.8 Ma) and the upper Gauss chron (2.5 Ma). Consequently, the temporal gap represented by the unconformity at the base of the Soan Formation cannot be tightly constrained at Tatrot vilage (Fig. 5).

The Dhok Pathan and older strata at Tatrot/Andar have been rotated counterclockwise ~32° (Opdyke and others, 1982). Previously, this rotation and the unconformity had been tentatively interpreted as a result of uplift of the Jogi Tilla structure (Fig. 3) in the early Pliocene (Burbank and Raynolds, 1988). New data require that this interpretation be revised. Thermal demagnetization of specimens collected from the Soan Formation above the unconformity at Tatrot village shows that they, too, have been rotated counterclockwise ($n = 12$; $k = 15$, $\alpha_{95} = 11.2°$, declination = 329.3°, inclination = 33.0°). This declination is not statistically different from the underlying strata (Fig. 8); therefore, it indicates that the primary rotation did not occur across the Dhok Pathan/Soan unconformity, but sometime after 2.5 to 4 Ma, following deposition of the youngest preserved Soan strata. Paleocurrents in the Soan strata at Tatrot village are oriented to the east-northeast and are not significantly different from the Nagri-age paleocurrents determined in adjacent areas (Fig. 6). Consequently, neither rotational nor paleocurrent data provide evidence for uplift at this time.

The presence of an unconformity separating the Soan and Dhok Pathan Formaitons, however, is suggestive of nearby tectonism. Moreover, Talchir pebbles and granules occur in very small abundances (<0.5 percent) in the basal Soan Formation conglomerate. Whereas the presence of Talchir clasts and the subtle unconformity argue for uplift of Talchir source areas, when compared to Bhaun, the smaller clast sizes and the lack of either differential rotation or contrasting paleocurrent directions across the unconformity suggest that the Tatrot sequence was farther removed from the uplift than was the Bhaun region. Finally, the presence of Talchir clasts indicates that the Jogi Tilla or Chambal structures (Fig. 3) could not be the uplifted source area because neither of these areas contains bedrock exposures of the Talchir boulder beds (Gee, 1980).

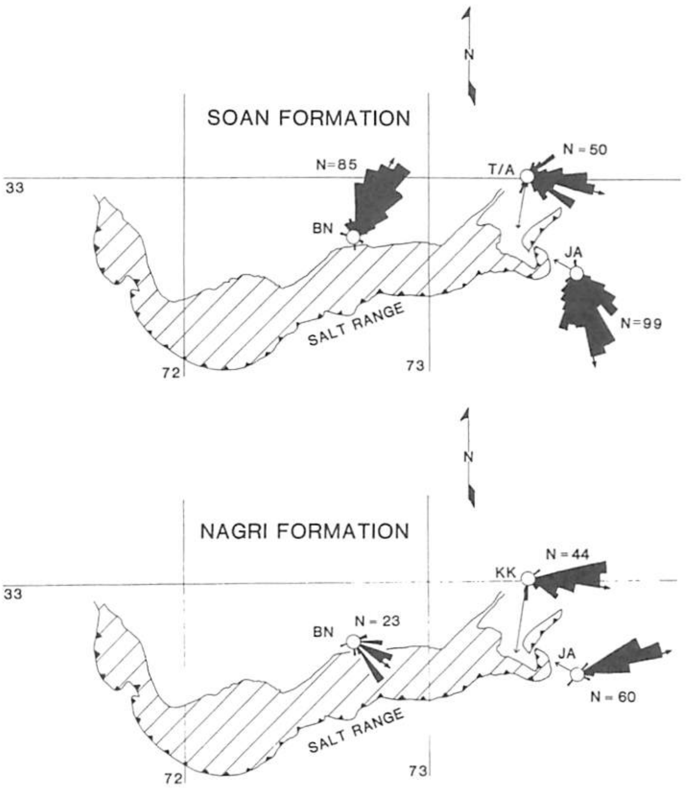

Figure 6. Paleocurrent directions related to Salt Range uplift. Rose diagrams are derived from axes of trough cross beds. Postdepositional rotations defined from tectonic and magnetic data have been removed. Long, thin arrows point to sampling localities. A, Paleocurrent directions derived from Soan Formation strata containing Talchir clasts. These younger directions are dispersed, reflecting flow to the north and south at Bhaun and Jalalpur, respectively, from elevated source areas and easterly flow at the more distal Tatrot villag site. B, Nagri-aged paleocurrents, 9-10 m.y. old, indicate easterly flow of a major fluvial system across the southern Potwar Plateau.

Kotal Kund section

The Kotal Kund section is located along the western limb of the Kotal Kund syncline that delimits the eastern termination of the east-west–trending portion of the Salt Range (Fig. 3). The magnetostratigraphy at Kotal Kund (Johnson and others, 1982) can be readily correlated with the magnetic polarity time scale (Mankinen and Dalrymple, 1979; Berggren and others, 1985); this match indicates the sequence spans an interval from >10 Ma to ~1.8 Ma (Fig. 5). The strata here have been rotated counterclockwise an average of 39° (Opdyke and others, 1982). There is, however, no differential rotation observed at the Dhok Pathan/Soan Formation boundary, nor is there an apparent unconformity at the boundary. The close correlation of the local magnetic results with the global magnetic time scale (Fig. 5) suggests that the measured section contains few significant temporal discontinuities. Insufficient paleocurrent data were collected from the Soan strata to determine reliably any differences between younger and older easterly dispersal systems at Kotal Kund (Fig. 6). At the base of the Soan Formation, however, at ~5 Ma, the clast composition changes significantly. At this stratigraphic level, scattered Talchir clasts as much as 3 to 4 cm in diameter and displaying subangular morphologies appear for the first time. At the expense of extrabasinal volcanics, the proportion of limestone clasts also nearly doubles (Fig. 7), and clasts of Eocene nummulitic limestones become more abundant compared to the underlying upper Nagri Formation (Table 2). As in the Bhaun section, the angularity of the younger clasts is remarkably different from the polished, well-rounded older clasts. Beginning with the basal Soan strata, the proportion of conglomerates increases dramatically upward in the section in comparison to the underlying Dhok Pathan Formation.

Pind Savikka section

The Pind Savikka section is located 4 km north of Kotal Kund along the eastern limb of the Kotal Kund syncline near the southwestern termination of the Jogi Tilla structure (Fig. 3). Al-

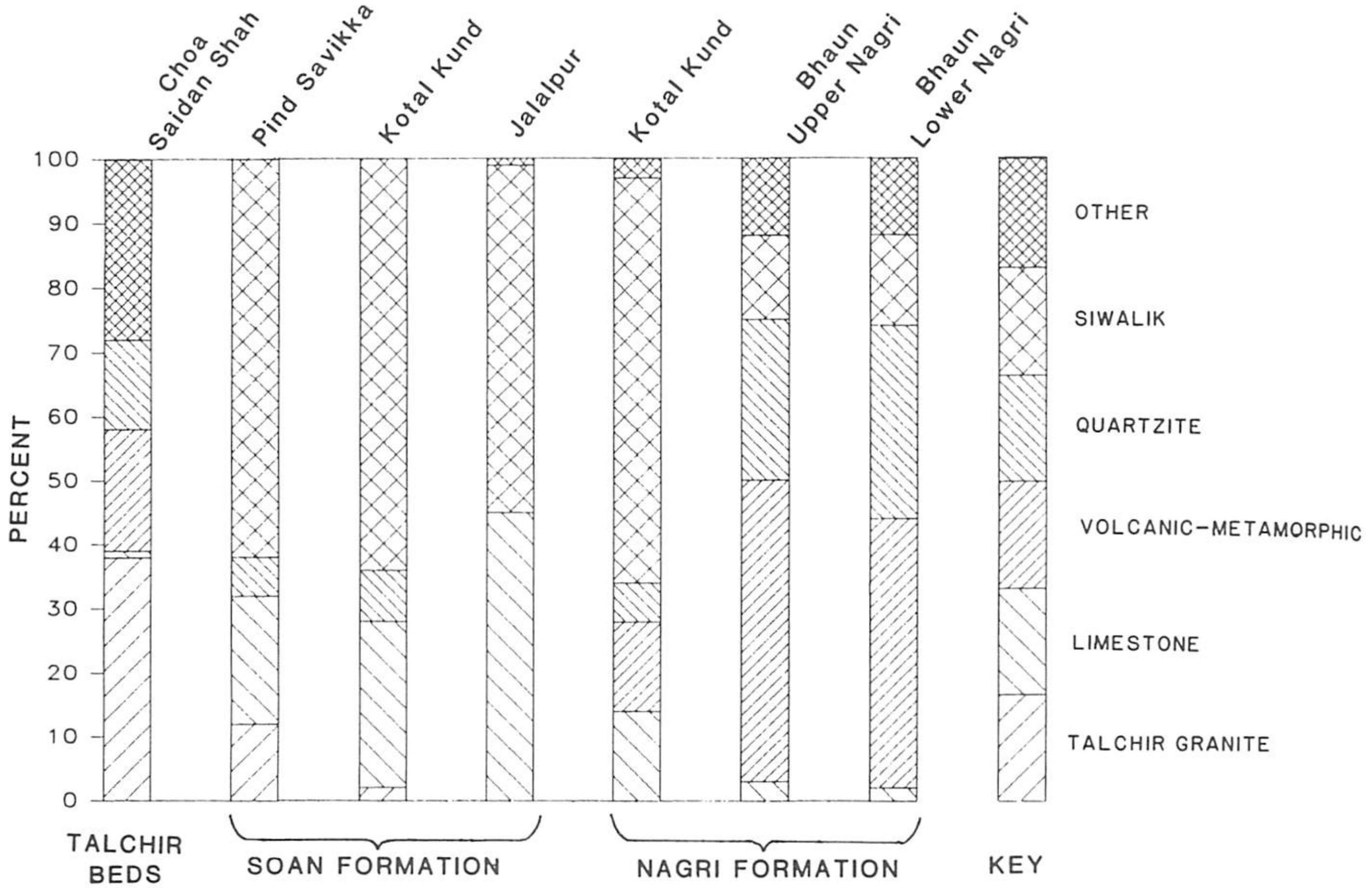

Figure 7. Conglomerate clast compositions for the Talchir boulder bed and for selected molasse strata; 100 to 200 clasts >1 cm in diameter were counted at each site. Only components >2 percent are depicted. In the molasse strata, two stratigraphic levels are compared. The first represent compositions of 9- to 10-m.y.-old Nagri Formation strata. The second represents less-than-5-m.y.-old Soan Formation strata from three localities in the eastern Salt Range. The Talchir boulder bed itself is dominated by the red granitic clasts that first appear in molasse strata younger than 5 m.y. old. In addition to containing Talchir clasts, sometimes in proportions too small to be depicted, the Soan Formation conglomerates contain an increased proportion of intraformational Siwalik clasts and pre-molasse carbonates in comparison to the older Nagri conglomerates.

though a thick succession extending through the Chinji Formation exists here, only the upper 600 m (~1.5 to 3.0 Ma) have been studied in detail (Frost, 1979). The magnetostratigraphy for this upper sequence indicates that the youngest preserved strata are ~1.5 m.y. old (Fig. 5). Although the low levels of alternating-field demagnetization used previously were apparently insufficient to remove all of a postfolding normal polarity overprint, a counterclockwise rotation of about 40° can be discerned in Frost's (1979) magnetic data. Analysis of conglomerate compositions (Frost, 1979) indicates that Talchir clasts appeared within the Soan Formation by at least 2.4 Ma (Fig. 8), and that they increase in abundance up-section until they constitute as much as 15 percent of the conglomeratic clasts (Fig. 7). No data concerning paleocurrents or unconformities are presently available for this section.

Jalalpur section

The Jalalpur section (Johnson and others, 1982) trends easterly along Jamarghal Kas from the eastern flank of the Chambal structure (Fig. 3) near the village of Jamarghal. This section represents the only dated succession presently available south of the major deformed structures of the central and eastern Salt Range. As such, it provides insights into depositional conditions along the Jhelum plain. The magnetostratigraphy at Jalalpur (Johnson and others, 1982) is instructive (Fig. 5). Based on fossil content, volcanic ashes, and the sequence of reversals, it clearly contains both Chron 9 (9 to 10.4 Ma) and the Gauss chron (2.5 to 3.4 Ma). In between, however, relatively few reversals have been discovered, and no reliable match can be made with the magnetic time scale. Given the density of sampling used

(Johnson and others, 1982), the paucity of reversals between 9 and 3.4 Ma can be used to argue statistically (Johnson and McGee, 1983) that a considerable amount of time is not stratigraphically preserved during this interval. No major hiatus, however, was identified in the succession during previous studies. In contrast to the other localities described north of the major deformational front, the Jalalpur section has undergone relatively minor (<10°) tectonic rotation (Opdyke and others, 1982). Talchir clasts are present in the section at ~2.0 Ma and persist into younger strata. Paleocurrent studies of the Gauss-age and younger Soan Formation strata indicate that they were deposited from rivers flowing nearly due south (Fig. 6). This direction contrasts sharply with the east and east-northeast directions observed in the Nagri Formation at Jalalpur for the top and bottom of Chron 9, respectively (Fig. 6).

DISCUSSION

The results described in the preceding section provide clear evidence for an episode of early Pliocene uplift of the Salt Range, and can be used to place constraints on several other tectonic events in the vicinity of the Potwar Plateau. Built on earlier studies at Bhaun, new analyses there, at Kotal Kund, and at Tatrot village demonstrate that Talchir clasts appear abruptly in the Siwalik sequence around 5 Ma, with nearly simultaneous appearances at all three sites in the basal Soan Formation (Fig. 8). Unconformities are associated with this compositional change at Bhaun and Tatrot, and the major paleocurrent change at Bhaun (Figs. 6, 8) suggests a new source area formed to the south at this time. The post-unconformity paleocurrent patterns at Bhaun and Tatrot suggest that a northerly- to northeasterly directed consequent drainage system developed on the north slope of the newly uplifted terrain and merged into an easterly directed depositional trough in more distal locations (see model, Fig. 4).

On the east side of the Kotal Kund syncline at Pind Savikka, clast compositional data from Frost (1979) indicate that the abundance of Talchir clasts increased from ~1 percent around 2.4 Ma to >10 percent by 1.7 Ma. This gives clear evidence for continued late Pliocene erosion of Talchir source areas in the Salt Range, but does not appear to coincide with the timing of the earlier episode of uplift (Fig. 8). Because the older portions of the Pind Savikka exposures have not been examined in detail, it is possible that the diachronous "first appearance" of Talchir clasts between Pind Savikka and other sections may be more apparent than real. At both Tatrot village and Bhaun, the abundance of Talchir clasts is <1 percent when they first appear. If a lower cut-off of 1 percent had been used to define their first appearance (as done by Frost, 1979), the Talchir clasts would not be documented until much higher in these sections, if at all. In addition, the persistence of sedimentation both at Kotal Kund and Pind Savikka until about 1.5 to 2.0 Ma suggests that the structural low of the present syncline may have been a long-lived feature at the eastern termination of the Salt Range that focused sedimentation along an axial trough and prevented earlier progradation of Talchir-bearing sands and gravels across the trough to Pind Savikka from the west.

Similar to the record from Pind Savikka, the data from Jalalpur indicate the presence of Talchir clasts by 2 Ma. Although a substantial hiatus is likely to exist between the strata that are 3.4 to 9.0 m.y. old, the unconformity marking this gap has not yet been identified. Such an unconformity could be a likely response to uplift of the nearby Salt Range. However, the absence of reliable temporal control in the early Pliocene precludes clear delineation of this event in the stratigraphic record. Whereas both the modern rivers and those flowing across this area during the interval from 9 to 10 Ma yield easterly current indicators, the late Pliocene streams that were transporting Talchir clasts were flowing almost due south (Figs. 6, 8). Perhaps the drainage system at that time was a continuation of the previously described Kotal Kund structural trough.

In addition to delineating an episode of early Pliocene uplift in the Salt Range, data from the sites near the eastern terminus of the range provide constraints on the deformation of the Chambal and Jogi Tilla structures (Fig. 3). The magnetostratigraphic records from Kotal Kund, Pind Savikka, and Jamarghal indicate that "typical" molasse sedimentation persisted until ~1.5 Ma. If the Kotal Kund syncline were in existence prior to this (as was hypothesized above), it was certainly a low-amplitude feature with gentle limbs in the late Pliocene. Considerable Pleistocene folding of the Kotal Kund syncline, and both uplift and eastward tilting of the Jalalpur section, occurred sometime after 1.5 Ma. The folding of at least the northern and central portions of the Kotal Kund syncline is viewed as a direct response to uplift and thrusting of the Jogi Tilla structure. The tectonic rotation of 30° at Tatrot village that is shown here to postdate the early Pliocene episode of Salt Range uplift is constrained only to be younger than about 4 to 2.5 Ma (Fig. 8). It is most likely to have also resulted from deformation of the Jogi Tilla structure, probably in early Pleistocene time. The easterly trending, southern portion of the Kotal Kund syncline may also have been deformed due to Jogi Tilla thrusting. Its orientation, however, parallel to the Salt Range and perpendicular to Chambal ridge (Fig. 3), suggests that at least part of the folding may be attributable to early Pleistocene Salt Range deformation, perhaps backthrusting, as suggested by Butler and others (1987). The termination of the Jalapur record at ~1.5 Ma indicates that Chambal ridge is likely to have been deforming contemporaneously with both the Jogi Tilla structure and the adjacent Salt Range in the early Pleistocene.

Examination of sediment-accumulation rates (Table 3) lends additional support to these ideas. At the sections where data are available within the piggyback basin above the Potwar detachment (Bhaun, Tatrot/Andar, Kotal Kund), there is a significant (~50 percent) decrease in the mean sediment-accumulation rate from 9 Ma until 5 Ma. This decrease could represent depocenter migration to more distal sites, as observed and expected in foreland basins (Beaumont, 1981; Raynolds and Johnson, 1985). However, higher rates of Dhok Pathan deposition are observed farther north (Raynolds, 1980; Occidental Petroleum, unpub-

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TABLE 3. DECOMPACTED SEDIMENT–ACCUMULATION RATES

Section	Chron 9 (8.92–10.42 Ma) (cm/ka)	Chron 6-5 (5.35–6.70 Ma) (cm/ka)	Chron 3 (Gauss) (2.47–3.40) (cm/ka)
Kotal Kund*	33	16	34
Tatrot/Andar*	34	21	-
Bhaun*	42	27	-
Jalalpur*	27	-	42
Pind Savikka†	-	-	40

*Compacted data from Johnson and others (1982).
†Compacted data from Frost (1979).

lished well logs). Consequently, it appears that the depocenter locally migrated north to a more proximal position and that decelerating subsidence was a precursor to uplift along the northern flank of the Salt Range.

At sites where extensive deposition continued following uplift (Kotal Kund, Pind Savikka, Jalalpur), middle to late Pliocene sediment-accumulation rates accelerate and actually attain higher rates than recorded during Chron 9 (Table 3). These enhanced rates may be a response to deformation along lateral ramps during thrusting and a resultant focusing of deposition along newly formed subsiding depressions (such as the Kotal Kund syncline) adjacent to the uplift.

Whereas the proximity of the deformed Siwalik sediments near the eastern terminus of the Salt Range to clearly thrusted structures suggests a direct causal link between thrusting and observed deformation in the early Pleistocene, the cause of early Pliocene Salt Range uplift is more obscure. This uplift might have resulted from either thrusting or from normal faulting: both mechanisms could cause differential uplift of the molasse basin, and both are reasonable possibilities in this setting. Motion along the down-to-the-north normal fault underlying the northern edge of the central and eastern Salt Range (Lillie and others, 1987; Fig. 2) could cause ~1 km of relief. Due to the possibilities either for considerable thickening of the evaporite-rich Salt Range Formation (Butler and others, 1987) or for stacking of imbricated thrust sheets, thrusting could generate even greater amounts of relief.

The key to distinguishing between these two possibilities is implicit in the stratigraphic data. Uplift had to be sufficient to strip off both the molasse sediments and the Paleogene-to-Permian carbonates and clastics in order to expose the Talchir beds as a source area. If this uplift took place at 5 Ma, it would have involved the entire molasse sequence of Dhok Pathan age and older. Along the north flank of the present Salt Range, these molasse strata are more than 3 km thick (Gee, 1980; Occidental Petroleum, unpublished well logs). The source of the Talchir clasts lies 10 to 25 km farther south, and, because the large-scale geometry of the foreland basin is probably controlled by lithospheric flexure due to loading (Beaumont, 1981; Jordan, 1981), the molasse wedge could be expected to taper toward the south. Based on an extrapolation of the preserved geometry of the molasse sediments, however, the change in average thickness is likely to have been less than 500 m. The thickness of Paleogene to Permian succession is highly variable along the length of the Salt Range (1,500 to 0 m). In the central Salt Range, which was the apparent source area for much of the Soan Formation preserved at Bhaun, the pre-molasse sequence above the Talchir strata is about 300 m thick. Consequently, in order to expose Talchir beds in the early Pliocene, at least 2,800 m of strata would have had to be eroded. This thickness greatly exceeds the throw of the down-to-the-north normal faults (Fig. 2). We conclude, therefore, that differential uplift due to normal faulting would have been insufficient to cause the observed depth of erosion. Additional support for this conclusion comes from the magnetic data from Bhaun showing that strong rotations occurred synchronously with Salt Range uplift (Fig. 8). It is difficult to envision 30° of counterclockwise rotation occurring due to normal faulting at sites that were more than 20 km from the fault zone at 5 Ma and were unlikely to have been actively involved in the deformation. Consequently, we conclude that an early Pliocene episode of thrusting along the Salt Range was responsible for the extensive uplift and erosion of Mesozoic and Tertiary strata in the early Pliocene. Uplift of this magnitude (>2.5 km) could be accomplished through massive thickening of the Eocambrian evaporites and/or detaching and stacking the entire Phanerozoic sequence either above the Salt Range Formation or above some other horizon of decoupling, such as the lithologic contrast between the Talchir beds and the underlying Cambrian strata (Butler and others, 1987).

Within the Salt Range itself, seismic data (Lillie and others, 1987) indicate a total depth to basement of 3 to 5 km, and drillhole data indicate more than 2 km of salt in places (Khan and others, 1986). Although molasse strata are 2 to 3 km thick on the upper and lower thrust plates to the north and south of the range, respectively, the seismic and drillhole data indicate that there is no appreciable thickness of molasse in the lower plate in the Salt Range itself. This suggests that, whereas the detachment appears confined primarily to the evaporite horizon north of the Salt Range, it cut up-section to the carbonate-molasse contact, when it ramped abruptly upward at the north edge of the Salt Range (Fig. 2). Because the Murree strata are tapering rapidly to the south in this region, this horizon in the Salt Range may be a kinematically weak zone resulting from 20 m.y. of post-Eocene weathering. These detached molasse strata were then thrust to the south, eroded, and buried along the site of the modern Jhelum plain. Comparable thicknesses of molasse strata have been nearly entirely eroded from the crest of the entire present-day Salt Range.

CONCLUSIONS

The analysis presented here provides new evidence for major deformational events within the northwestern Himalayan foreland basin during the Pliocene and Pleistocene. Chronologies based on magnetic polarity stratigraphies provide refined temporal constraints on these events. Data from the central and eastern Salt Range indicate that a major event of thrusting around 5.0 Ma caused over 2.5 km of uplift and concomitant rotations locally. Thrusting and uplift occurred along the Chambal and Jogi Tilla structures around 1.5 Ma, and thrusting was also probably active concurrently in the easternmost Salt Range (Butler and others, 1987). These later events determined the present form of the Kotal Kund syncline and the geometries of the ranges that delimit the northern margin of the Jhelum Plain. Although no direct chronologic constraints have been placed on the backthrusts along the southwestern portion of Domeli ridge (Fig. 3), these are probably consanguinous with the Chambal and Jogi Tilla structures.

The location of the Salt Range thrusts at the southern limit of the relatively undeformed Potwar Plateau, some 100 km south of the limit of major deformation, is attributable to the presence of Eocambrian evaporites that have facilitated the development of a long sled-runner thrust beneath the Potwar (Seeber and others, 1979; Lillie and others, 1987; Butler and others, 1987). The remarkable conclusion from the present study is that considerable Salt Range thrusting occurred at 5 Ma, several million years before major deformation terminated in the northern Potwar basin (Burbank, 1983; Burbank and Raynolds, 1984). In fact, if one were to examine a north-south transect running from the Main Boundary Thrust north of Rawalpindi to the eastern Salt Range (Fig. 9), it becomes evident that, rather than a unidirectionally southward propagation of deformation across the Potwar Plateau, out-of-sequence thrusting has occurred on a very large scale several times during the past 5 m.y. Lillie and others (1987) have suggested that the Salt Range detachment became active as deformation was transferred southward from a "triangle zone" of thrusts and backthrusts underlying the northern limb of the Soan syncline to the Salt Range. Based on previously available dates (Burbank and Raynolds, 1984), this was thought to have happened ~2 Ma, and the preexisting normal faults were thought to have been utilized as thrust ramps that were overrun by 20 to 25 km of thrusting during Pleistocene time (Lillie and others, 1987). The model of Butler and others (1987) is similar in timing to the scheme of Lillie and others (1987).

A revision of these models seems to be required by new temporal constraints on the history of deformation. There appear to be reliable chronologically controlled evidence for the following events: (1) thrusting along the Attock thrust and in the vicinity of the Peshawar basin during late Miocene and Pliocene time (Burbank, 1983; Burbank and Tahirkheli, 1985; Yeats and Hussain, 1987)—this major deformation ended ~3 Ma with minor reactivation at ~0.4 Ma; (2) major motion (at least 6 km of shortening) along the Main Boundary Thrust between 2.1 and 1.9 Ma (Burbank and Raynolds, 1984); (3) thrusting along the Riwat fault between 3.5 and 3.0 Ma (Burbank and Raynolds, 1987) with a minimum of 6 km of shortening; (4) thrusting in the Salt Range both at 5 Ma and during the early and late Pleistocene (Yeats and others, 1984) with a total of 20 to 30 km of shortening (Lillie and others, 1987; Butler and others, 1987); (5) deformation of Jogi Tilla, Chambal, and Domeli structures ~1.5 Ma. In summary, during the past 5 m.y., deformation has been distributed over a broad region and has occurred in a nonsystematic fashion (Fig. 9). Although the total amount of shortening calculated here for individual fault zones is of the correct magnitude to have accommodated the ~1 cm/yr of convergence that is estimated as the rate of underthrusting (Molnar, 1984), this accommodation was irregularly distributed in both space and time. Whereas out-of-sequence thrusting has been well described previously (for example, in a hindward imbricating fan of thrusts), it is rare to document its occurrence on such a large scale (>100 km) and with such precise temporal constraints as are now available in northern Pakistan.

What causes the repeated switching of the locus of deformation from north to south and back again (Fig. 9)? What role did the bedrock ramp (Fig. 2) play in the thrusting? Why would thrusting initiate in the Salt Range at 5 Ma and then fail to accommodate most of the subsequent shortening in the foreland? It is interesting to note that a major structural and depositional rearrangement was occurring in the syntaxial area 150 km to the northeast (Fig. 1) at precisely that same time (Burbank and Raynolds, 1984; Burbank and others, 1986). Is there some causal relationship between these events? We speculate that changes in the geometry and taper of the detached wedge (Davis and others, 1983; Dahlen and others, 1984) caused this switching, and that in a dynamically deforming proximal foreland basin, progressive changes in the geometry and distribution of loads occasionally surpass stress thresholds that precipitate a dramatic rearrangement of the deformational pattern and could lead to large-scale out-of-sequence thrusting. In particular, recent thrust-wedge models predict that deformation should occur throughout the wedge (Davis and others, 1983; Platt, 1986; Yin, 1986) and not just at the leading edge. It is anticipated that motion of the thrust wedge will alter the stress field within it and that loci of deformation will shift in response to this modified stress regime. Therefore, the expectation should be for deformation to occur throughout the wedge, such that out-of-sequence thrusting should

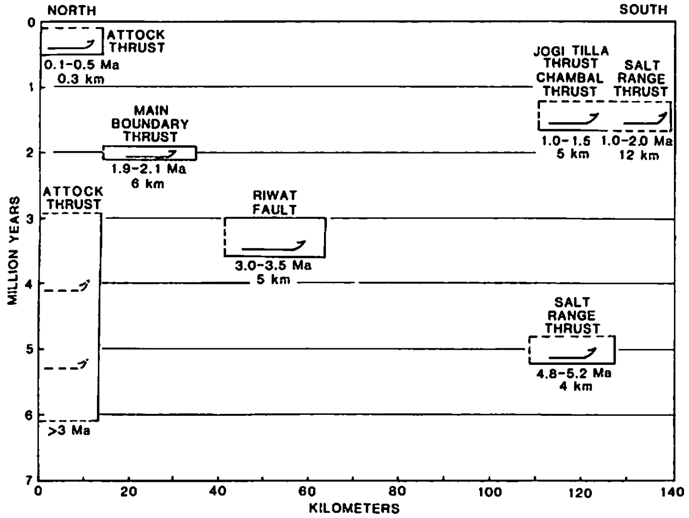

Figure 9. Time-space diagram along the north-south transect of Figures 1 and 2 from the Margala Hills to the Salt Range. Thrusts not lying directly along the transect (Attock Thrust, Chambal Thrust, Jogi Tilla Thrust) are projected perpendicularly (approximately along strike) onto the transect. Each box represents the time and space during which the thrust is interpreted to have been active. The time boundaries are dashed where the temporal constraints are uncertain. The right edge of the box represents the present position of the fault trace and does not represent portions of the thrust surface that may have been eroded away. For clarity, the left margin of each thrust box is truncated, although deformation clearly extended to the north of each thrust. Below each box, the time constraints for thrust motion are cited, and an estimate of the minimal amount of shortening as determined from structural and stratigraphic analysis is depicted. In many cases, the time of thrust initiation can be well specified, but the termination of thrusting is less certain, as shown by the dashed lines. The pattern of thrust initiation indicates that, within the thrust wedge of northern Pakistan, out-of-sequence thrusting has been extensive on a large spatial scale during the past 6 m.y.

be normal. It is interesting to observe in Pakistan the rather large distances (>100 km) over which these adjustments take place. Preservation of the critical stratigraphic and structural information is usually insufficient to reliably document the temporal relationships between deformational events over such large distances. The chronologic, stratigraphic, and structural data from the Himalayan foreland in Pakistan serve to validate these models. They raise the possibility that, given continued success in dating episodes of deformation, further tests and refinements of thrust-wedge models will be possible in this and other active thrust settings.

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