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Stratigraphic Keys to the Timing of Thrusting in Terrestrial Foreland Basins: Applications to the Northwestern Himalaya

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Abstract

Precise determination of the timing and nature of deformational events in foreland basins is critically dependent on the interpretation of stratigraphic indicators of tectonic activity within a detailed chronologic framework. Frequently data from numerous stratigraphic sections must be synthesized in order to generate a clear definition of a structural event and its response within a sedimentary sequence. In terrestrial deposits, magnetostratigraphic studies can provide the temporal control necessary to establish a reliable and coherent synthesis of tectonism that is based on an amalgamation of the diverse responses to, and indicators of, tectonic activity found in geographically separated localities. Useful indicators in this type of analysis include: 1) classical indicators of tectonism, such as the timing of changes in paleocurrents, provenance, and facies, and the ages of unconformities; and 2) indicators based on magnetic data or precise chronologic control, such as the history of syn- and post-depositional tectonic rotation and changes in the rate of sediment accumulation. Three examples based on the interpretation of such stratigraphic data from the northwestern Himalayan foreland basin are used to illustrate diverse thrusting events during the past 5 million years, including initial thrust propagation, later episodes of reactivation, and large-scale out-of-sequence thrusting. These examples illustrate the high degree to which reliable specification of the sequence of thrust events that are closely spaced in time but are distributed across a broad region is critically dependent on the availability of detailed, time-controlled stratigraphic records.

Introduction

Situated along the margins of collisional mountain ranges, most foreland basins are characterized by a succession of transient depocenters that migrate generally outward from the orogenic axis (Raynolds and Johnson 1985; Puigdefabregas *et al.* 1986). This migration is modulated primarily by deformation along the proximal basin margin (Miall 1978; Homewood *et al.* 1986), where there is progressive encroachment of thrusting and associated folding during continuing convergence (e.g., Armstrong and Oriel 1965; Beaumont 1981; Jordan 1981). The systematic displacement of depocenters is a response to crustal loading by successive thrust sheets, but this large-scale trend does not necessarily reflect the complexity of local faulting and associated sedimentation in the more proximal localities.

The objectives of this paper are to describe several ways in which thrusting episodes affecting terrestrial sediments can be discerned in the stratigraphic record, to show how detailed time constraints can be placed on these tectonic events, and to illustrate how the synthesis of well dated, local records of tectonism and sedimentation facilitates the development of a more comprehensive view of regional tectonic patterns. Recent stratigraphic studies of the northwestern Himalayan foreland that have used magnetic-polarity stratigraphy (Opdyke *et al.* 1979; Frost 1979; Moragne 1979; G. Johnson *et al.* 1979; Raynolds 1980; Burbank 1982; N. Johnson *et al.* 1982, 1985) and fission-track dating (G. Johnson *et al.* 1982; Burbank 1982) to provide chronologic control are used here to depict the local response to nearby tectonism. When considered at a regional scale, these data indicate that thrust-front migration is not smooth and systematic, but rather is characterized by complex sequences of deformation, unevenly distributed in both time and space. These conclusions concerning the pace and sequence of tectonic events are only possible due to the availability of tight temporal constraints.

unconformities, tectonic rotations, and changes in paleocurrents, provenance, facies, and sediment-accumulation rates.

Unconformities

Unconformities developed on folded molasse strata give clear indications of tectonic disruption (Fig. 17.2A). During prolonged intervals with multiple episodes of thrusting, progressive unconformities may develop adjacent to the thrust (Riba 1976; Anadon *et al.* 1986). Frequently, the hiatus represented by these unconformities diminishes rapidly toward more distal locations, so that a nearly continuous record of sedimentation, punctuated merely by scattered diastemic surfaces, characterizes the distal stratigraphic record. By dating the youngest strata below and the oldest strata above, these tectonic unconformities can provide ages constraining the timing of deformation. Whereas, close to the fault, the direct relationship between the unconformity and the faulting can be demonstrated clearly, it is also here that the greatest erosion of underlying strata occurs. For such cases, the age of tectonism cannot be closely constrained. Consequently, more distal localities are usually preferable for precisely dating an episode of faulting (Burbank and Raynolds 1984). However, to be useful, the tectonic significance of the distal unconformity must be unambiguous.

Within the intermontane basin, widespread unconformities are generated on the back side of the thrusted terrain, as consequent streams develop on the dip slope (Fig. 17.2A). This zone can be locally extended during thrusting (Platt 1986; Yin 1986), and renewed uplift can cause decoupling and gentle folding of newly deposited intermontane sediments (Burbank and Johnson 1983). Both the intensity of folding and the extent of the unconformities diminish basinward, such that uninterrupted deposition frequently prevails in the intermontane basin center, despite the major uplift along the distal basin margin. As in the molasse sediments on the distal side of the new thrust, constraining the age of the unconformity also helps to specify the time of deformation.

Rotations

Tectonic rotations of blocks of variable scales occur during compression, and these can be defined through statistical analysis of the magnetic data from single or multiple sites. At the largest scale (100 to >1,000 km), differential convergence between two colliding continental masses or fragments may cause a steady, regional rotation about a vertical axis amounting to 1–2° per million years (Minster and Jordan 1978). At the small scale, localized shearing along a thrust front and associated tear faults may create extensive and complex rotations of small blocks (<1 km). However, neither of these two types of rotations is very useful for dating thrust events. The large-scale rotations cannot be tied to specific, local tectonic movements, and the small block rotations, although directly related to specific events, are usually difficult to date due to limited exposure and disrupted stratigraphy.

Between the largest and smallest scales, rotations of intermediate scale blocks (1–100 km) are particularly useful in defining thrust-belt deformation. As thrust sheets glide forward, they may undergo a differential rotation about a vertical axis due either to the specific geometry of the sliding mass and/or the terrain being overridden, or to the irregular character of the slippage surface, which varies in its ability to facilitate gliding (Fig. 17.2B; Seeber *et al.* 1981; Butler *et al.* 1987). Similarly, shear stresses exerted by an advancing thrust sheet can generate rotations of the strata that are being folded and eroded in front of the thrust (Fig. 17.2B). In each of these two cases, dating of the rotational events can help to delimit the history of thrust movement. Indeed, in particularly well dated successions, rotational studies can reveal a record of motion from initiation to completion that is more detailed than that discernable in the physical stratigraphic and structural record (e.g., Hornafius *et al.* 1986).

Facies, Provenance, Paleocurrents, and Sediment-Accumulation Rates

In front of a newly formed thrust sheet, higher-gradient streams frequently supplant the previous fluvial network in terrestrial foreland basins. The detrital load of these rivers usually increases such that they introduce coarser-grained sediments, including gravels in many proximal localities, into the terrain adjacent to the thrust (Fig. 17.2C; Eisbacher *et al.* 1974; DeCelles *et al.* 1987; Hirst and Nichols 1986). Consequently, an upward-coarsening succession, sometimes with abrupt basal contacts, may record the nearby thrusting events. The propagation of the coarse facies from an uplifted block is time transgressive, so that the first appearance of a thrust-related facies at any given locality is unlikely to provide an accurate date for the tectonic event by itself. However, dating the coarse-grained influx at several localities along a line perpendicular to the thrust front localities can permit an assessment of the rate of transgression. This rate may be extrapolated back in time and space toward the thrust front to estimate the time of the inception of progradation from the thrusted terrain. Whereas in the Himalayan foreland most thrusting events are associated with coarse-grained sediments, in other foreland basins, such as in the northern Rockies (Beck and Vondra 1985; Winslow *et al.* 1985), fine-grained facies are sometimes localized adjacent to uplifts by thrusting events. Given both the potentially diverse depositional response to thrusting and the observation that coarse-grained facies may have nontectonic origins (e.g., glacial outwash), their genetic relationship to a given thrust must be evaluated before they can be used to date thrust activity.

Within the newly formed intermontane depression behind the thrust, two distinctive facies changes occur in our model (Fig. 17.2C). Vigorous uplift can readily pond transverse streams, such that lacustrine and high-sinuousity fluvial facies often replace less sinuous, higher-gradient stream deposits along the axial portions of the valley (Burbank and Johnson 1983). Secondly, rapid uplift promotes the development of coarse-grained deposits shed off the flank of the thrusted terrain and prograding toward the intermontane basin center (Fig. 17.2C; Steidtmann and Schmitt 1988: this volume).

Changes in provenance frequently accompany or precede these facies variations (Blatt 1967; Fuchtbauer 1967). Because thrusting inevitably disrupts previous drainage patterns, the ensuing fluvial reorganization can cause some compositional variability at many localities. Moreover, the newly thrusted terrain, which formerly lay below the prevailing depositional plain, can become a new source area for both the foreland and the intermontane basin (Fig. 17.2D). If this new source varies distinctively from the lithologies previously contributing to foreland deposition, then observable changes in provenance may be interpreted as a direct response to thrusting (Puigdefabregas *et al.* 1986; DeCelles *et al.* 1987). Because debris from newly exposed lithologies pervades all facies, provenance changes are often less time-transgressive than the consanguinous facies changes (see Jordan *et al.* 1988: this volume, for further discussion), and, therefore, the ages of provenance variations may more closely date specific tectonic events than do site-specific facies variations.

In terrestrial environments, it is inevitable that thrusting causes some drainage reorganization in the disrupted terrain. Consequently, important paleocurrent changes can provide distinctive records of thrusting events (Fig. 17.2E; e.g., Eisbacher *et al.* 1974; Burbank and Raynolds 1984). Whereas the course of major streams may be little altered by thrusting (Oberlander 1985), the pattern of many tributaries is frequently dramatically changed. The uplifted thrust terrain becomes a drainage divide for local streams. Longitudinal drainage develops along the axis of the intermontane basis, whereas in the deformed region in front of the thrust, synclinal axes and strike valleys may control the local fluvial network. The record of these paleocurrent changes provides useful insights into the topographic changes that accompanied thrusting.

The rate of net sediment accumulation in most foreland basins is modulated in part by the rate of subsidence of the basement in response to sediment and tectonic loading. Sea-level changes and the rate of sediment production exert additional, but often less important, control on sediment accumulation. Two contrasting responses to thrusting can occur in terrestrial foreland basins. In the incipient stages of development of a new thrust in a more distal posi-

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basin may be diverted subparallel to the thrust until they can exit along the lateral thrust ramp, whereas with more extensive thrusts (3), a largely centripetal drainage may develop throughout most of the intermontane basin. In either case, the thrusting causes a reversal of paleocurrents along the back side of the thrust. F: Changes in sediment-accumulation rates during the incipient growth of thrust-cored anticlines. Beginning at time T_0, antiformal growth causes a decrease in sediment-accumulation rates in the region where uplift is progressing. At time T_1, the thrust uplift exceeds the accumulation rate and the sequence is truncated. G: Sediment-accumulation rate variations during and following thrusting. Toward the center of the intermontane depression (i), rates may be nearly unperturbed by thrusting. Immediately behind the thrust (ii), sediment accumulation will be slowed and then terminated by erosion during thrusting. Subsequently, intermontane sediments can be accumulated (after T_1). Ahead of the thrust (iii), loading causes accelerated sediment accumulation during thrusting (T_0-T_1).

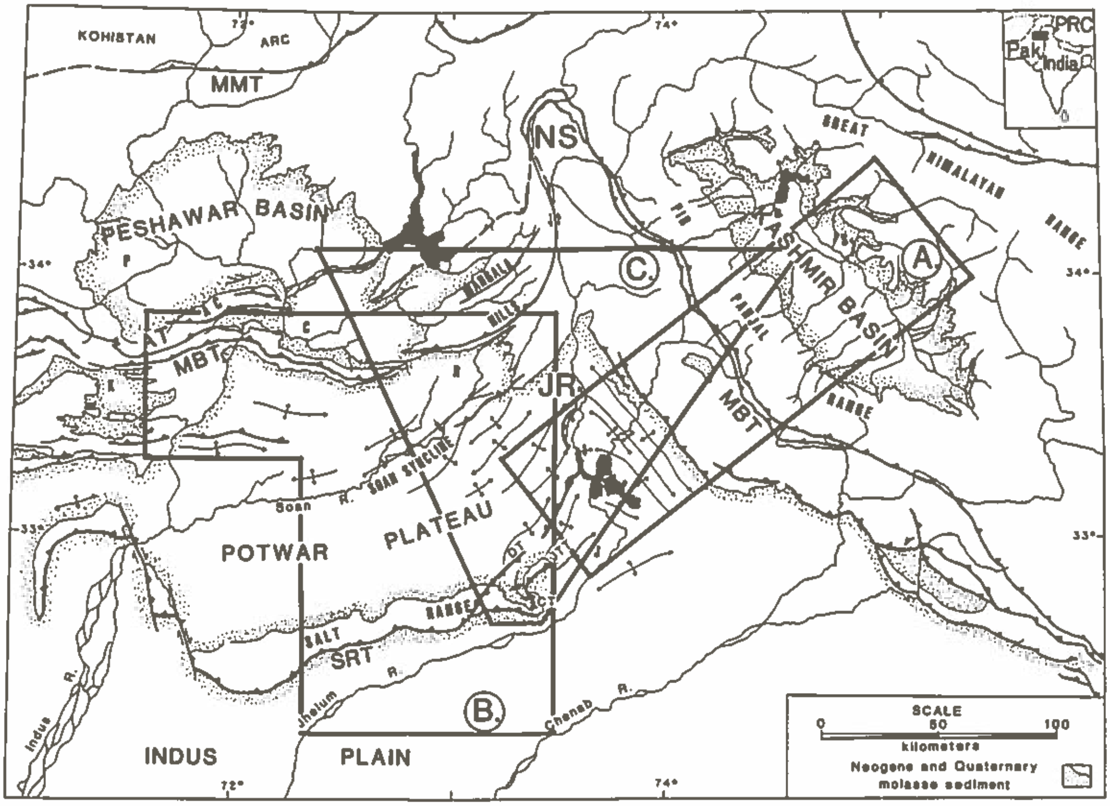

Fig. 17.3. Map of the northwestern Himalayan foreland basin, the southern margin of Kohistan, the southwestern margin of the Himalaya, and the major intermontane basins in the vicinity of the Northwest Syntaxis (NS). The major anticlinal axes in the deformed molasse sediments, as well as major thrust faults (barbed lines) and strike-slip faults in the region surrounding the Jhelum Re-entrant (JR) are delineated. Box A: Figure 17.4; Box B: Figure 17.7; Box C: Figure 17.10. Major thrust faults: Attock Thrust (AT); Main Boundary Thrust (MBT); Main Mantle Thrust (MMT); Salt Range Thrust (SRT). Other localities: Campbellpore (C); Jhelum (J); Kohat (K); Peshawar (P); Rawalpindi (R); Srinagar (S); Attock-Cherat Range (AC); Margala Hills (M).

number of magnetostratigraphic studies have been completed in the northwestern Himalayan foreland basin and adjacent intermontane basins (Fig. 17.3). The tectonic implications of some of these chronologic studies have been described by G. Johnson *et al.* (1979), N. Johnson *et al.* (1982, 1985), Burbank and Raynolds (1984), and Burbank *et al.* (1986). Data from this region are used here to demonstrate how stratigraphic and structural information can be integrated within a reliable chronologic framework to provide a synthesis of both local and regional tectonism. The examples serve: 1) to illustrate the initiation and subsequent recurrence of thrusting along a major fault system; 2) to delimit an interval of uplift that precedes by several millon years the previously accepted age of fault development in this region; and 3) to define out-of-sequence thrusting events on the local scale. When considered in concert with relevant structural data, these examples from widely separated localities suggest both regional coherence in a chronologic and structural framework and potential causal linkages between disparate deformational events.

The Kashmir Basin and the Main Boundary Thrust (India)

The Kashmir Basin is one of the largest late Cenozoic intermontane basins in the Himalayan chain. It lies along the eastern limb of the Northwest Syntaxis (Fig. 17.3), where it is bounded to the northeast by the mountains of the High Himalaya and to the southwest by the Pir Panjal Range. The Pir

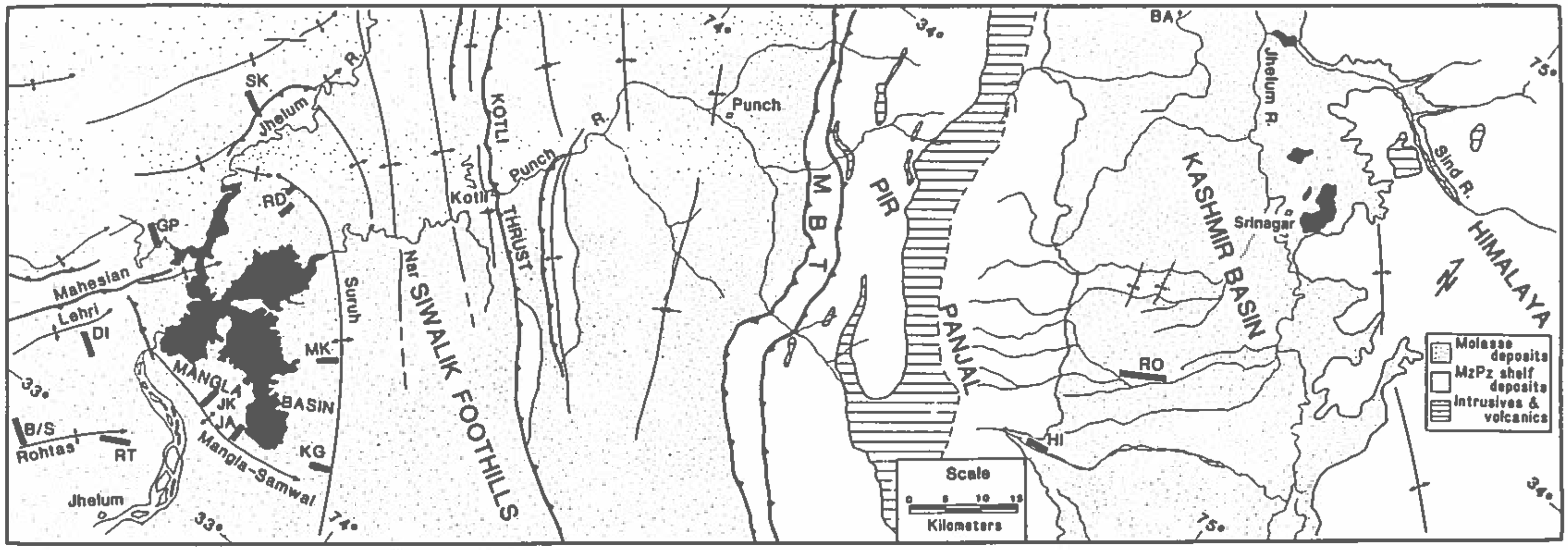

Fig. 17.4. Simplified geologic map extending from the northeastern margin of the Kashmir basin across the Main Boundary Thrust (MBT) to the Jhelum River in the eastern Potwar Plateau. The stippled pattern (molasse deposits) represents both Siwalik and Murree fluvial sediments, as well as the predominantly lacustrine Karewa sediments in Kashmir. Section locations are shown by black rectangles: Baramula (BA); Basawa/Sanghoi Kas (B/S); Dina (DI); Ganda Paik (GP); Hirpur (HI); Jari (JA); Jhel Kas (JK); Kas Guma (KG); Mawa Kaneli (MK); Rata-Dadial (RD); Rohtas (RT); Romushi (RO); Sakrana (SK). For location of area, see Box A in Figure 17.3.

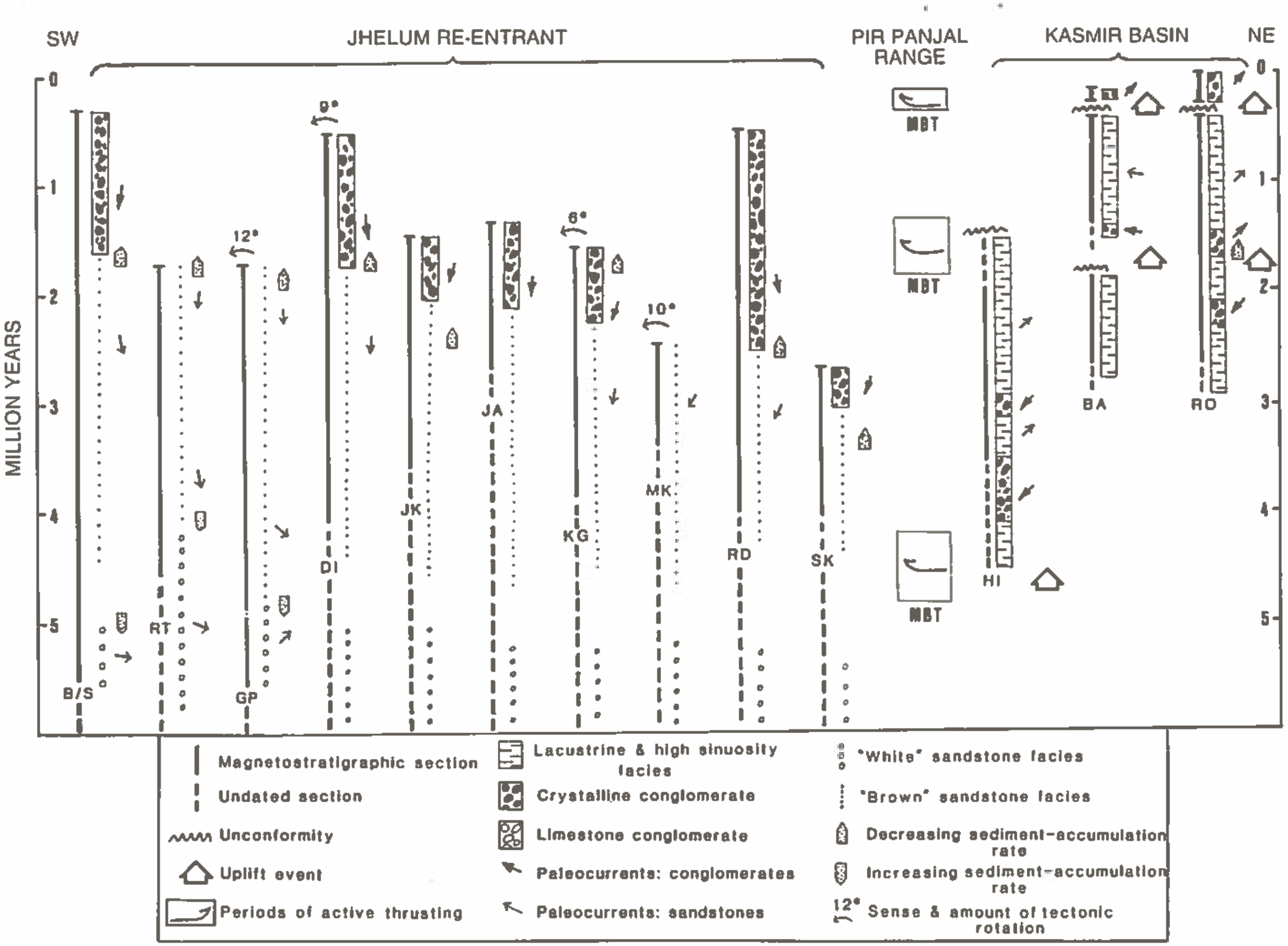

Fig. 17.6. Schematic representation of tectonic and sedimentologic events for the local sequences aligned along the Kashmir-to-Jhelum traverse. (For location, see Fig. 17.4). The solid vertical line represents the temporal duration of each section as interpreted from the magnetostratigraphic data. The amount of post-depositional rotation is determined from the magnetostratigraphic data from each section. Those sections showing no rotation are those whose mean magnetic orientation is not significantly different from geographic north and south. Each of the events (influx of conglomerates, initiation of tectonic uplift, erosion, changes in sediment-accumulation rates, and paleocurrent direction) is shown in its proper temporal position in each profile. Section abbreviations are the same as those for Figure 17.5. Concurrent changes in the tectonic indicators listed above are used to delineate the initiation of thrusting on the Main Boundary Thrust (MBT) between 4 and 5 Ma. Recurrent uplift events (at ~1.9 and 0.4 Ma) are similarly inferred from changes in sediment-accumulation rates, unconformities, and paleocurrent changes. Data are from Johnson *et al.* (1979), Raynolds (1980), and Burbank (1982).

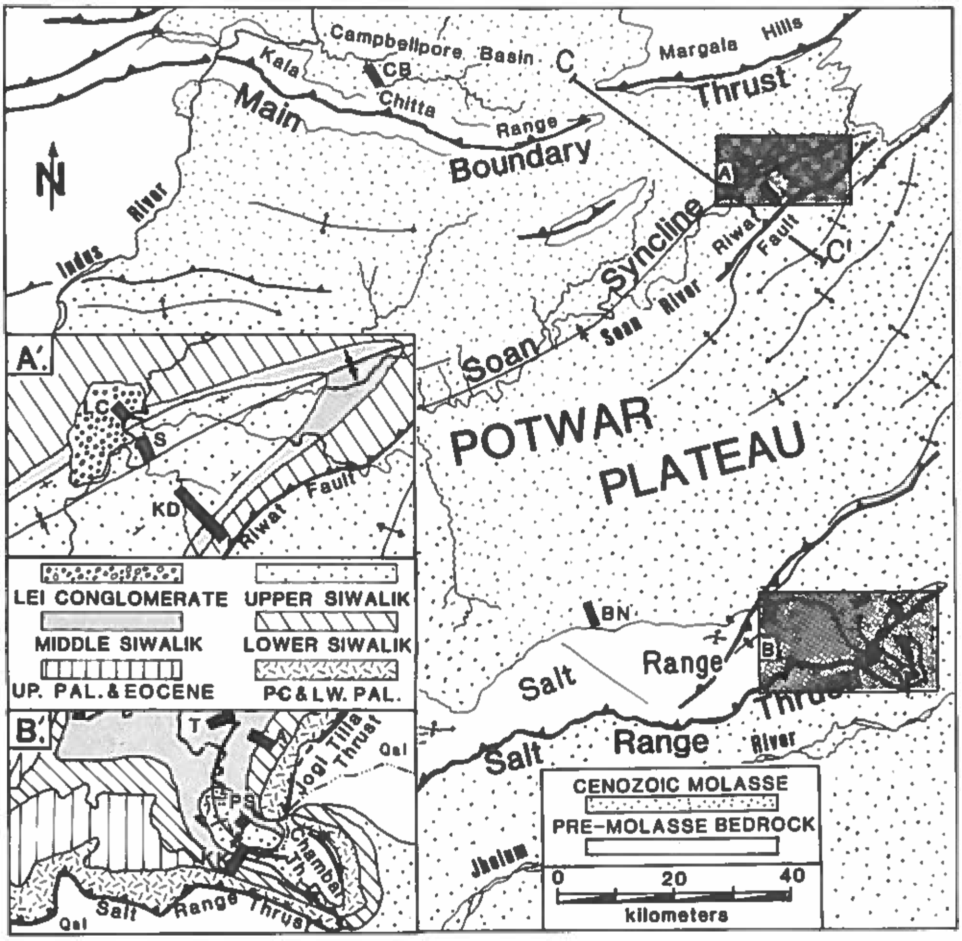

Fig. 17.7. Tectonic map indicating the major thrusts and folds in the vicinity of the Soan Syncline and the eastern Salt Range on the western side of the Jhelum Re-entrant (for location, see Box B, Fig. 17.3). The allochthonous Potwar Plateau (including the Soan Syncline) is riding above the Salt Range Thrust. Late Cenozoic molasse sediments are shown by the stippled pattern. The studied area of the Soan Syncline (A) between the MBT and the Riwat Fault is shown in inset Map A'. Magnetic sections: Kas Dovac (KD); Soan (S); Lei Conglomerate (LC). The position of the Campbellpore Basin (CB) section is shown in the upper left part of the main map. The studied area of the eastern Salt Range (B) is shown in inset map B'. Magnetic sections: Andar (A); Kotal Kund (KK); Pind Savikka (PS); Tatrot (T). Note that the Upper Paleozoic and Eocene strata (vertical stripes) include the Talchir boulder source area. The position of the Bhaun (BN) section in the central-eastern Salt Range is shown on the main map. Line C-C' indicates the position of the cross section in Figure 17.9B. Salt Range Thrust modified from Yeats *et al.* (1984).

southerly source of the conglomerate indicates that uplift to the south defined a new piggyback basin at this time. This uplift probably resulted from early Pliocene movement along at least a segment of the Salt Range Thrust (Seeber *et al.* 1981). Rotational data (Opdyke *et al.* 1982) collected along the back slope of the present Salt Range Thrust indicate differences of rotation of up to 30° between localities less than 30 km apart. Such data imply inhomogeneous behavior of the advancing thrust sheet, perhaps due either to segmentation (e.g., Fig. 17.2B) or to multiple deformational events affecting different portions of the thrusted terrain.

Whereas at Bhaun, rotational data across an unconformity help to define a thrusting event, farther east in the Salt Range, lack of differential rotation across an unconformity of both the same age and probable genesis helps to define a still younger episode of thrusting. The Jogi Tilla structure, a southeast-verging succession of thrusts that bring thrusts suggests that the most likely explanation for their rotation and folding is that thrusting along both the Jogi Tilla and Chambal structures (Fig. 17.7) during Pleistocene time primarily generated the deformation observable today. Lesser movement along the Salt Range Thrust may also have been involved (Butler *et al.* 1987). In reconstructing the thrusting events in this region, the rotational data from several nearby sections, along with provenance, unconformity, and paleocurrent data, are critical to the interpretation of the deformational history. Without them, the sequence of Tatrot/Andar would probably be incorrectly interpreted as recording only a single thrusting event.

The Soan Syncline and Main Boundary Thrust (Pakistan)

Whereas structural cross-cutting relationships and stratal attitudes can often permit the sequence of thrusting to be discerned in imbricate fans of thrusts, the sequence of motion along widely separated thrusts is frequently difficult to resolve due to the absence of original cross-cutting structures or to the erosion of intervening strata following deformation. Chronologic data from magnetostratigraphy can provide the temporal control of the stratigraphic record needed to resolve these timing difficulties, even when no cross-cutting information is available. In this example from northern Pakistan, two major faults are spaced about 30 km apart. Despite this large separation, chronostratigraphic studies here can confine deformational episodes to narrow time windows and can clearly demonstrate that out-of-sequence thrusting has occurred.

The Soan Syncline lies about 20 km south of the MBT in Pakistan and is truncated along its southern margin by the Riwat Fault (Fig. 17.7). Chronologic control of the synclinal strata is derived from magnetostratigraphic studies by Moragne (1979), Raynolds (1980), and Burbank and Beck (unpublished data). The southernmost section at Kas Dovac spans an interval dated at ~10–2.4 Ma (Fig. 17.5). Strata older than ~3.5 Ma contain abundant Eocene limestone clasts carried by rivers flowing from source areas to the northwest. A syndepositional unconformity truncates the Kas Dovac section at ~3.5 Ma, and the overlying, finer-grained, Gauss-aged strata (Fig. 17.5) contain no limestone pebbles, but instead contain quartzites and volcanic clasts apparently derived from the northeast (Fig. 17.9A). This unconformity dies out to the north, where sedimentation continued unabated throughout this interval. According to our model (Fig. 17.2A), the diminution of the depositional hiatus to the northwest should indicate uplift in the southeast. Whereas the strata below the unconformity are counterclockwise rotated an average of >30° (Burbank and Raynolds 1984), the overlying sequence is essentially unrotated (Fig. 17.9A). Consequently, these data suggest that thrusting along the Riwat Fault along the southern margin of the present Soan Syncline at ~3.5 Ma (Fig. 17.9B) caused a rotation of the underlying strata and created an axial drainage (now occupied by the Soan River). This drainage pattern (Fig. 17.9C) could explain both the lower energy facies and the exclusion of limestone clasts that is observed in the supraconformable sequence on the northern flank of the Riwat structure.

The vertically dipping northern limb of the Soan Syncline comprises at least 6 km of molasse strata (Gill 1952) ranging from ~2.1 to >9.5 Ma (Figs. 17.5, 17.9; Moragne 1979; Raynolds 1980). The entire sequence is overlain by the subhorizontal Lei conglomerate, the base of which is dated at ~1.9 Ma (Figs. 17.5, 17.9; G. Johnson *et al.* 1982). Thus, a strong compressional event between 2.1 and 1.9 Ma is seen to have terminated sedimentation at Soan and caused >6 km of uplift and erosion (minimum rate of >30 m/10^3 yr) prior to deposition of the Lei conglomerate 200,000 years later. This deformation is viewed as a response to large-scale motions on the MBT to the north (Figs. 17.7, 17.9). This interpretation is reinforced by the initiation at this time (Fig. 17.5) of low-energy intermontane sedimentation in the Campbellpore basin (Burbank 1982; G. Johnson *et al.* 1982), a piggyback basin defined by movement along the MBT (Fig. 17.9).

The well dated depositional sequences in the Soan region provide extraordinarily tight temporal constraints on the timing, sequence, and rate of deformation of thrusted strata. Clear definition of syndepositional unconformities along with tightly constrained ages on angular unconformities define discrete chronologic windows within which deformation occurred. Although it is perhaps rare that deformational events can be specified so clearly through stratigraphic analysis, the studies in the Soan area aptly illustrate the manner in which the time resolution of the magnetic time scale can bring structural events into sharp focus.

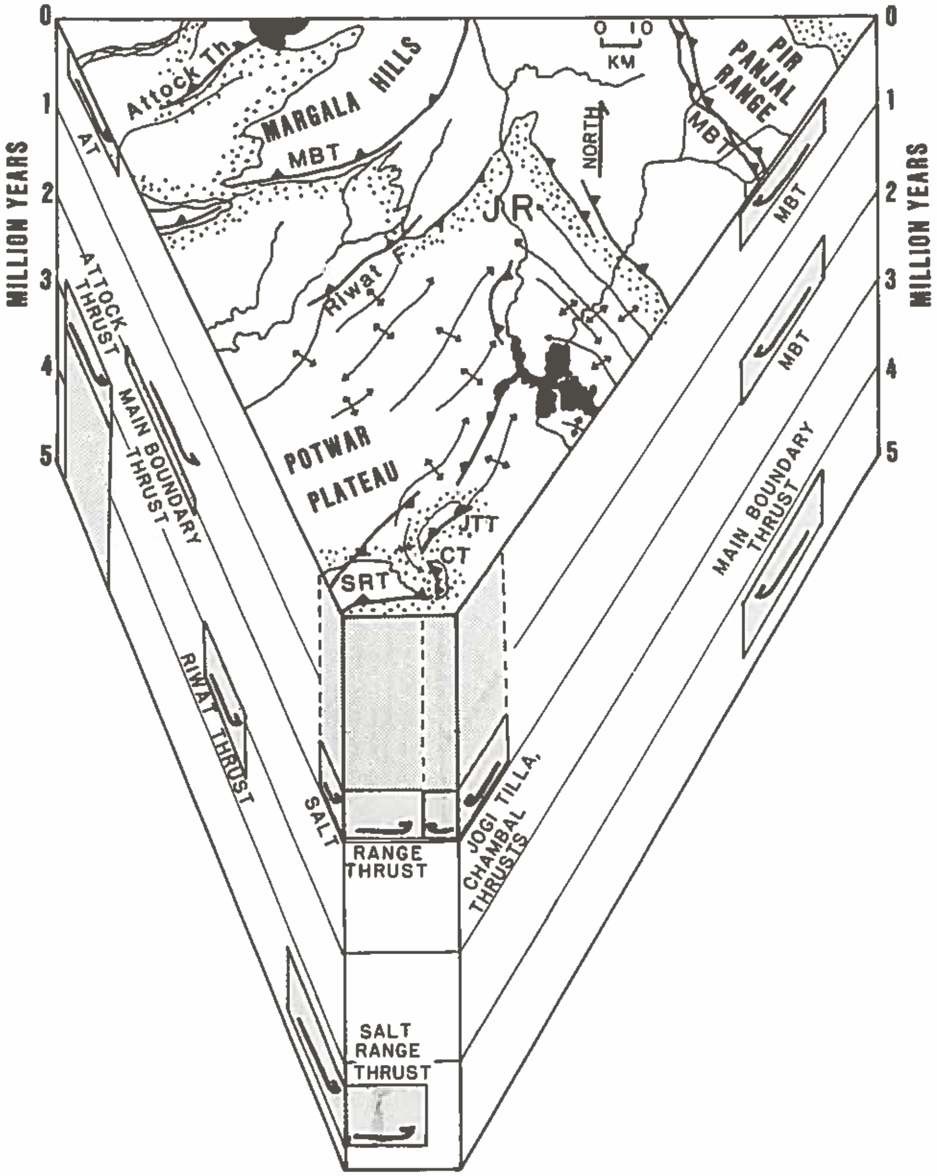

Fig. 17.10. Summary of fault motions in the study area (area C, Fig. 17.3). The vertical axis represents time (0–5 Ma). The locations of faults are determined from orthogonal projections onto the faces of the block. The movement history of the Attock Thrust (AT) is discussed in Burbank (1983) and Burbank and Tahirkheli (1985). The shaded boxes delineate the time and space domain over which each thrust is interpreted to have been active. The data suggest that thrusting does not systematically become younger southward, particularly in the eastern Potwar region, where the Salt Range and Riwat Thrusts each moved prior to major motion on the MBT along the Margala Hills and Kala Chitta Range.

Summary and Conclusions

These examples from the northwestern Himalaya foreland basin illustrate several ways in which stratigraphic data related to deformation can be interpreted within a reliable chronologic framework. The detailed history of thrusting that emerges from such studies provides new insights into the possible sequence and pattern of deformational events in a foreland basin. Previously it was thought that the thrusts described here developed from the Himalaya sequentially as deformation rippled systematically from north to south across the basin (Gansser 1964; Burbank and Raynolds 1984). These examples show

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