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Late Cenozoic tectonics and sedimentation in the north-western Himalayan foredeep: I. Thrust ramping and associated deformation in the Potwar region

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ABSTRACT

The deformed proximal margin of the Himalayan foreland basin of northern India and Pakistan contains a sequence of over 3000 m of Neogene and Quaternary clastic rocks known as the Siwalik Group. These rocks record the influence of external tectonic controls exerted by the adjacent Himalayan orogenic belt together with internal, syndepositional structural controls emanating from within the foreland basin itself. The application of a magnetic polarity stratigraphy to constrain the chronology of sediment accumulation allows for the documentation of the onset, duration, and termination of various structural events preserved in the sedimentary record with a precision which may approach ~20,000 to ~50,000 yr. Analysis of magnetostratigraphies from more than 20 sites across the Potwar Plateau and adjacent regions of the north-western Himalayan foredeep define two intervals of major deformation, both of which are associated with minor precursor and post-deformational sedimentologic changes. The first event initiates in the Miocene and culminates in the mid-Pliocene between 4·5 and 3·5 Myr BP. This event is manifested by strong folding, uplift and rotation in areas adjacent to the present Salt Range. The second deformational interval spans 2·1–1·6 Myr BP and preserves a record of massive deformation throughout much of the Potwar region. This disruption is interpreted to be a response to progressive stress accumulation and paroxysmal release due to the overriding of a major basement fault by the Salt Range detachment.

INTRODUCTION

The record of NW Himalayan tectonism is preserved in an extensive apron of late Palaeogene to Quaternary sedimentary succession exposed in the outer Himalayan foothills and adjacent Indo-Gangetic Plain of northern Pakistan and India (Gansser, 1964). The onset of molasse sedimentation is a response to initial orogenic activity in the Himalaya, and is represented by the mixed fluvial/deltaic and near-shore marine facies of the Murree/Dharamsala/Dagshai/Kasauli Formations of the lesser Himalaya. These Eocene to Oligocene and early Miocene facies represent the initial clastic record of the development of intracontinental subduction which began in the Mid-Eocene due to plate collision. Subsequently, progressive outward (southward) displacement of the zone of Himalayan deformation has resulted in motion within the Main Boundary Thrust (MBT) zone and the resulting confinement of a zone of late (syn-) orogenic fluvial facies, the Siwalik Group, to a deformed foredeep margin and evolving foreland basin primarily to the south of the zone of deformation (Fig. 1).

Seismic reflection data from south of the MBT zone in Pakistan has confirmed the existence of salt-constrained detachment development under the greater part of the Potwar Plateau and the presence of sub-thrust basement faults (Lillie *et al.*, 1985). The latter appear to have acted as stress concentrators during the late Neogene and Quaternary. This paper addresses the implications of this evidence in conjunction with a detailed consideration of the magnetic polarity stratigraphy of a number of localities exposing the Siwalik Group. It explores their bearing on the interpretation of deformational events and sedimen-

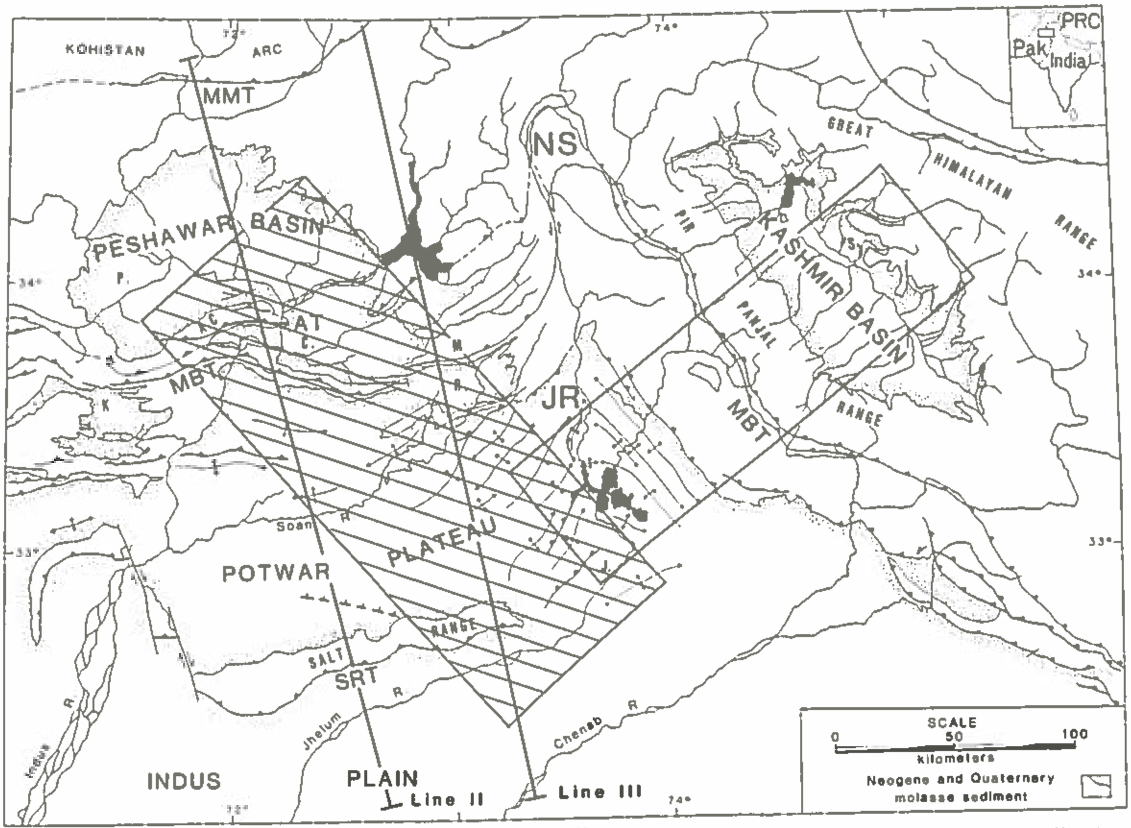


Fig. 1. Schematic outline of major structural features of the Himalayan foreland basin, northern Pakistan and India. Area covered in this report, outlined and cross-hatched; companion paper (Burbank *et al.*, this volume) outlined. Location of schematic structure sections (Fig. 2) are shown. Symbols as follows: AC, Attock–Cherat Range; AT, Attock Thrust; C, Campbellpore (now Attock); H, Hirpur; J, Jhelum; JR, Jhelum Re-entrant; K, Kohat; M, Margala Hills, MBT, Main Boundary Thrust; MMT, Main Mantle Thrust; NS, NW Syntaxis; P, Peshawar; R, Rawalpindi; S, Srinagar; SRT, Salt Range Thrust.

tologic responses during the latest Neogene and Quaternary within the proximal Himalayan foredeep and adjacent intermontane basins lying primarily to the west of the Jhelum River. In a companion paper (Burbank *et al.*, this volume), the region to the east of the Jhelum River and Northwest Syntaxis (Fig. 1) are analysed and the data from the entire region are synthesized.

STRUCTURAL ELEMENTS OF THE NORTHERN PUNJAB AND ADJACENT AREAS

Faulting in the Punjab foreland

It has long been recognized that exposures of the Late Tertiary molasse sequence of the Himalaya are restricted almost entirely to the first rugged foothills rising to the north of the Indo–Gangetic plain. In India, this Tertiary Belt is often quite narrow, ranging from 50 to less than 5 km in width. In the Potwar Plateau and related Salt Range of Pakistan, the deformed belt attains unusual widths of over 100 km. The belt is terminated on its northern side by the MBT zone which carries early Tertiary or Mesozoic rocks of the Hazara Himalaya (Gansser, 1964; Fuchs, 1975) over the younger Siwalik molasse sequence. The southern limit of molasse exposure is defined by the outer limit of compressional deformation induced by the plate convergence in the vicinity of the Salt Range.

The Salt Range and Potwar Plateau (Fig. 2) are the result of a shallow dipping thrust that has carried an entire post-Cambrian stratigraphic sequence southwards along a detachment localized within the

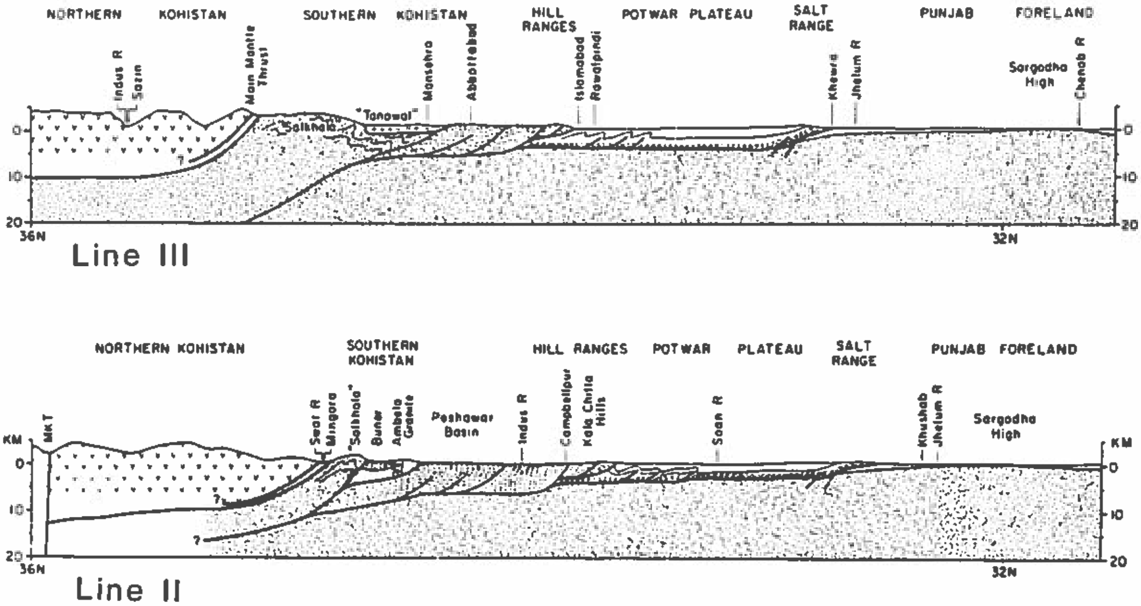


Fig. 2. Schematic cross-sections of the foreland margin of northern Pakistan. See Fig. 1 for location of sections (modified from Yeats & Lawrence, 1984).

Cambrian-aged Salt Range Formation. This structural interpretation is founded on early work in the Salt Range by Wynne (1878), Cotter (1933), Wadia (1945a, b) and Gee (1945, 1947, 1980). That the entire Potwar Plateau is allochthonous was first postulated in a cross-section by Cotter (1933) and later discussed by Voskresenskiy (1978). Cotter's views have been supported by recent data which allow for the interpretation that active deformation is taking place with very little seismic response (Seeber & Armbruster, 1979). This aseismic deformation appears due to aseismic slippage within a ductile detachment surface primarily constrained within the salt horizon. Recent evaluation of reflection seismic data from the central Potwar Plateau has further confirmed the presence of an extensive salt basin (the Salt Range Formation) at the stratigraphic base of the Phanerozoic section underlying large portions of the central and southern Potwar, as well as occurring slightly south of the Salt Range itself (Lillie & Yousuf, 1986; Lillie *et al.*, 1985).

The Salt Range and Potwar Plateau are bounded on the east by the Jhelum River, where thrusting diminishes, and an increasing proportion of the compressional deformation is taken up in a series of frontal monoclines, simple folds, blind thrust-cored folds and thrust-cored folds. Whereas in the central and western reaches of the Plateau, the Soan syncline broadens and occupies much of the allochthonous sheet (see, e.g. cross-section by Pilgrim, 1913 and Fig. 2), to the east, the Potwar Plateau sediments become more intensely folded until at the Grand Trunk Road in the easternmost Potwar Plateau, the entire Siwalik outcrop is thrown into folds (Figs 3 and 4). This phenomenon, likely a response to thinning of the Salt Range Formation at depth, is an expression of the repeatedly upward cutting of the detachment slip surface, resulting in the frequent thrust-cored anticlines encountered along this trend. Similar relationships constrained by salt basin-boundary conditions have been reported elsewhere and have been shown to grossly affect the style of deformation in the suprathrust sheet (Davis & Engelder, 1985).

There is also a systematic change in structural style as one proceeds from north to south across the Potwar Plateau. Several writers (Pinfold, 1919; Cotter, 1933; Gill, 1951b) have described the transition from steeply faulted, isoclinally folded beds in the north (generally north of the Soan River), through a zone of less steep faulting and tight folds to a realm of gentle folds in the south. In general, examination of the variation in and style of structural development of the Potwar Plateau (Gill, 1951a, b; Martin, 1962) has been concerned with the analysis of folding patterns defined by concentric folding. Martin (1962), in a series of

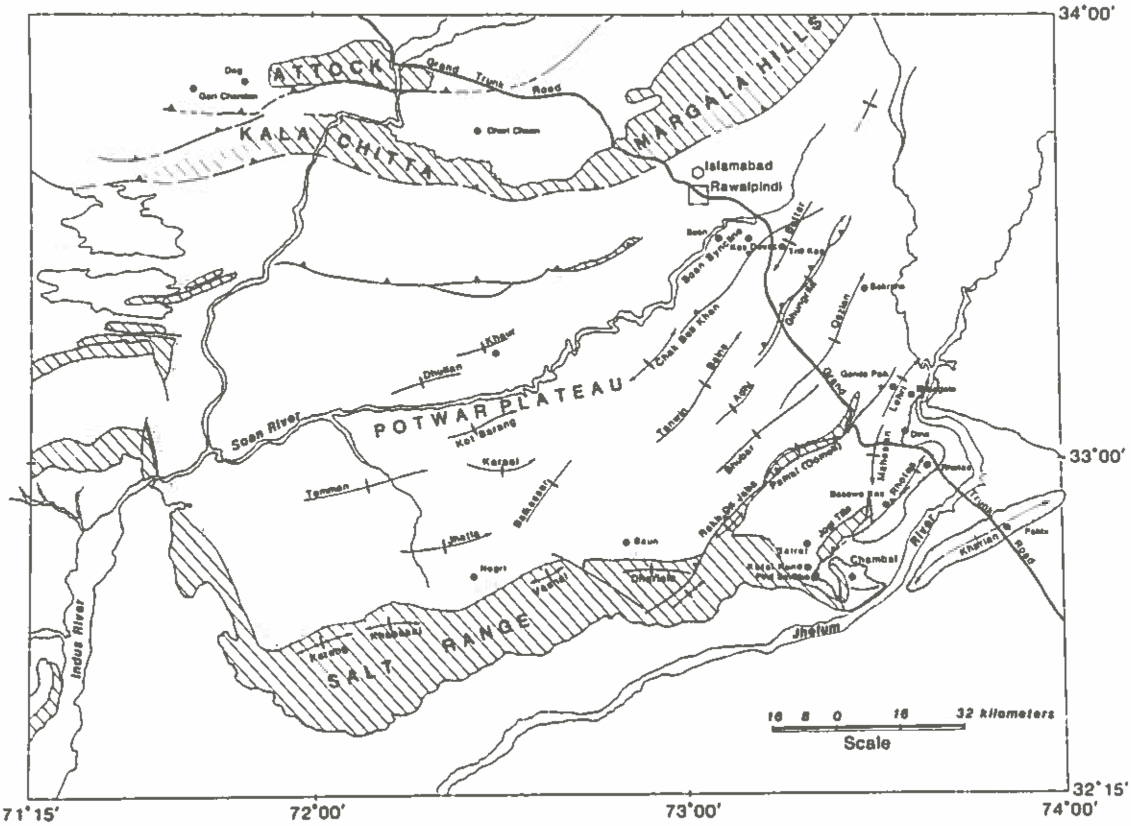


Fig. 3. Locality map of the Potwar Plateau and adjacent areas of northern Pakistan showing principal structural features discussed in text. Location of palaeomagnetic sections utilized as data base (see Fig. 5) are indicated (closed circles).

sections across several structures of the Potwar including the Lehri–Mahesian folds (Fig. 3), points out the interrelationship of folds and thrust faults in describing faults that are warped by subsequent folding. This may explain the anomalous, steeply dipping faults reported in various structures of the eastern Potwar (Gill, 1951b). Martin sees this deformation to be the result of a continuous application of compressive stress, with the rock response varying according to the stress trajectory and the stage of deformation attained by the structure.

Basement faulting

Voskresenskiy (1978) pointed out the likelihood of pre-existing basement faulting playing an active role in controlling the behaviour of the Potwar detachment. At the time, however, the nature of the presumed ramping was not defined. Reflection seismic data recently released by the Pakistan Oil and Gas Development Corporation (OGDC) (Lillie & Yousuf, 1986; Lillie *et al.*, 1985) now demonstrate clearly the character of this thrust geometry. Several north-dipping normal faults affect the sub-thrust basement in the areas of the central Potwar Plateau and Salt Range south of the Soan River (Lillie, 1986). At least one of these (Figs 1 and 2) has exerted a major control on detachment behaviour, and it perhaps ultimately constrained the greater Potwar Plateau during initial compressive deformation until such time as a ramping episode occurred resulting in the Salt Range overthrust. The influence of basement faults on the fold/thrust geometry in the eastern Potwar Plateau has not been fully evaluated. We hypothesize that due to a diminution in the thickness of the lubricating Salt Range Formation, an increase in the frictional component of the thrust along the slip surface results in the frequent upthrusts and the observed tightening of deformational style (Fig. 4).

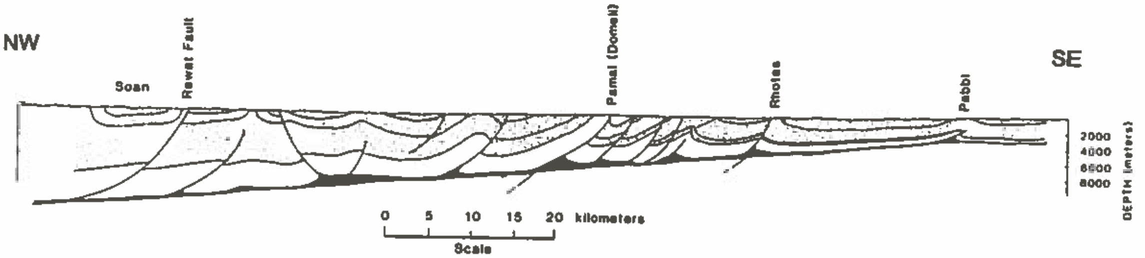


Fig. 4. Schematic structural cross-section along the Grand Trunk Road traverse, eastern Potwar Plateau. See Fig. 3 for location of traverse. Salt Range Formation (black); pre-orogenic platform sediments (white); syn-orogenic clastics, including Murree and Siwalik Groups (stippled).

The nature of basement control on foreland sequences elsewhere (Wiltscko & Eastman, 1983) and the influence of associated salt basin geometry on fold/thrust geometry (Davis & Engelder, 1985; Jenyon, 1985) provide evidence that the greater Potwar Plateau/Salt Range detachment represents an interplay between two rather complex mechanisms. Further evaluation of this relationship is warranted in so far as a genetic relationship may be shown to exist between the normal faulting in the foreland basement and the distribution of the Salt Range Formation in the late Proterozoic/early Cambrian.

A discussion of the timing of events associated with the deformation of the Himalayan foreland basin and the Salt Range ramping event(s) is developed herein. In it we explore the time-constrained stratigraphic record and use it to analyse both the general pattern of structural disruption, as well as the precise timing and consequences of a ramping event.

SEDIMENTARY DYNAMICS OF THE NORTHERN PAKISTANI FOREDEEP MARGIN

Sedimentary dynamics of molasse deposition

Peshawar Basin

To the north of the Main Boundary Thrust, a series of intermontane basins are developed on allochthonous bedrock terranes (Figs 1 and 2). From the Peshawar Basin in the NW across the Campbellpore Basin to the overthrusted northern margin of the Potwar Plateau, these intermontane basins become progressively smaller and more abbreviated in their stratigraphic record to the south. Magnetostratigraphic data in combination with the physical stratigraphy at a number of dated locations permit us to delineate details in the sequence of basin development. Although we cannot at present specify the timing of the initiation of thrusting in areas immediately adjacent to the Peshawar Basin, we can nevertheless use magnetostratigraphic data from synorogenic clastic facies within the basin to provide a chonologic constraint on the cessation of thrusting along the southern margin of the basin. This serves to constrain the history of movement along the Main Boundary Thrust zone in the Trans-Indus regions.

Two sites within the Peshawar basin provide these data (Burbank & Tahirkheli, 1985): the Dag section (Fig. 3) lies adjacent to a thrust ridge(?) of severely deformed Palaeozoic(?) slates and early Tertiary carbonates (Tahirkheli, 1970), whereas the Garhi Chandan sequence rests unconformably on strongly folded and erosionally truncated Murree strata of Late Oligocene to Early Miocene age. The ~3 Myr age of onset of synorogenic clastic deposition in both stratigraphic sections (Fig. 5) indicates that major structural deformation had shifted out of the basin interior at this time. In each section, initial low-relief floodbasin or lacustrine facies are displaced basinward by an influx of fanglomerates shed centripetally off the basin margin. Between 2·6 and 1·6 Myr these fan sediments prograded northwards across the southern basin margin at an average rate of 2 cm yr^{-1}. We interpret these chronologic and stratigraphic data as indicating that: (1) thrusting and major uplift of the Attock–Cherat Range (and segments of the Main Boundary Thrust zone in this area) occurred just prior to 3 Myr ago; (2) this uplift impounded the pre-existing southerly flowing river systems; and (3) the resultant low-energy sedimentation was displaced to the north by the gradual influx of fanglomerates from the uplifted southern basin margin.

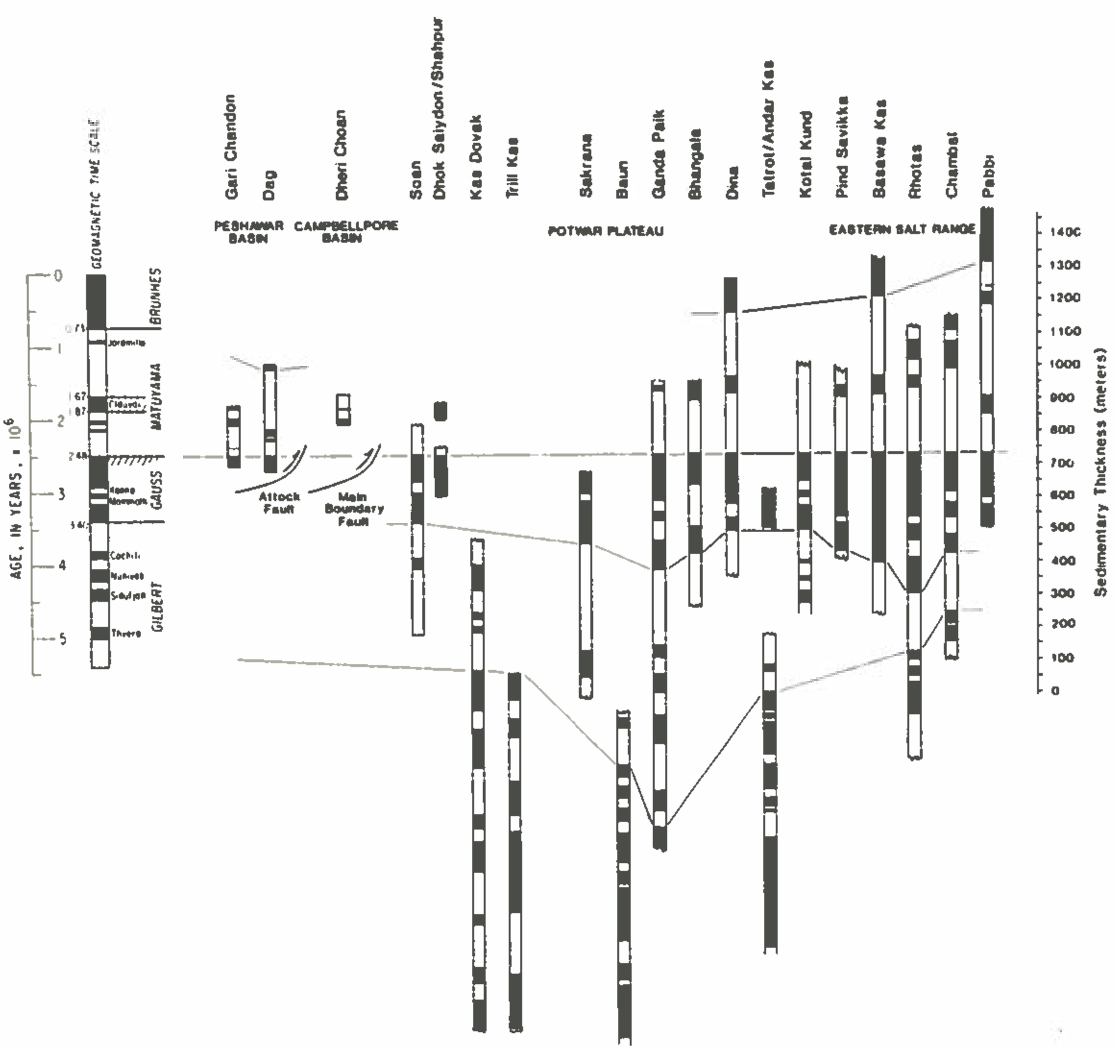


Fig. 5. Correlation of local magnetic polarity sections from the Peshawar and Campbellpore Basins, the Potwar Plateau and Eastern Salt Range regions of northern Pakistan with the magnetic polarity time-scale. See Fig. 3 for location of sections. Normal polarity intervals (black); reversed polarity intervals (white). Data from numerous sources (see text).

Attock Range

In the Attock–Cherat Range (Fig. 3) along the southern margin of the Peshawar basin and in isolated nearby inliers, exposures of the Oligocene and Early Miocene-aged Murree Formation are well developed (Meissener *et al.*, 1974). These terrestrial redbeds represent an early stage of molasse deposition following the initiation of intracontinental subduction along the Main Mantle Thrust of the Hindu Kush and Kohistan Himalaya in the earlier Cenozoic. In the Cherat Range, the Murrees and the underlying carbonates of Eocene age have been complexly deformed by a series of faults and low-angle thrusts (Burbank, 1983; Burbank & Tahirkheli, 1985). This deformation in combination with the absence within the Peshawar basin of molasse facies equivalent to Lower and Middle Siwalik strata of middle and late Miocene age suggest that major tectonic disruption of this terrane occurred in the vicinity of the Peshawar basin between 5 and 10 Myr, a timing which may help to explain the relatively source-proximal, sandy-bedded, braided stream environments characteristic of the type Nagri Formation *sensu strictu* of the Siwalik Group in the central and western Potwar Plateau further to the south.

Campbellpore Basin and Kala Chitta Range

Major movement along the Main Boundary Thrust zone and the development of the Campbellpore basin (Figs 1 and 2) to the south are well constrained by chronologic data. The local basement of Eocene Nummulitic limestones is strongly deformed, and there are no known exposures of Miocene and early Pliocene-aged Murree and Siwalik molasse within the basin. On the basis of two fission-track dates (G. D. Johnson *et al.*, 1982; Burbank, 1982) and the local magnetic polarity stratigraphy, the oldest exposed intermontane sediments in the Campbellpore basin (Dheri Choan, Fig. 5) date from ~1·8 Myr (Burbank, 1982, G. D. Johnson *et al.*, 1982). Although no large, stable lakes appear to have existed within the basin, the sedimentation pattern is interpreted as resulting from a sluggish, meandering fluvial system (Bloch, 1981) with transient floodbasin lacustrine deposits several kilometers in diameter that were frequently interstratified with fluvial deposits. The intermontane nature of deposition is emphasized by this depositional pattern which is typical of ponded systems found in basins with actively rising flanks (Miall, 1979), rather than of the braided systems that characterized the external molasse of the Himalaya. The record of uplift and deformation of the Kala Chitta Range (Fig. 3), the eastern extension of the Cherat Range, is essentially a record of the history of movement of the Main Boundary Thrust in this region bordering the northern Potwar Plateau.

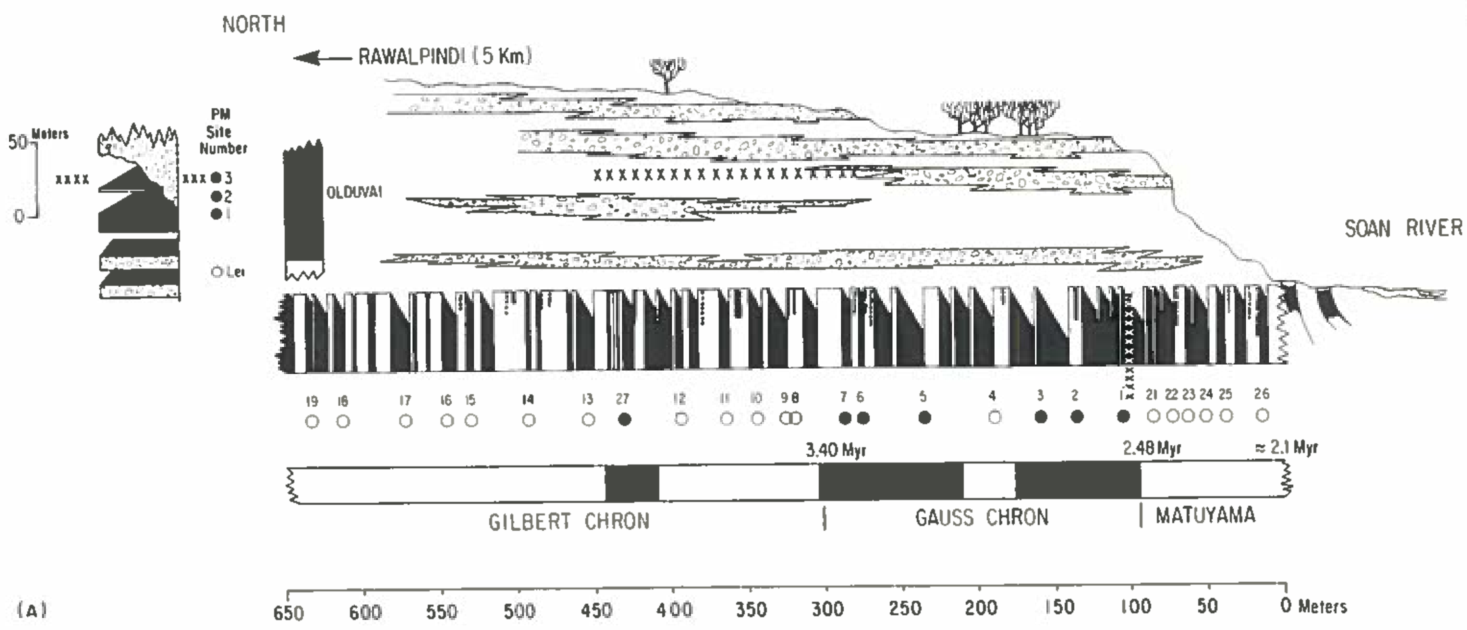
Khairi Murat Range and associated terrain

The area of the northern Potwar Plateau to the south of the Kala Chitta Range and the MBT zone and north of the Soan Syncline is dominated by complexly folded and faulted rocks of Eocene, Oligocene and Early Miocene age (the Nummulitic limestones, Murree and Lower Siwalik formations). Characterized by often vertical dips, thrust-bounded ridges and tight isoclinal folding, the terrane represents a deeper level of structural exposure than is found to the south in the Potwar. Seismic data (Lillie *et al.*, 1985) shows poor reflector characterization making difficult the resolution of thrust/detachment geometry in this region. Because no well developed late Neogene and Quaternary molasse is exposed in this structural block in the central and eastern Potwar (with the exception of the Lei Conglomerate—see below), our interpretation of the timing of structural deformation in this zone must be inferred from adjacent terrain.

Soan Syncline

The Soan Syncline is the first major structural flexure encountered south of Rawalpindi. This syncline broadens and flattens to the SW and is the major structural feature of the central Potwar Plateau (Figs 3 and 4). The syncline is a flat bottomed, SW plunging fold with a steep north-western flank and a more shallow south-eastern flank. Moragne (1979) measured and interpreted the magnetic polarity stratigraphy of a steeply dipping 650 m section near the north-eastern nose of the syncline in the vicinity of the Grand Trunk Road (Soan section), and he determined that the exposed rocks range in age from the middle Gilbert to lower Matuyama Chron (Fig. 5). Moragne's interpretation of the magnetic polarity stratigraphy is supported by a fission track (zircon) date of $1{\cdot}9 \pm 0{\cdot}4$ Myr on a volcanic ash near the polarity reversal interpreted as the Gauss/Matuyama boundary (Fig. 6).

Further SW, on the same flank of the syncline, an unconformable and flat-lying ash has been dated by the fission track method (zircon) at $1{\cdot}6 \pm 0{\cdot}22$ Myr (G. D. Johnson *et al.*, 1982). Exposed in portions of the central Soan Syncline and overlapping on to its north-western margin are the Lei conglomerates, a Siwalik formation which overlies the flat-lying ash and which is consanguinous with deformation of the Main Boundary Thrust zone to the north and of the bulk of the foredeep margin of the northern Potwar Plateau (Fig. 6). The two ash beds discussed above and their associated magnetic polarity stratigraphies constrain the timing of deformation of this fold to within the interval from 2·1 to 1·9 Myr BP (Raynolds & Johnson, 1985). Evidence from additional palaeo-



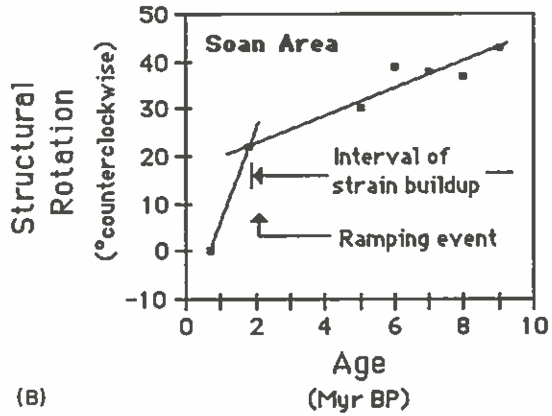


Fig. 6. (A) Schematic representation of the Soan Syncline sequence 2 km south of Rawalpindi showing evidence of termination of deposition, folding, truncation, and renewed deposition of upper Siwalik Group sediments between approximately 2·1 and 1·8 Myr BP. Modified from Raynolds & Johnson (1985). (B) Amount of structural rotation of Siwalik Group sediments determined for rocks of known age from the Soan area (Kas Dovak; Dhok Sayidan; Soan localities). Data from Raynolds (1980).

magnetic considerations suggests that truncation of the Soan sequence and deposition of the Lei Conglomerate was followed by minimal deformation subsequent to the Olduvai magnetic polarity subchron.

Chak Beli Khan Anticline

The Chak Beli Khan anticline (Fig. 3) is a small fold that defines the gently dipping southern margin of the Soan Syncline in the central Potwar Plateau. Good exposures of sandstones which characterize the ancestral Indus depositional system in the Middle Siwalik formations (Raynolds, 1981) occur in the core of this fold. The south-eastern flank of this structure, steepened and in places fractured and overturned, is expressed along strike to the NE as the Riwat Fault. In the SW, the structure does not expose rocks of Pliocene–Pleistocene age and does not provide palaeomagnetic data useful to the interpretation of Late Neogene/Quaternary deformational events.

Along the NW flank of the Chak Beli Khan structure, Late Neogene rocks are well displayed along Kas Dovac where over 3000 m of Siwalik strata are exposed (Raynolds, 1980). This structural flank is truncated by the Riwat Fault (Wadia, 1928), which places Lower Siwalik sediments over Middle Siwalik formations near the town of Riwat (Fig. 3). As a classic example of a thrust fault dwindling in throw and merging into an overturned fold, the Riwat Fault dies out to the NE near the apex of the Soan syncline, and to the SW along the north-eastern flank of the Chak Beli Khan anticline.

The data from Kas Dovac (Raynolds, 1980) suggest that the Riwat fault and the uplift associated with its overthrusting block was initially expressed between the upper Gilbert and upper Gauss chrons yielding depositional hiatus of nearly 0·7 Myr. The abrupt exclusion of limestone clasts from the supra-unconformable sequence at Kas Dovac implies that axial drainage had become established in the basin which prevented the deposition of NW-derived clasts on the SE flank of the Soan Syncline. A scenario of deformation can be evolved whereby the Riwat Fault uplifted the SE flank of the syncline sometime between 3·4 and 2·7 Myr. By 2·6 Myr the Riwat Fault had largely ceased to move, inducing only a very slight dip to the post-2·6 Myr section at Kas Dovac. Deposition continued as consequent drainage within the newly developed structure became established resulting in unusual thicknesses of fine-grained facies being deposited until about 2·1 Myr.

Tanwin/Bains Anticline

The Bains fold trends to the NE, where it is kinked into a more northerly trend (Fig. 3). This fold is dissected by tributaries of the Soan River and exposes additional ancestral Indus River facies of various Middle and Lower Siwalik formations in its core. Sandstones which characterize the ancestral Jhelum River system in various Upper Siwalik formations in the eastern Potwar Plateau (Raynolds, 1981) are only sparsely preserved on the flanks of the fold due to a relatively deep level of erosion across this structure. The synclines separating the Bain fold from the Chak Beli Khan and the Adhi–Gungrilla structures do not appear to contain extensive sequences of Upper Siwalik-aged rocks except in the structural saddle near the Grand Trunk Road. The Riwat fault truncates the fold axes of both the Bain Anticline and that of the syncline to the west. These cross-cutting relationships, which are very clear on aerial photographs, form one of the most decisive pieces of evidence supporting evidence for extensive thrust faulting within the eastern portion of the Potwar thrust sheet prior to 2·6 Myr ago.

Buttar (Mankiala) Anticline

North-east of the Bains structure and across the Mandra structural saddle, the *en echelon* Buttar fold (Fig. 3) is developed. This fold was investigated by Small (1980) and preserves on its western flank over 1000 m of ancestral Jhelum River sandstones and mudstones above the characteristic ancestral Indus River sandstones of the Middle Siwaliks. The Buttar fold trends NE and is truncated by the Kahuta Fault. East of the Buttar fold, in the syncline separating it from the Gungrila fold, a thick lens of quartzite conglomerate is preserved. This conglomerate facies forms gently rounded resistant hills and is a characteristic facies found associated with many of the synclines in the eastern Potwar. Magnetostratigraphic studies by Small (1980) indicate that the Buttar fold had not yet undergone deformation by 5·5 Myr ago as this time is characterized by rivers coursing freely across the site of the structure. Rocks younger than 5·5 Myr are not preserved along the west flank of this structure.

Adhi–Ghungrila Anticline

The Adhi structure (Fig. 3) is developed entirely in Middle and Lower Siwalik formations, and no ancestral Jhelum River sandstones of Upper Siwalik age are found on either of its flanks. This structure has proven hydrocarbon reserves (determined by PPL and AMOCO). To the north, the Ghungrila structure is flanked by a northward thickening sequence of Upper Siwalik rocks. A 600 m section was measured and sampled near the village of Pandori on the western flank of the Ghungrila fold (Fig. 3) (Raynolds, 1980). In this area, over 1300 m of ancestral Jhelum River sandstones of Upper Siwalik age overlie ancestral Indus River sandstones of Middle Siwalik age. On the northern end of the Ghungrila anticline (at about 33·5° latitude) a distinct change in sandstone coloration takes place. Brown coloured, Jhelum facies sandstones of the Upper Siwalik sequence are gradually replaced along strike by pale grey-green coloured sandstones that resemble more closely white sandstones of Indus-facies type common in Middle Siwalik formations. On the eastern flank of the structure, in the vicinity of the Grand Trunk Road, a small thickness of quartzite conglomerates is preserved, dipping towards the town of Gujar Khan. These conglomerates are approximately 1000 m above the Indus facies sandstones exposed in the anticlinal core.

Qazian Anticline

East of Gujar Khan, the poorly exposed Qazian fold occurs. This fold is largely covered by the late Pleistocene Potwar Silts on its southern end, while to the north it is flanked by massive quartzite conglomerates. This structure was recently drilled by Gulf Oil with hydrocarbon shows having been reported. We have no precise chronostratigraphic data on this structure.

Jabbar Anticline

The Jabbar structure is a short anticline with a box-fold termination on its southern edge. To the north, this fold is truncated by the Jhelum Thrust (Fig. 3) (Wadia, 1928). An 800 m section was measured and sampled near the village of Sakrana on the western flank of the fold (Raynolds, 1980) (Fig. 5). The top of this section encounters thick quartzite conglomerates which are dated as occurring in the middle portion of the Gauss Chron. These conglomerates are inferred to have been transported across the site of the future structure at that time. The surface relief of this structure thus dates from less than about 3 Myr. Below the conglomerates, the sandstones are transitional between the typical Jhelum-facies sandstones of the Upper Siwalik formations and the paler white sandtones of Indus-facies type described from the northern end of the Ghungrila structure. The Jhelum Thrust carries gently dipping Middle Siwalik rocks westward over the Jabbar structure. This is the locus of the change in structural strike associated with the Jhelum structural re-entrant (Visser & Johnson, 1978).

Baun Basin

A 1700 m section of Siwalik sediments exposed along the Sauj Kas, 10 km south of the central Potwar town of Chakwal and along the north flank of the Salt Range has been studied, and a palaeomagnetic stratigraphy developed which spans a nearly 5 Myr record from *c.* 9·5 to 4·0 Myr BP (Opdyke *et al.*, 1979, 1982; N. M. Johnson *et al.*, 1982) (Figs 3 and 5). This site, near the eastern termination of one of the principal sub-thrust normal faults under the Potwar detachment (Lillie *et al.*, 1985; Lillie & Yousuf, 1986), records a differential rotation of pre-Gilbert Chron Dhok Pathan Formation and Gilbert chron-aged Upper Siwalik sediments (Opdyke *et al.*, 1982). In addition to containing coarse clastics representing both Eocene-aged carbonates and late Palaeozoic Talchir Formation clasts of Salt Range-derived fanglomerates beginning about 4·5 Myr BP, the entire earlier Siwalik section has been rotated up to 35° counter-clockwise. Younger sediments of apparent Gilbert Chron age from this same site are essentially unrotated. As a result, it can be interpreted that the rotation of the detachment in the Sauj Kas region was completed by the Gilbert Chron (Opdyke *et al.*, 1982). The rocks of this sequence can be traced well to the east to just north of the western Pamal (Domeli) Ridge.

Pamal (Domeli) Anticline

To the east of the Baun Basin exposures and to the south of the Jabbar fold, the Pamal (Domeli) Ridge (Fig. 3) rises as a major asymmetrical thrust-faulted anticline overturned towards the south. This fold exposes Eocene-aged carbonates in its core. Northwards, the fold is offset by cross-cutting faults of small throw and finally merges with the Jabbar fold. In its southern extension, the Domeli ridge overthrusts the adjacent syncline to the SE. Within the syncline, beds become more conglomeratic along strike as the thrust trace is approached. Further south, the thrust overlies its own debris. This structure was examined in the Ganda Paik section where a 1500 m section was measured (Raynolds, 1980) (Fig. 5). The section displays a marked facies change with the exclusion of thick channel sandstones and the advent of conglomeratic stringers. Those conglomerates containing derived Nummulitic debris occur at about 2·5 Myr. This is interpreted to be the time at which Eocene strata began to be unroofed along the nearby portion of the Domeli Ridge, and this detritus was shed into the adjacent syncline, a process continuing today. The structural setting was such that the large rivers draining the northern mountains no longer flowed across this site after 2·5 Myr. This exclusion of the ancestral Jhelum River system is a manifestation of the confinement of the river course into the Jhelum re-entrant axis to the east of Ganda Paik.

Kotal Kund Syncline and Mount Jogi Tilla

One of the most significant records of Pliocene–Pleistocene sedimentation events in the eastern Salt Range occurs in the Kotal Kund syncline, occupied in its greater extent by the Bunha River (Fig. 3). Here three sections have been studied (Opdyke *et al.*, 1979; Frost, 1979; G. D. Johnson *et al.*, 1982; N. M. Johnson *et al.*, 1982) which provide evidence of uplift and truncation of a portion of the Middle Siwalik Dhok Pathan Formation sometime after 4·6 Myr BP and before the deposition of the Upper Siwalik Tatrot beds of Gauss age (Tatrot–Andar Kas locality) on the northern flanks of the Mount Jogi Tilla structure. Jogi Tilla is a complex of four recumbent, south-verging thrust folds which expose most of the Phanerozoic section present in the eastern Salt Range (Wynne, 1870; Pascoe, 1930; Fermor, 1931; Gee, 1980).

To the west of the Jogi Tilla lies the Kotal Kund syncline which continued to receive sediments until about 1·6 Myr BP (Frost, 1979) at which time the major centre of deposition shifted out and to the SE to the vicinity of the syncline now occupied by the combined Bunha/Jhelum Rivers. The Pind Savikka and Kotal Kund localities collectively record this event. It appears that continued deformation has taken place in the form of tilting and rotation, affecting all sites within the basin.

Mahesian–Lehri Anticline

The Lehri and Mahesian structures (Fig. 3) are a tightly joined pair of anticlines which have been described by Martin (1962). These two concentric folds are *en echelon* features that have been compressed together along a series of thrust faults. Lower Siwalik facies rocks are exposed in the core of the Mahesian fold. This fold pair is surrounded by a mantle of Upper Siwalik sediments. A section was measured on each flank; to the west at Bhangala and to the east near the town of Dina (Raynolds, 1980). The northern end of the Lehri structure is terminated in a dramatic box fold that is well exposed along the shore of Mangla Reservoir. Forming the top of the measured section near Dina on the western side of these structures, is a thick sequence of conformable quartzitic conglomerates evincing subsequent activity of the ancestral Jhelum River across the region. The section sampled at Bhangala illustrates that channel sandstones persisted at this site until just after 2·4 Myr. After this time, thin and laterally discontinuous sandstones carry angular Siwalik clasts. The implication is that this locality began being influenced by deformation about 2·3 Myr. Although separated from Ganda Paik by only a few kilometres, the channel sandstones persist about 75 m higher in the section at Bhangala. At the prevailing rate of sediment accumulation (30 cm/1000 yr), this thickness represents a lag of 250,000 yr between the onset of the deformation which affected these adjacent folds.

Rhotas Anticline

The Rhotas anticline occurs east of the Mahesian/Lehri pair of folds (Fig. 3). Although it is a simple fold on its northern end, the Rhotas structure is complex and broken by faults to the south in the vicinity of Mount Jogi Tilla (see above). A well exposed 1350 m sequence of Upper Siwalik rocks was sampled along the northern termination of this fold SW of the Grand Trunk Road (Raynolds, 1980). This sequence also preserves quartzitic conglomerates in the top part of the section (preserved on the western flank of the fold, just north of the Kahan River). The Rhotas fold is overlain by a distinctly unconformable quartzite conglomerate which sweeps across the anticlinal axis and is preserved in patches mantling the crest of the fold. The section measured on the apex of the Rhotas fold ends in rocks that are about 1·4 Myr old (Raynolds & Johnson, 1985). At that time, the Jhelum River flowed across the structure. The central part of the fold has been investigated by Opdyke *et al.* (1979) and G. D. Johnson *et al.* (1979) who describe a section measured from Basawa Kas, 12 km SW (Figs 3 and 5). This section preserves a younger sequence of rocks, allowing for a maximum age of surface expression of the Rhotas fold of 0·4 Myr to be derived.

Kharian (Pabbi) Anticline

East of the Rhotas structure, on the east side of the Jhelum River (Fig. 3), the outermost NE-trending anticline is developing. The Kharian or Pabbi fold (Wynne, 1877, 1879), mapped and studied by palaeomagnetic criteria by Keller (1975) and Keller *et al.* (1977), is a gently asymmetric anticline probably representing draping of the Tertiary section over a blind thrust. The age of surface expression for the Pabbi Hills is less than 0·4 Myr (Johnson *et al.*, 1979). While structural models imply that this fold is underlain at depth by a north-westwardly dipping blind thrust, a lateral component of compression, perhaps related to stratigraphic thinning of the Salt Range Formation at depth, has resulted in the structure being offset into three distinct segments to the SW.

SALT RANGE THRUST RAMPING

Time resolution and interpretation of magnetostratigraphies

The dynamics of sediment accumulation in an actively evolving foreland basin can be assessed utilizing time-constrained measures of synorogenic sedimentary facies behaviour (Raynolds & Johnson, 1985; Burbank & Raynolds, 1984). Whereas most palaeontologically based determinations of time in stratigraphic successions involve resolution limits of 10^6 yr, magnetic polarity stratigraphy, determined from rocks as young as the late Neogene and Quaternary, may be useful at resolution limits 10^4–10^5 yr, yielding a significant improvement in our ability to characterize the rates of geological processes (Raynolds & Johnson, 1985). When a local magnetic polarity stratigraphy is successfully correlated to the global magnetic polarity time-scale, the resultant ability to define chronostratigraphically the reversal succession at a locality is a powerful tool in describing sedimentary dynamics. We have evaluated more than 20 localities exposing Siwalik Group rocks and their palaeomagnetic stratigraphy in this report (Fig. 5) and have been able to recognize a number of relationships which allow for precise statements to be made regarding the timing of certain sedimentation-controlling tectonic events in the subsiding Himalayan foredeep. The reader is referred elsewhere to the details of the magnetic polarity analysis upon which some of our interpretations have been based (Burbank, 1982; G. D. Johnson *et al.*, 1979; N. M. Johnson *et al.*, 1982, 1985; Opdyke *et al.*, 1979, 1982; Raynolds, 1980).

The net sediment accumulation at a given depositional site has a tendency to define a sigmoidal curve when accumulated sediment thickness is plotted against time (Fig. 7). This response can be interpreted as representing the transition from low sediment-accumulation-rate conditions in the distal foredeep position to passage into maximum sediment-accumulation-rate conditions in the foredeep depocentre followed by attenuation of sediment accumulation rates in the deforming proximal foredeep position. Important to the issues raised in this paper, the record of sediment accumulation at a given site may illustrate several inflection points along the graphic plot discussed above which represent significant tectonic events affecting the site (Fig. 7) (see also Johnson *et al.*, 1979; Raynolds & Johnson, 1985). In particular, the initiation of uplift and deformation and cessation of the depositional record at a given site can be used collectively with similar data from other sites to effect an interpretation of a more regional nature. We have attempted this for the northern Pakistani foredeep.

Initial early to middle Pliocene deformational events in the southern Potwar

The previously described chronostratigraphic data serve to define the nature and timing of compressional events in the Potwar Plateau and adjacent areas of northern Pakistan. Arguments presented by N. M. Johnson *et al.* (1982) and Opdyke *et al.* (1979, 1982) based on palaeomagnetic criteria allow for the recognition of a period of deformation occurring in the southern Potwar Plateau–eastern Salt Range in latest Miocene (*c.* 8–4 Myr BP).

Within the Kotal Kund Syncline localities in the eastern Salt Range, sediment-accumulation rates diminished about 7·9 Myr BP (N. M. Johnson *et al.*, 1982) (Fig. 7) and the depositional record is truncated at about 4·6 Myr BP. Approximately 32° of counter-clockwise rotation occurred after this time. Subsequently, deposition recommenced during the mid-Gauss Chron at approximately 3·0 Myr BP (Opdyke *et al.*, 1979) (Fig. 8). We interpret this to represent the initial response to the ramping thrust of the Potwar detachment which resulted in a complex arrangement of frontal anticlines and the tip-stick thrust fronts of the Pamal (Domeli) and Jogi Tilla structures.

In the Baun Basin locality at Sauj Kas, in the central Salt Range, diminished sediment-accumulation rates began in post-Chron 9 time (~8·5 Myr BP) (N. M.

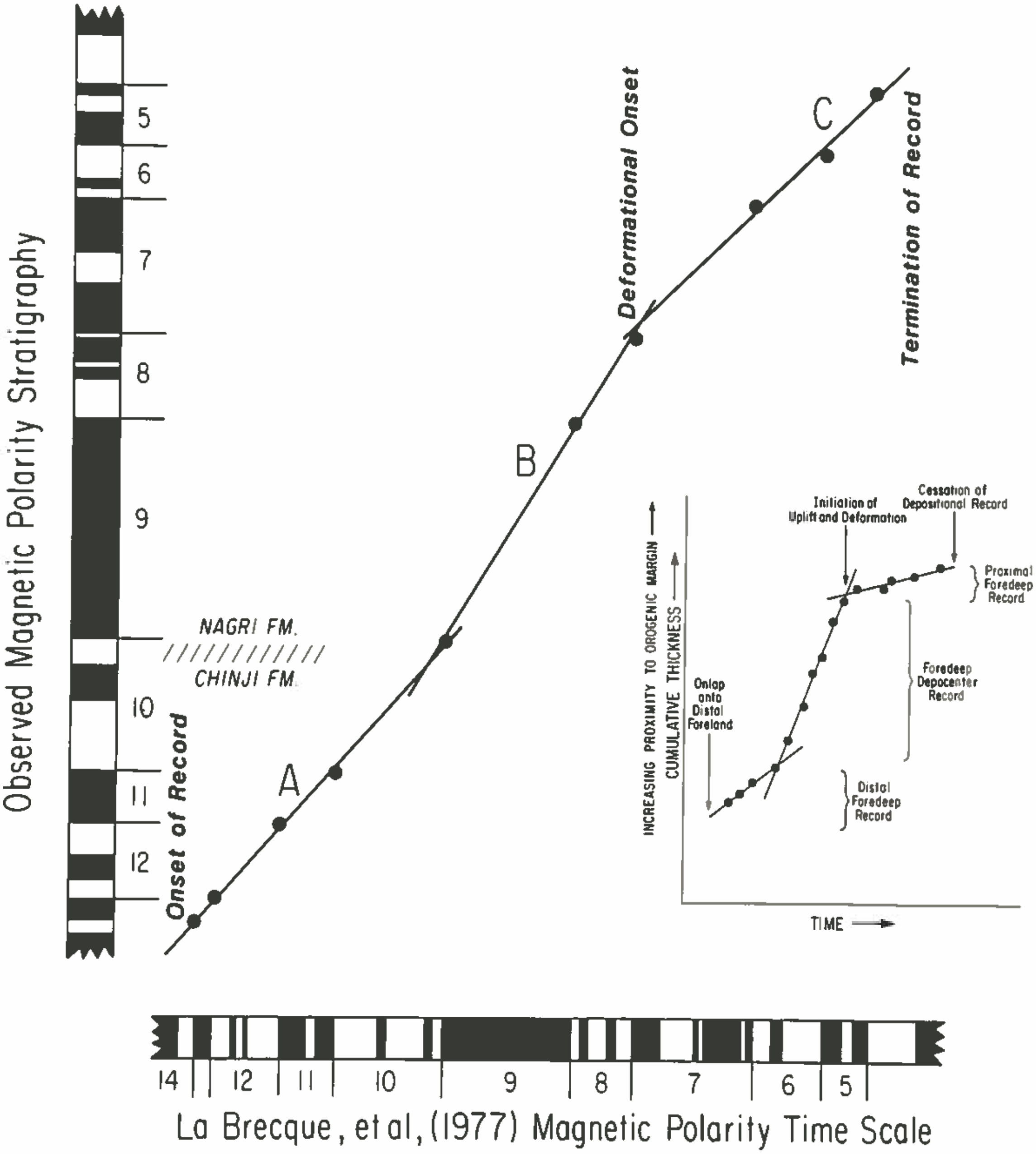


Fig. 7. Sediment accumulation record of Siwalik Group sediments at Tatrot-Andar, eastern Salt Range (see Fig. 3). Theoretical sediment accumulation record of a typical external molasse. Inflection points represent tectonically important events influencing the sedimentation record. Data from N. M. Johnson *et al.* (1982).

Johnson *et al.*, 1982) and a transition from typical Middle Siwalik facies (Dhok Pathan Formation (?)) to Upper Siwalik facies containing identifiable clasts derived from the Salt Range occurs in the medial Gilbert Chron (~4·5 Myr BP) (Opdyke *et al.*, 1979). Additionally, the Dhok Pathan beds exhibit a significant tectonic rotation of nearly 30° not present in the overlying Upper Siwaliks (Fig. 8).

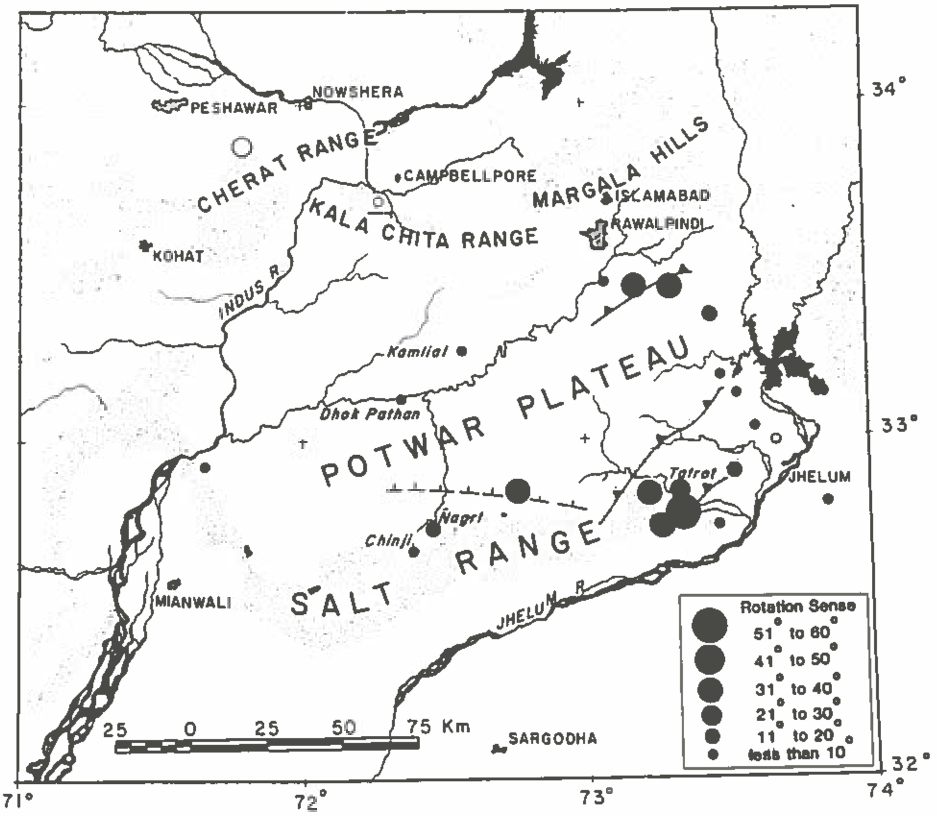


Fig. 8. Magnitude of structural rotation determined from mean of normally magnetized sites from various localities in the Potwar Plateau and adjacent areas of northern Pakistan. See Fig. 3 for locality names. Counter-clockwise rotation, solid circles; clockwise rotation, open circles.

The combined evidence from the various late Miocene events described above provides reasonable constraints on the initial motion on the Potwar–Salt Range detachment. Although now appearing to be constrained by faulting in the sub-thrust basement, this motion may be viewed as one of slippage of the Potwar detachment in the late Miocene until fault-bounded basement highs or steep ramps in the Indian foreland were encountered at some time less than 6·0 Myr ago. The main phase of this early deformation leading to both major uplift and rotation appears to be confined to an interval of 4·5–3·0 Myr ago.

The initial structural response to the encounter of the Potwar detachment with the basement highs of the foreland appears to be the buckling of portions upper thrust sheet, structural rotation of certain segments and the shedding of some of the upper stratigraphic section along the uplifted dorsal flank and leading frontal edge of the thrust sheet. The data from the Kotal Kund area, as well as other sections bounding the Pamal (Domeli) Ridge and Jogi Tilla suggest that these features, having experienced rapid deformation in the early Pliocene, exerted some control on sedimentation patterns in the eastern Salt Range basins during latest Noegene and Quaternary. It appears that the break-up of the Salt Range in the east into a number of smaller, sub-parallel, digitate ranges (the Bakrala, Domeli and Joji Tilla, including the Chak Beli Khan Anticline/Riwat Fault further to the north) may reflect the cutting upwards of the Potwar detachment at a number of locations coinciding with proximity to the eastern edge of the Salt Range Formation salt basin.

Just to the west of the Kotal Kund area, the position of the eastern limit of one of the major sub-thrust faults of the Potwar basement (Figs 2 and 3) can be defined. Whereas this fault may have restricted motion of the detachment in the central Potwar for a period of time, its absence, coupled with the thinning of the Salt Formation of the eastern Potwar, resulted in a more properly defined imbricate thrust system as seen along the Grand Trunk Road traverse (Fig. 4).

Late Pliocene to early Pleistocene deformational events

The development of numerous folds affecting Siwalik Group rocks within the central and eastern Potwar is a record of approximately 20% shortening along the breadth of the detachment which has occurred from approximately 3·0 Myr ago to the present (Fig. 4). A south-eastward younging of the onset of deformation and the initiation of 'surface expression' (Johnson *et al.*, 1979; Burbank & Raynolds, 1984) can be generally demonstrated based on palaeomagnetically constrained data from Siwalik Group outcrops located on the structures encountered in the Grand Trunk Road traverse (Figs 5 and 6). These data suggest that significant deformation occurred in the middle Matuyama (from approximately 2·2 to 1·5 Myr BP). It is suggested here that this 700,000 yr episode was primarily characterized by the Potwar detachment having successfully overriden the basement warp or fault with the subsequent development of the Salt Range proper. In fact, we view the major movement on the MBT, the 'snapping shut' of the Soan Syncline, and the related deformation across the Potwar to be a direct response to the stress transmitted across the breadth of the Potwar from the impinging basement ramp near the Salt Range.

Truncation of the Soan Syncline sequence and deposition of the Lei Conglomerate

The timing of thrusting along the Main Boundary Thrust zone that is inferred from Campbellpore sediments receive spectacular confirmation from the stratigraphy and chronology of the strata exposed in the Soan Syncline, south of the Main Boundary Thrust zone (Fig. 4). Immediately adjacent to the fault zone, Siwalik molasse strata have been severely folded and deeply eroded. Farther south, the Soan Syncline provides the first good exposures of the youngest pre-thrusting strata. Here, in the vertical northern limit of an asymmetric syncline, at least 3000 m of Siwalik sediments are preserved. According to the local magnetic polarity stratigraphy (Raynolds, 1980; Moragne, 1979), these range in age from greater than 9 to 2·1 Myr (Fig. 6). These upturned strata are overlain by the flat-lying Lei conglomerate which has a basal age (G. D. Johnson *et al.*, 1982; Raynolds, 1980) of ~1·9 Myr. The conglomerates are polymictic and reflect lithologies exposed in the uplifted bedrock terrain along the Main Boundary Thrust zone.

These chronologies indicate that, prior to 2·1 Myr, typical external molasse deposition was occurring at the site of the present Soan Syncline. During the succeeding 200,000 yr, as over 3,000 m of uplift and erosion took place at a mean minimum rate of 15 m Myr^{-1}, the syncline snapped shut. Subsequently, the Lei conglomerate prograded across the erosionally truncated syncline. We interpret this succession of events as a direct response to thrusting along the Main Boundary Thrust zone, deformation of the proximal strata adjacent to the thrust, and erosion of the newly uplifted regions along the boundary fault area. In agreement with the basal age (~1·8 Myr) of the Campbellpore sediments in the piggy-back basin, chronologic data from the Soan Syncline define a period between 2·1 and 1·9 Myr of rapid deformation within this region in response to movement along the MBT.

The subsequent termination of significant deformation in the northern Potwar plateau beginning after 1·9 Myr (Figs 5 and 6) reflects the transference of deformational events to the region of the Salt Range and its eastern extensions. The entire northern portion of the Potwar Plateau thus became a passenger on the detachment.

Salt Range ramping

The Salt Range ramping event was initiated approximately 2·2 Myr ago. In addition to generating the large-scale deformation in the northern Potwar, it significantly altered the character of sediment accumulation in the eastern extension of the Salt Range at a number of localities. Probably the most affected were the most proximal sites in the Bunha River basin localities of Tatrot, Kotal Kund and Pind Savikka, which experienced an abrupt termination of sediment accumulation about 1·5 Myr ago (Frost, 1980; G. D. Johnson *et al.*, 1982; Raynolds & Johnson, 1985). The onset of uplift of the Salt Range and a presumed further outward displacement of proximal compressive effects can be seen in the Rhotas and Pabbi Hills data, sites which lie possibly at the edge of the Salt Range Formation salt basin and which, therefore, are likely related to the periodic upward cutting of the Salt Range fault discussed above. The attainment of surface expression in the Rhotas anticline, based upon the magnetic polarity record, is less than 0·4 Myr BP. The same data for the Pabbi Hills anticline is a little less certain, but the attainment of surface expression is also about 0·4 Myr BP (G. D. Johnson *et al.*, 1979).

SUMMARY

The timing of events associated with the development of the Potwar Plateau/Salt Range detachment and related basins to the NW can be interpreted by means of local magnetic polarity stratigraphies. From the evidence discussed above, it appears that the Himalayan foreland basin of northern Pakistan, which is dominated by the Peshawar and Campbellpore basins and the Potwar Plateau and associated thrust-related structures, has a history of deformation which extends from latest Miocene (*c.* 8·0 Myr) to the present.

Initial compressive events in the foreland margin in late Miocene are evinced by a depositional hiatus of mid-Miocene to mid-Pliocene duration in areas to the north of the Main Boundary Thrust zone (the Peshawar and Campbellpore Basins). To the south, in the vicinity of what is now the northern margin of the Salt Range, attenuation of sediment accumulation rates is noted at a number of localities, particularly along the eastern portions of the range (Kotal Kund and Baun localities).

Strong deformation of the area north of the Main Boundary Thrust zone continued through the Pliocene and culminated with the structural development of the Peshawar Basin ~3 Myr ago. Prior to the major deformation along the MBT, two intervals of earlier deformation can be discerned in the Potwar. Within the southern Potwar and eastern Salt Range, data from Kotal Kund and Baun indicate that slowing sediment-accumulation rates preceded an interval of folding, uplift, and rotation that culminated between about 4·5 and 3·5 Myr BP. Subsequently, major movement along the Riwat fault sometime between about 3·4 and 2·7 Myr BP and initial uplift in the Ganda Paik area ~2·5 Myr BP are seen as precursor events presenting an early response to increasing stress accumulation within the Potwar as the basement ramp was initially expressed. Deformation is expressed in several styles depending upon the geographical limits of the Salt Range Formation (the detachment slip surface). In the central Potwar, little evidence of early Pliocene deformation in the form of thrusting exists. Rotation of the detachment sheet, in some localities of up to 30°, is recorded (Fig. 8). To the east, the upward forcing of the detachment surface resulted in the early Pliocene expression of the Chak Beli Khan/Riwat, and Jogi Tilla structures.

The open folds developed in the central and eastern Potwar during the Pliocene (the Soan, Bain, Buttar, Gungrilla/Adhi, Jabbar, and Ganda Paik areas) exhibit attenuation of sediment accumulation in post-3 Myr time (Fig. 9), suggesting that these sites were actively deforming at that time. This appears to be an expression of increasing strain within the Potwar detachment.

The onset of late-orogenic sedimentation beginning in the Peshawar and Campbellpore basins and evidence of significant detrital input from an uplifting Main Boundary Thrust zone terrane (perhaps the Attock Thrust) beginning about 2·7 Myr ago, and the deformation of the Soan Syncline commencing about 2·1 Myr, suggests significant motion along the fault zone at that time.

The abrupt initiation of folding of the Soan sequence about 2·1 Myr ago, with an associated progradation of locally derived clastics across the basin, the termination of sedimentation in the Campbellpore basin and basin-flanking sites in the Peshawar basin about 1·5 Myr ago, the termination of sedimentation over many of the folds in the eastern Potwar (listed above) and the cessation of sedimentation in the Kotal Kund region at 1·6 Myr serves to fix the timing of development of the Salt Range ramping event. This major structural episode, resulting in the Potwar detachment overriding a major sub-thrust basement fault having a throw in excess of 1 km (Lillie *et al.*, 1985), can be inferred to have taken place between 2·1 and 1·6 Myr ago. The resultant termination of significant deformational events in the northern Potwar at that time is an expression of the transference of strain release to the frontal portion of the detachment.

Since 1·6 Myr, the central and northern Potwar, as inferred from our analysis of the palaeomagnetic stratigraphy, has ridden passively upon the detachment. Deformation along the leading edge of the detachment continues as in the case of the Lilla structure of the Jhelum plain south of the central Salt Range and in the thrust-cored Rhotas and Pabbi structures of the eastern extension of the Salt Range (Fig. 3).

Although complex, and not representing a case of a simple migrating foredeep, the data from the northern Pakistani foreland basin serves as an excellent example of the intimate interaction between tectonic

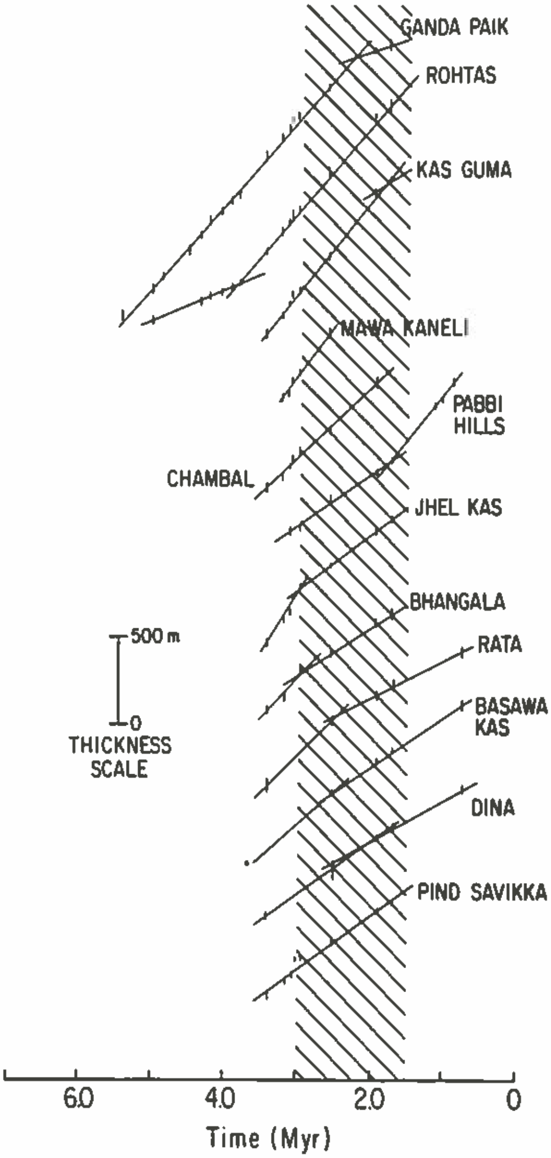


Fig. 9. Sediment accumulation records for a number of sites in the eastern Potwar Plateau, northern Pakistan. An attenuation of the rate of sediment accumulation is generally noted between 3·0 and 1·6 Myr BP in these localities evincing the onset of structural deformation. See Fig. 3 for locations. Selected sites from the Pir Panjal foothill belt (Kas Guma, Mawa Kaneli, Jhel Kas, and Rata) (see Burbank *et al.*, this volume) are included for comparison.

cause and sedimentological effect. We hope this example can serve as a model to illustrate the surprising abruptness and out-of-sequence thrust chronologies which may be observed in certain types of foreland basins.

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