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Sequential late Cenozoic structural disruption of the northern Himalayan foredeep

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Chronologies for the Siwalik molasse and intermontane basins along the southern margin of the Himalaya and Hindu Kush Ranges constrain the timing and pattern of facies migration and structural disruption of the Indo-Gangetic foredeep. This synthesis indicates that quiescent intervals are punctuated by pulses of rapid deformation as thrusting migrates in a stepwise fashion across the foredeep.

THE large-scale southward migration of tectonic deformation away from the axis of the Himalayan orogen has long been recognized[1–4]. Extensive thrusting and nappe development in the vicinity of the Main Central Thrust in the Himalayas and of the Main Mantle Thrust in the Hindu Kush occurred primarily during the middle Cenozoic[4–10]. In contrast, the development of the Main Boundary Thrust (MBT) and related thrusts along the northwestern margin of the Indo-Gangetic foredeep (Fig. 1) has been largely confined to the Plio-Pleistocene[1,2,4,10]. Using magnetic-polarity stratigraphy and fission-track dating, Johnson *et al.*[11] and Opdyke *et al.*[12] have shown that close temporal constraints can be placed on tectonic events recorded by the molasse sediments of the western Himalaya. However, a precise chronology for the succession of events by which thrust faulting disrupted sedimentation within the molasse basin has not been previously delineated. The synthesis presented here is based on the analysis of lithofacies, provenance, and accumulation rates of strata in 14 recently dated sections. Integration of these data reveals the detailed timing of the progressive migration of deformation across the proximal foredeep margin in northern Pakistan and northwestern India during the past 5 Myr (Fig. 1).

Two distinct depositional settings, the largely undisturbed foredeep and the intermontane basins, are found adjacent to the deformational front. In the Indo-Gangetic foredeep, molasse sediments are typically characterized by sheet sandstones representing low-sinuosity, laterally-migrating rivers[13,14], siltstones

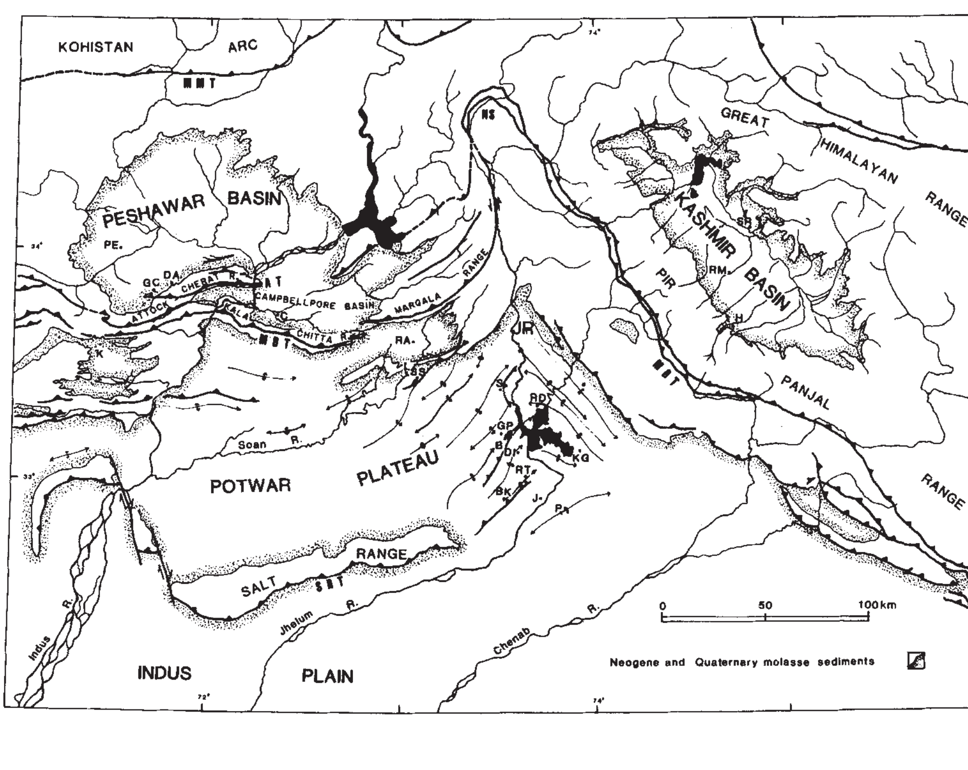

Fig. 1 Map of the northwestern portion of the Indo-Gangetic foredeep, the southern margin of the Himalaya and Hindu Kush, and the major intermontane basins in the vicinity of the North-west Syntaxis (NS). The major anticlinal axes in the deformed molasse sediments, as well as major thrust faults (barbed lines) and strike-slip faults in the region surrounding the Jhelum Re-entrant (JR), are delineated. During the Plio-Pleistocene, structural deformation has progressively migrated southwards across the foredeep in response to the ongoing Indo-Asian collision. Major thrust faults: AT, Attock Thrust; MBT, Main Boundary Thrust; MMT, Main Mantle Thrust; SRT, Salt Range Thrust. Locations of measured and dated stratigraphical sections: B, Bangala; C, Campbellpore; DA, Dag; DI, Dina; GP, Ganda Paik; GC, Garhi Chandan; H, Hirpur; KG, Kas Guma; L, Lei; RD, Rata-Dadial; RT, Rohtas; RM, Romushi; S, Sakrana; SS, Soan Syncline. Other localities: BK, Basawa Kas; J, Jhelum; P, Pabbi; PE, Peshawar; RA, Rawalpindi; SR, Srinagar.

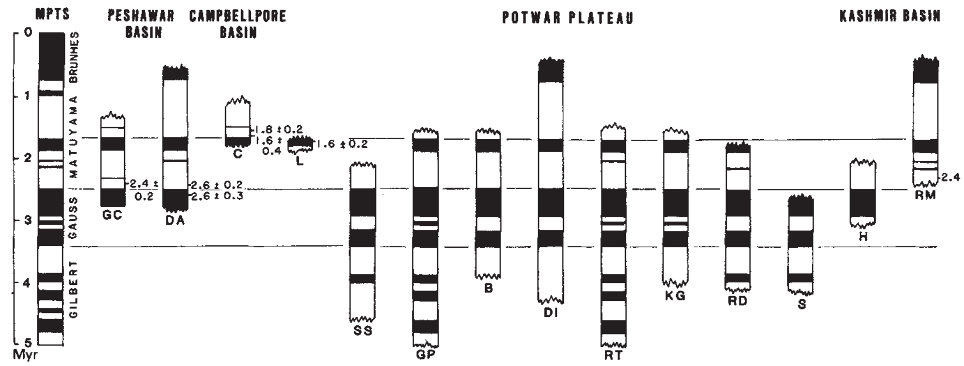

Fig. 2 Comparisons of locally determined magnetic-polarity stratigraphies (MPSs) with the magnetic-polarity time scale[41,42]. Fission-track dates on volcanic ashes are shown with 2σ errors at their appropriate stratigraphical positions. The magnetostratigraphical correlations are based on recognition of identifiable chrons or subchrons and are aided by both fossil occurrences and the frequent presence of prominent ashes straddling the Gauss–Matuyama transition. The fission-track dates from Lei and from the lower ash at Campbellpore are reported in ref. 29. The Soan Syncline section is from ref. 31. For a detailed discussion of other sections and fission-track dates, see refs 13 and 24. The local MPSs are arranged as they would be encountered along a traverse from the Peshawar Basin southeastwards to the Potwar Plateau and then northeastwards to the Kashmir Basin. In order: MPTS, magnetic-polarity time scale; GC, Garhi Chandan; DA, Dag; C, Campbellpore; L, Lei conglomerate; SS, Soan Syncline; GP, Ganda Paik; B, Bangala; DI, Dina; RT, Rohtas; KG, Kas Guma; RD, Rata-Dadial; S, Sakrana; H, Hirpur; RM, Romushi. Note that based on the sediment accumulation rates in the dated portion of the Hirpur sequence, the base of the underlying conglomeratic and mudstone section is interpreted to be ~4 Myr old[19].

with numerous palaeosol horizons developed on broad, interfluvial floodplains[15–17], and subsidiary ribbon sandstones representing higher sinuosity rivers[17]. Lacustrine strata are virtually absent within the molasse sediments[11–17]. The molasse sequence, 6,000 m thick, is exposed in the Himalayan foothills, where it is termed the Siwalik and Rawalpindi Groups[18]. In contrast, the intermontane basins, such as the Kashmir and Peshawar Basins, are dominated by proximal alluvial-fan facies, intermediate braided-river sediments, and extensive high-sinuosity fluvial and shallow lacustrine sediments that extend across the central portion of the basins[19–21]. These sequences occur in tectonically ponded valleys that lie inside the deformational front of the Himalayan fold-and-thrust belt. It is the predominant control on the style and rate of sediment accumulation exerted by the tectonic environment that permits us to unravel the patterns of regional tectonic evolution by dating strategically located stratigraphical sections.

Western limb of Jhelum Re-entrant

The Potwar Plateau represents the outermost and youngest of the series of intermontane basins in the western Himalaya. It is separated from the southernmost ranges of the Hindu Kush by the Peshwar and Campbellpore intermontane basins (Fig. 1). Earthquake-hypocentre distributions suggest that the Peshawar Basin is underlain by a subhorizontal detachment surface[22,23]. This surface is inferred to continue southward as a largely aseismic detachment beneath the Potwar Plateau and to break the surface at the southern edge of the Salt Range. The Attock Thrust and the MBT (Fig. 1) are inferred to represent splays off this detachment surface[22,23]. Late Cenozoic movement along these thrusts has uplifted the Attock–Cherat Range and the Kala Chitta–Margala Range which define the southern margins of the Peshawar and Campbellpore Basins, respectively (Fig. 1). To constrain the deformational chronology of the northern foredeep, we have dated sections: (1) within the Peshawar and Campbellpore Basins; (2) near the bounding faults; and (3) across the Potwar Plateau.

Along the northern flank of the Attock Range in the Peshawar Basin (Fig. 1), mid-to-late Pleistocene uplift has exposed intermittently the uncomformable contact of the basin-filling sediments with the underlying Oligocene–Miocene bedrock[24,25,43]. Two magnetostratigraphical sections from this area commence in the upper Gauss chron, as indicated by three fission-track dates on ashes straddling the overlying reversal interpreted as

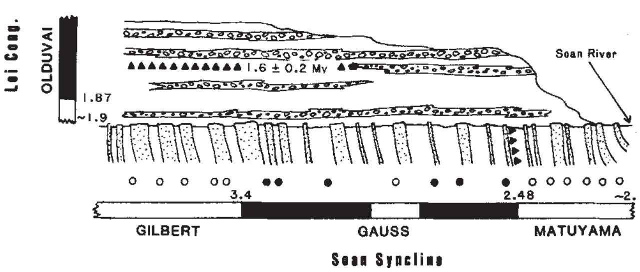

Fig. 3 The northern limb of the Soan Syncline, where nearly vertical strata of typical Siwalik molasse sediments are truncated and overlain by the generally underformed Lei conglomerate. Only the upper portion of >3,000 m of molasse sediments is shown. ▲, Enclosed volcanic ashes. The magnetostratigraphy[31] indicates that these strata encompass the Gauss chron and that the youngest preserved sediments extend into the lower Matuyama chron, probably to ~2.1 Myr. The overlying Lei conglomerate includes an ash dated at 1.6±0.2 Myr (ref. 29) on the basis of which the normal-polarity magnetozone is interpreted as the Olduvai subchron. The base of the Lei conglomerate must predate the Olduvai and is interpreted as ~1.9 Myr. Thus, between 2.1 and 1.9 Myr ago, >3,000 m of uplift and erosion (mean minimum rate of 15 mm yr^{-1}) occurred as the Soan Syncline was strongly compressed in response to thrusting along the MBT.

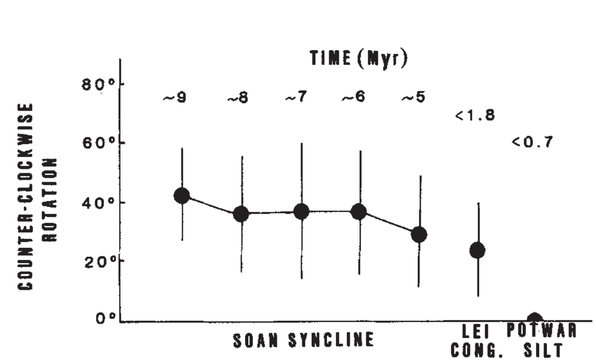

Fig. 4 Post-depositional rotation of foredeep sediments in the vicinity of the Soan Syncline. Amount of rotation is based on the deviation of the mean orientation of the normal and reversed magnetic sites from a given time interval with respect to the theoretical north–south axial dipole. The chronologically constrained data indicate that up to 15° of counterclockwise rotation occurred between 9 and 2 Myr ago. However, the most rapid rotation of over 20° occurred between 1.8 Myr and the present, following the development of the Soan Syncline.

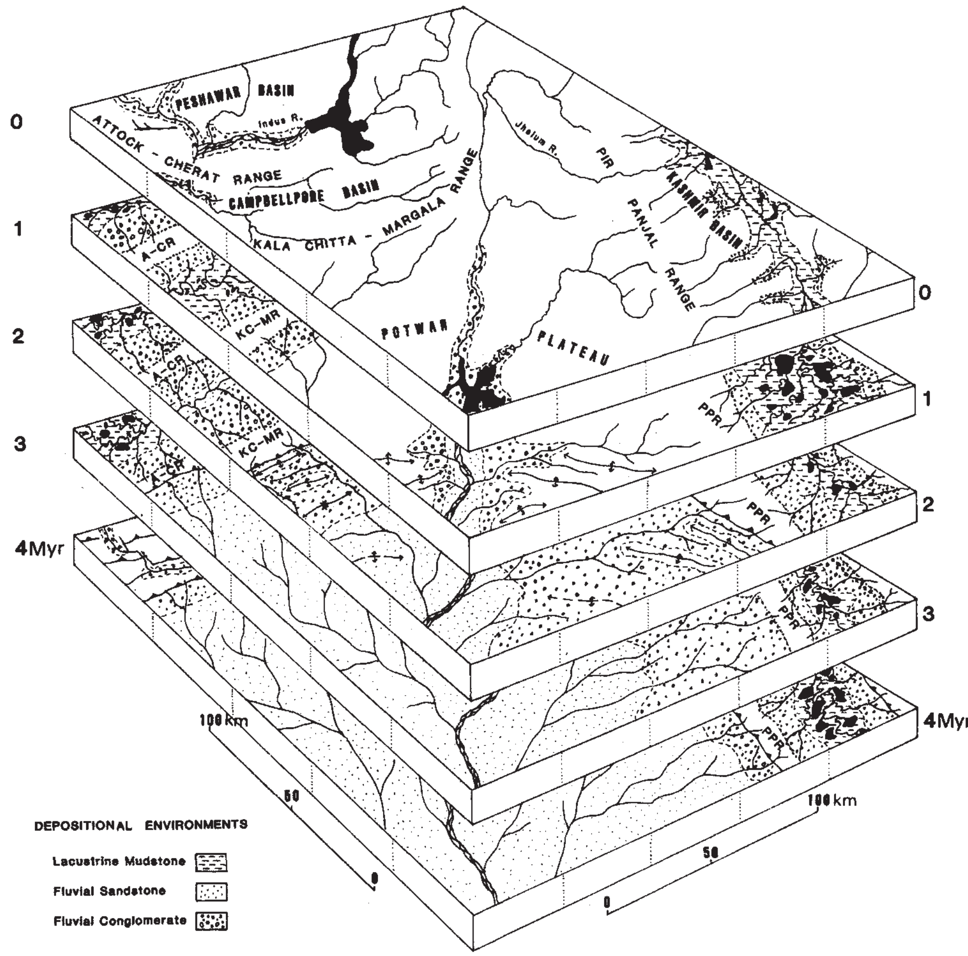

Fig. 5 Reconstructed structural and depositional relationships in the vicinity of the North-west Syntaxis at 1-Myr intervals during the past 4 Myr. Changes in facies relationships and the pattern of structural deformation are depicted adjacent to thrusts active at each interval. The zone of molasse deposition beyond the intermontane basins becomes increasingly restricted as thrusting and anticlinal growth migrate across the foredeep. Conglomerate facies and strong structural deformation in positions proximal to active faults grade laterally to indisturbed sheet sandstones in distal settings. A–CR, Attock–Cherat Range; KC–MR, Kala Chitta–Margala Range; PPR, Pir Panjal Range.

the Gauss–Matuyama transition (Fig. 2). Based on the estimated age of the basal depositional contact at Garhi Chandan, intermontane sedimentation in the Peshawar Basin is inferred to have begun ~3.0 Myr ago. Before this, movement along the Attock Thrust (Fig. 1) had caused uplift of the ancestral Attock Range and generated a tectonic depression on the northern side of the uplifted terrane. This tectonic event ponded the fluvial systems which had previously drained across the region and localized sediment accumulation in the newly formed basin.

The Campbellpore Basin is an elongate depression enclosed by the Attock Range to the north and the Kala Chitta–Margala Range to the south (Fig. 1). Despite the brevity of the sections along the western Haro River[24,26–28] (Fig. 2), the presence of several volcanic ashes permits precise dating of the basin fill[24,29] and indicates that sedimentation in the Campbellpore Basin had commenced by ~1.8–1.7 Myr ago. We can conclude that the thrusting along the MBT (Fig. 1) which uplifted the Kala Chitta Range and delimited the southern margin of the Campbellpore Basin had commenced at least 1.9 Myr ago.

Further information on the onset and duration of thrusting is provided by a section on the southern side of the MBT. The Soan Syncline (Fig. 1) is located ~20 km south of the MBT near Rawalpindi, where it is developed in sediments of the Upper Siwalik Group. The Soan Syncline is strongly asymmetric with a vertically standing northern limb and a gently dipping southern limb[30]. The magnetostratigraphy of the Upper Siwalik sediments in the northern synclinal limb[31] indicates that the youngest deformed strata are ~2.1 Myr old (Figs 2 and 3) and that the sequence, which is >3,000 m thick, extends well into the Upper Miocene[13]. The horizontally-bedded Lei conglomerate unconformably overlies the vertical strata of the northern limb of the syncline. A fission-track date of 1.6 ± 0.2 Myr on an enclosed ash[29] indicates that the normal-polarity interval is the Olduvai subchron and that the oldest strata of the Lei conglomerate are likely to be ~1.9 Myr old (Figs 2, 3).

These chronological data delineate a very brief interval of rapid tectonic deformation in the latest Pliocene. During a period of ~200,000 yr beginning around 2.1 Myr ago, >3,000 m of structural relief was developed and was accompanied by rapid erosion. By 1.9 Myr ago, the deformed sequence had been truncated by erosion, and the Lei conglomerate spread southward across the area (Fig. 3).

We interpret the deformation of the Soan Syncline as a response to the initiation of major movement along the MBT around 2.1 Myr ago. The Lei conglomerate represents the proximal, transgressive facies shed from the rising Kala Chitta–Margala Range to the north. The horizontal aspect of the Lei conglomerate today, the gentle dips (<5°) found in the intermontane sediments of the Campbellpore Basin[22,25,26], and the absence of conglomerates younger than 1.6 Myr (Fig. 2) suggest that major movement along the MBT was short lived and had largely ceased by the end of the Pliocene. Following deposition of the Lei conglomerate, major rotation of the Soan area began (Fig. 4). We view this rotation as coincident with the propagation of the detachment surface[22,23] beneath the Potwar Plateau towards the modern Salt Range and with the resulting development of the Potwar Plateau as an allochthonous unit.

During the Pleistocene, tectonic disruption migrated systematically southwards across the central and eastern Potwar Plateau. Three magnetostratigraphical sections[13,32] from the eastern Potwar (Fig. 2) constrain this history of tectonism. Two intervals of conglomeratic sedimentation are present in most sections: one in the upper portion of the comformable molasse sequence (sometimes intraformational in nature) and one overlying the deformed and eroded molasse strata. The first appearances of conglomerates are time-transgressive events related to either an influx from extrabasinal, bedrock uplifts or intrabasinal deformation. In addition, the timing of initiation of conglomeratic sedimentation at a given section is a function of the spatial relationship between the section and the former axis of

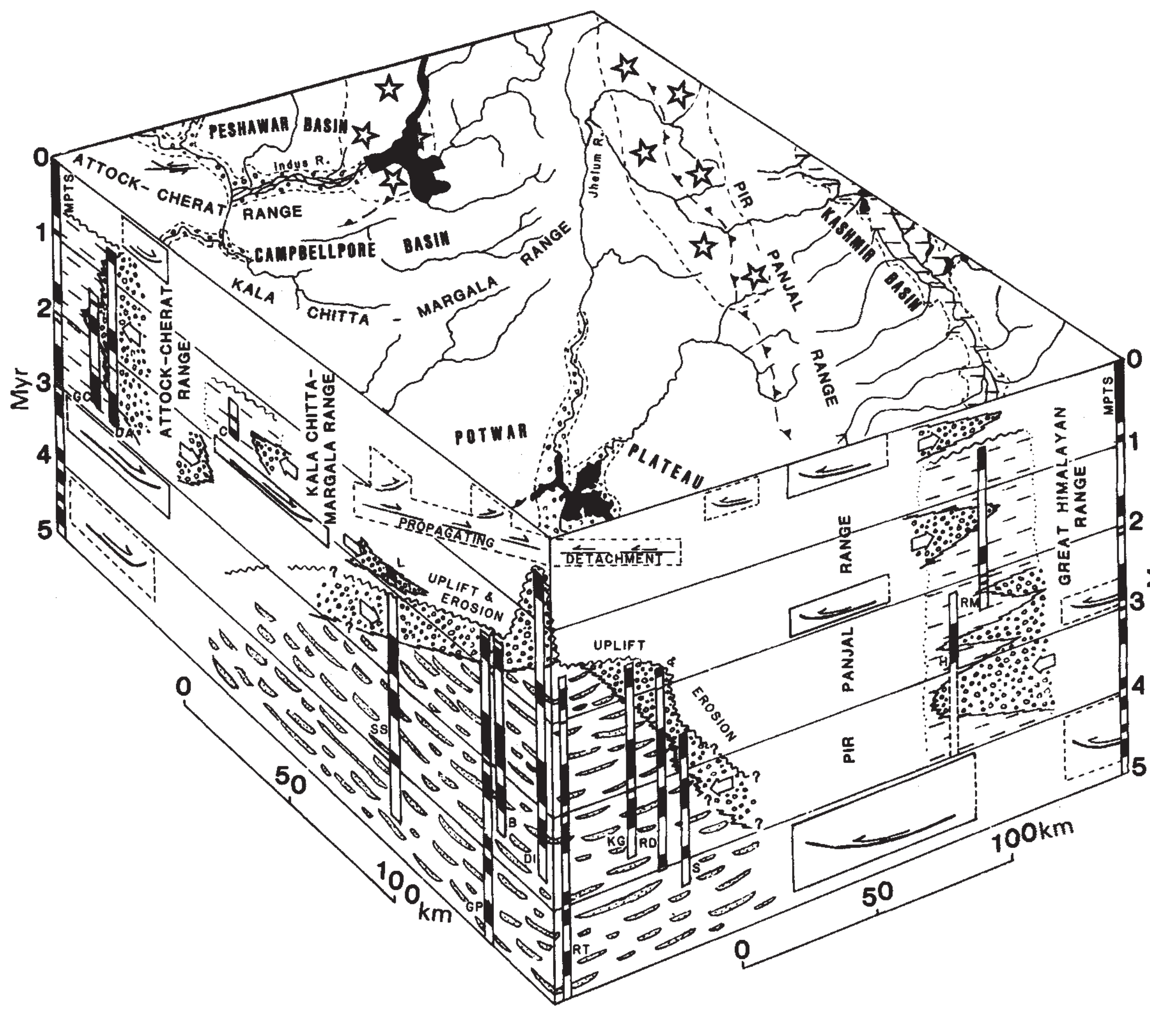

Fig. 6 Time–distance block diagram of the Himalayan foredeep and adjacent ranges in the vicinity of the North-west Syntaxis. The vertical dimension extends back to 5 Myr. The dated sequences described in this study and shown in Fig. 2 are depicted in their chronological range and are projected from their geographical location on to the transects defining the sides of the block. The abbreviations next to each magnetic column are as in Figs 1 and 2. Medial sections such as Sakrana (S) could be projected onto either face. The northeastern face is chosen here based on the affinities of the conglomerates at Sakrana with those from Rata–Dadial (RD) and Kas Guma (KG). For each of the stratigraphical sections, generalized depositional and facies relationships are shown in their proper chronological position (for example, the southward progradation of conglomerates from Sakrana across the eastern Potwar Plateau after 3 Myr). The intermontane basins are dominated by low-energy (largely lacrustine) facies punctuated by conglomeratic influxes. Two broad phases of molasse sedimentation across the Potwar Plateau are shown: a channel-and-floodplain interval succeeded by late-stage polymictic conglomerates. Large, open arrows indicate the prevailing palaeocurrent directions at different times. The boxes enclosing a thrust-fault symbol delineate both the spatial and chronological intervals over which the thrusts are interpreted to have been active. Dashed boxes show less well constrained periods of thrusting. On the left-hand panel, thrusting, folding and intermontane basin formation are seen to progress in a stepwise fashion from the Peshawar Basin to the south-east between 4 and 1 Myr ago. On the right-hand panel, three intervals of uplift in the vicinity of the Pir Panjal Range have defined the Kashmir Basin, controlled palaeocurrent patterns, and deformed the adjacent foredeep to the south-west. The surface of the block illustrates active, present-day processes. Deposition is largely restricted to the axial portions of the intermontane basins and narrow floodplains. Regions of high seismicity within 10–15 km of the surface[22] are shown by stars. Presently- or recently-active faults that break the surface seem to be associated with shallow seismicity.

local fluvial deposition. Intraformational conglomerates first appear at Ganda Paik and Bangala (Fig. 1) about 2.0–1.9 Myr ago, synchronous with the inferred movement along the MBT. At the same time, decreasing rates of sedimentation are observed at Ganda Paik, Bangala, and, farther to the south, at Dina (Fig. 1), where extrabasinal conglomerates first appear around 1.6 Myr ago. The youngest comformable molasse strata in each section provide a limiting date on the cessation of sedimentation, as a wave of folding, uplift and erosion traversed the region. Thus, to the south-east of the Soan Syncline where deformation began around 2.1 Myr ago, the topmost conformable strata are progressively younger at Ganda Paik and Bangala (~1.6–1.5 Myr) and at Dina (~0.5 Myr). The youngest strata preserved farther south-east at Rohtas (Fig. 1) are ~1.5 Myr old. However, the presence of molasse strata as young as 0.4 Myr on the Rohtas anticline some 10–15 km farther south-west[11,12] (BK, Fig. 1) suggests significant truncation of the Rohtas section.

Eastern limb of Jhelum Re-entrant

The Kashmir intermontane basin is separated from the Indo-Gangetic foredeep by the thrust-faulted Pir Panjal Range (Fig. 1). South of the Pir Panjal, the Siwalik molasse is well exposed in a series of thrust-cored anticlines where measured and dated stratigraphical sections record the history of fluvial systems flowing from the Himalayas. Although the detailed timing of tectonic events in the enclosing ranges and the bounding foredeep cannot be delineated as precisely as in the region to the west, three intervals of deformation can be discerned in both the intermontane sediments of Kashmir and the molasse sediments to the south.

In Kashmir, the basin-filling Karewa Formation[19,21,33–36] is >1,300 m thick. Magnetostratigraphical sections from Hirpur and Romushi (Figs 1 and 2) indicate that Karewa sedimentation spans the interval from ~4 Myr to the present[19]. This deposition began as a response to the initial emergence of the ancestral Pir Panjal Range ~4.5 Myr ago. Although molasse sedimentation across the Potwar region to the south continued uninterruptedly during this interval[13], major changes in clast lithologies in the molasse and in drainage patterns (from east-flowing to south-flowing)[13,37] signal the concomitant onset of structural development of the Jhelum Re-entrant[38]. In addition, for the first time in Upper Siwalik sediments, polymictic conglomerates appear in abundance, reaching Sakrana (Fig. 1) by 3.1 Myr ago and prograding southwards across Rata-Dadial (2.5 Myr) and Kas Guma (2.1 Myr). This onslaught of conglomeratic sedimentation appears to be a time-transgressive response to the initial uplift of the Pir Panjal Range.

Concurrently in Kashmir, palaeocurrent indicators[19] suggest that pulses of uplift, presumably thrust-related, occurred along the northeastern margin of the basin until ~2 Myr ago. Subsequently, diminution of this thrusting[38] and accelerated uplift of the Pir Panjal Range redirected palaeocurrents towards the north-east. This interval of tectonism is synchronous with that previously described in the north-central Potwar and is recorded concurrently by a deceleration in molasse sedimentation rates at Rata-Dadial and Kas Guma (Fig. 1). This deceleration is likely to signal the onset of development of the thrust-cored anticlines in the foredeep in response to intensified thrusting and uplift to the north. Subsequently, progressive uplift and erosion spread southwards across the eastern Potwar, as evidenced by the youngest comformable strata at Sakrana (<2.7 Myr), Rata-Dadial (<1.8 Myr) and Kas Guma (<1.4 Myr). The youngest deformation in the Potwar is recorded in sections at Pabbi[32,39], Basawa Kas[11,12] (P, BK; Fig. 1) and Dina, where erosion supplanted sedimentation <0.5–0.4 Myr ago. This third phase of tectonism is contemporaneous with the most recent interval of rapid uplift, totalling 1,300–3,000 m, of the Pir Panjal Range in southern Kashmir[19].

Synthesis

The use of magnetostratigraphy in conjunction with fission-track dating provides an insight into the chronology of the late Cenozoic structural disruption of the northern margin of the Indo-Gangetic foredeep in northern Pakistan and India. Figure 5 illustrates the reconstructed depositional and tectonic conditions in 1-Myr increments between 4 Myr and the present. The time–space perspective diagram in Fig. 6 illustrates the concurrent evolution of both arms of the North-west Syntaxis.

Intermontane basin development commenced in Kashmir 4–5 Myr ago and progressed contemporaneously with major changes in palaeocurrents and provenance in the adjacent foredeep. Dated sequences in the Peshawar and Cambellpore intermontane basins and in the Soan Syncline delineate the sequential southward migration between ~3.0 and 1.8 Myr ago of major thrust faulting, uplift, and the concurrent development of intermontane basins on the back side of the uplifted terranes. During this time interval, the locus of thrusting shifted some 50 km to the south. The duration of significant movement along the major thrusts (Attock, MBT) is envisaged as rather brief (<0.5 Myr). Contemporaneous deformation and erosion of sedimentary sequences in front of the thrusts often occurred at rapid rates ($\geq$15 mm yr^{-1}). Subsequent to the development of the imbricated, thrust-bounded ranges and basins in northern Pakistan and to a second pulse of uplift in Kashmir, the locus of major deformation continued migrating towards the south, where it caused folding, faulting and rotation of the Potwar Plateau[13,32,40], and propagation of the detachment surface to the Salt Range.

Whereas the initial development of the Kashmir and Peshwar Basins does not appear to be synchronous, a pulse of deformation associated with thrusting along the MBT is manifested across a broad region of the northwestern foredeep around 2–1.5 Myr ago. Development of the Campbellpore Basin, snapping shut of the Soan Syncline, and renewed uplift of the Pir Panjal Range were apparently contemporaneous with the disruption of molasse sedimentation across the Potwar Plateau as thrust-cored anticlines began to grow along the northern foredeep margin.

Conclusions

Because of the temporal resolution provided by magnetostratigraphical studies, the timing and duration of tectonic and sedimentary events in the northern Himalayan foredeep can now be reconstructed with greater detail than was previously possible. The chronological data emphasize the sporadic nature of tectonism in this collisional setting. Although the rate of convergence of the Indian subcontinent with Eurasia[41] appears steady during the studied time interval, this detailed reconstruction of the northwestern Himalayan foredeep indicates that prolonged periods of quiescence and uniform sedimentation were punctuated by brief, intense intervals of deformation as the locus of thrust faulting encroached in a stepwise fashion on the adjacent foredeep. This sporadic tectonism may be regarded as the pulse of an orogenic process which, when integrated over time intervals in excess of 1 Myr seems to be continuous.

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