PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Folding and imbrication of the Indian crust during Himalayan collision

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India collided with a northern Kohistan–Asian Plate at about 50 Ma ago, the time of ocean closure being fairly accurately defined from syntectonic sediments as well as the effect on magnetic stripes on the Indian Ocean floor. Since collision, Asia has over-ridden India, developing a wide range of thrust scrapings at the top of the Indian Plate. Sections through the imbricated sedimentary cover suggest a minimum displacement of over 500 km during Eocene to recent plate convergence. This requires the Kohistan region to the north to be underlain by underthrusted middle to lower Indian crust, deformed by ductile shears and recumbent folds. These structures are well seen in the gneisses immediately south of the suture, where they are uplifted in the Indus and Nanga Parbat syntaxes. Here there are several phases of thrust-related small-scale folding and the development of a large folded thrust stack involving basement rocks, the imbrication of metamorphic zones and the local development of large backfolds. Some of the important local structures: the large late backfolds, the Salt Ranges and the Peshawar Basin, can all be related to the necessary changes in thrust wedge shape as it climbs through the crust and the three dimensional nature of the thrust movements associated with interference between the Kohistan and western Himalayan trends.

INTRODUCTION

The Kohistan region of northern Pakistan (figure 1) is one of the best regions in which to study Himalayan tectonics, because (i) the area is relatively accessible, in that it is crossed by numerous valleys including those of the major Indus and Swat Rivers and (ii) there is a full section of the mountain belt preserved within one country, from the suture zone between Indian and Asian Plates to frontal thrust ranges. The area has been studied by reconnaissance mapping and detailed surveys over the past eight years, by research teams from the U.S.A. (notably Dartmouth College and Corvallis, Oregon) and from the U.K. (notably Leicester, Leeds and Imperial College), working in close collaboration with the Universities of Peshawar and the Punjab and the Pakistan Geological Survey. This paper summarizes some aspects of structure of the overthrust Indian Plate, mainly with the results of the Anglo–Pakistani research. Summaries of the deformation in the northern plates are given by Coward *et al.* (1986, 1987) and Pudsey *et al.* (1986).

The suture between Indian and Asian Plates, often known as the Main Mantle Thrust or

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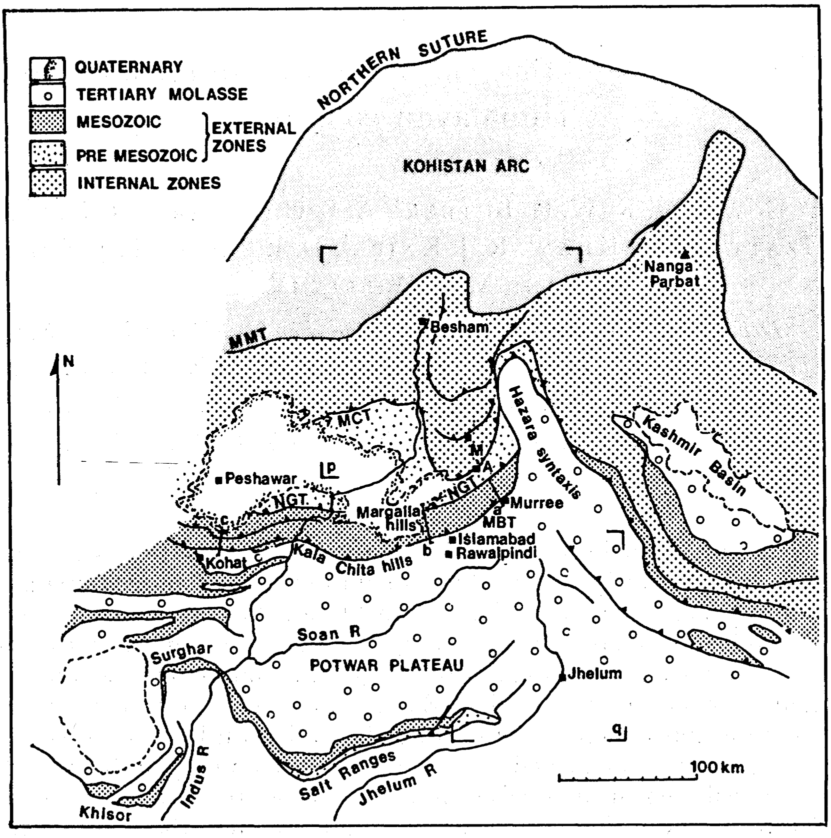

FIGURE 1. Location map for northern Pakistan, showing the distribution of the main thrusts (MMT, Main Mantle Thrust; MCT, Main Central Thrust; MBT, Main Boundary Thrust; NGT, Nathia Gali Thrust), the Kohistan island arc and the internal and external zones; M, Mansehra, A, Abbottabad. Box p shows the location of figure 5, box q shows figure 15. Sections lines a, b and c are shown in figure 11.

MMT (Tahirkheli & Jan 1979; Bard *et al.* 1980) can be mapped as an irregular but generally northward-dipping thrust, folded around later structures developed in the underlying Indian Plate (figure 1). On its hanging-wall are metamorphosed basic and ultrabasic rocks of the Kohistan island arc (Bard *et al.* 1980; Bard 1983), which form a terrane accreted to the Asian Plate during the middle Cretaceous (Coward *et al.* 1986, 1987).

The docking of the Kohistan island arc with the Asian Plate was followed by major folding and shearing of the lower part of the arc and then ocean subduction south of the arc, generating the early Tertiary Kohistan calc-alkaline batholith (Coward *et al.* 1986). Ocean closure occurred at about 50 Ma, the date being constrained by (i) magnetic anomaly patterns of the Indian Ocean, which show a dramatic slowing in the spreading rate at this time (Molnar & Tapponnier 1975; Patriat & Achache 1984) and (ii) the ages of the earliest post-collisional sediments in the suture zone and on the Indian Plate (Bossart & Ottiger 1988; Searle *et al.* 1987). There was subsequent obduction of the Kohistan arc, together with the adjacent part of the Asian Plate, over Indian continental crust.

Throughout most of its length, the MMT forms a discrete ductile fault zone, although in the Swat region there is a ten kilometre wide zone of blueschists, greenschists and ophiolites of the Indian Suture Mélange (Kazmi *et al.* 1984, 1986). This high-pressure assemblage is generally thought to be associated with the collisional event, representing rocks trapped between the Asian and Indian Plates. However, mineral ages of about 75 Ma have been obtained on phengites from blueschists near the Shangla pass, east of Swat (Maluski & Matte 1984), much earlier than the proposed age of collision. Hence, the high-pressure rocks may record an earlier phase of deformation, possibly related to subduction of the Tethyan ocean beneath Kohistan or one of the deformation events within the Kohistan arc (Coward *et al.* 1987).

In the Nanga Parbat area, the MMT carries rocks of the upper part of the Kohistan arc onto basement gneiss (the Nanga Parbat gneisses) and cover metasediments of the Indian Plate. The lower part of the Kohistan arc must have been transported to the north by a process of subduction shearing or break-back thrusting, so that the upper part of the Kohistan arc lies directly against the Indian continent. Details of this geometry are provided by Butler & Prior (1988*a*).

The hanging-wall geometry of the MMT is carried intact onto Indian continental crust which subsequently deformed at various *P–T* conditions. On the basis of 'Himalayan' age metamorphism this deformed Indian crust can be divided into internal (metamorphosed) and external (non-metamorphosed) zones. The internal zone is dominated by a folded and imbricated basement-cover sequence, deformed generally in the amphibolite facies, although locally preserving only greenschist facies assemblages. These are intruded by abundant Himalayan age granites and pegmatites. Some of the pegmatites contain garnet and tourmaline and appear superficially similar to leucogranites to the east in the main Himalayan ranges of India and Nepal, which gives young Tertiary ages (Scharer *et al.* 1984) with high $^{87}Sr/^{86}Sr$ initial ratios, suggesting that they were derived by partial melting of the subducting Indian Plate. The majority of the granites, however, appear mineralogically and texturally distinct from these Himalayan leucogranites although, like them, they are of young Tertiary age derived by partial melting of the local Indian Plate. In Pakistan, the southern boundary of the internal zone is marked by the Mansehra and Panjal thrusts (Coward & Butler 1985), which form an equivalent structure to, but not necessarily coeval with, the Main Central Thrust (MCT) in the Himalayan ranges to the east (Gansser 1964). The southern thrust sheets near Mansehra, carry a granite dated at about 500 Ma (Le Fort *et al.* 1980), intruded into already metamorphosed sediments. This dates the basement rocks of the internal zones as Cambrian or older.

The external zone consists of only slightly metamorphosed or non-metamorphosed Precambrian to Recent sediments. Precambrian slates and greywackes form a basement to a Lower Palaeozoic quartzite and clastic sequence of variable thickness, overlain by a thick carbonate sequence of the Abbottabad Formation (Calkins *et al.* 1975; Latif 1974). To the south, the thrust sheets involve dominantly younger sediments; the southernmost thrust which involves Precambrian basement can be mapped as the Nathia–Gali thrust (Coward & Butler 1985). In the hills north of Islamabad (figure 1), the thrusts involve mainly Mesozoic to Lower Tertiary carbonates with overlying foreland basin sediments of Upper Eocene to Miocene age known as the Murree Formation of the Rawalpindi Group. Along the mountain front, from Islamabad to the Kohat area, the Mesozoic and Cainozoic carbonates are carried on to this Cainozoic molasse on a series of faults that have been correlated with the Main Boundary Thrust (MBT) in India (Windley 1983). South of the MBT in Pakistan there is a thick imbricated sequence of Miocene to Quaternary molasse, termed the Siwalik Group (Pilgrim 1910). This forms part of the foreland basin to the Western Himalayan arc and the Kohistan ranges, but unlike the foreland basin of India and Nepal, it is here disrupted by thrusts that detach above the basement in Cambrian salt to emerge along the Salt Ranges and Surghar and Khisar Ranges (figure 1). Here Mesozoic to Cainozoic rocks have been emplaced on river gravels and fanglomerates as young as 400000 years BP (Johnson *et al.* 1979; Yeats *et al.* 1984).

DEFORMATION AND THE THRUST WEDGE

Preliminary cross sections through the thrust belt from the MMT to the Salt Ranges, have been published by Coward & Butler (1985) and Coward *et al.* (1987). These were the result of an essentially two-dimensional study and were constructed in such a way that all the thrust geometries were restorable on to an initial stratigraphic template. To gain minimum estimates of orogenic shortening, the original stratigraphic thicknesses were maximized while still being compatible with observed geology. Therefore, a maximum-thickness layer cake stratigraphy was adopted for the restored template. Thinner or more complex stratigraphic geometries would have required necessary increases in orogenic contraction. The section in Coward & Butler (1985) also assumed a consistent SSE direction of thrust transport, a feature in accord with the knowledge of thrust zone kinematics at that time. More recent studies indicate these assumptions to be locally invalid, in that there are thickness and facies changes and some variations in, and interference between, different transport directions. Nevertheless, we consider these sections to give a reasonable indication of the structure so that Coward & Butler's (1985; see also Butler & Coward 1988) estimates of the amount of shortening appear realistic. They calculated that the shortened Indian Plate rocks between the foreland and the MMT, restored to about 730 km, for a present distance of 260 km, indicating a shortening of 470 km. The decoupling surface at the base of the thrust zone must lie within the upper crust and is locally uplifted and eroded as, for example, around the Hazara syntaxis. The thrusts in the Mesozoic to Cainozoic carbonates north of Islamabad appear to curve on the map, to join the fault at the western margin of the Hazara syntaxis (figure 1). This fault is considered to be the decoupling surface to the imbricate sequence and to have been uplifted and folded by later deeper structures developed from the main NW–SE trending Himalayan thrusts of Kashmir (Seeber *et al.* 1981; Coward 1983). The decoupling surface for the Kohistan thrusts gradually cuts deeper in the crustal profile towards the internal zone, presumably to carry lower crustal rocks at depth in the north. However, recent work around the most northerly part of the Indian continent, exposed around the Nanga Parbat syntaxis (Butler & Prior 1988*a*) has found a probable Phanerozoic cover sequence, directly under the MMT. Not only does this imply that the MMT detachments run in upper crustal levels at least this far north, but it also directly requires an additional 150 km displacement greater than that estimated by Coward & Butler (1985) for shortening of the Indian continental crust. We suggest that over 600 km shortening is accommodated beneath the suture (the MMT).

In general, the crustal load resulting from stacked Indian continental crust propagated systematically towards the foreland, to generate flexural subsidence and the southward migration of the Indus–Ganges foredeep with time (Burbank 1983; Lyon-Caen & Molnar 1985). Some thrust movement may be attributable directly to plate movements between India and Asia, the thrust displacement directions being parallel to the NNW–SSE relative plate movement vector (cf. Patriat & Achache 1984). However, many of the structures in both the internal and external zones appear more complex and it is tempting to relate these to the bulk strain necessary to maintain the critical taper of the thrust wedge. Davis *et al.* (1983) have analysed thin-skinned thrust wedges in terms of Coulomb failure criteria, where the wedge shape of a thrust mass largely depends on its internal strength and its basal shear strength. Such theory may be applied qualitatively to larger regions of mountain belts, where Coulomb criteria are not applicable (Platt 1986). Thrust wedges with low basal shear strength, for example wedges moving over sediments with a high fluid pressure, or over salt deposits, will require only a low critical taper, that is, there will be a very gentle slope to the mountain front (Davis & Engelder 1985; Butler *et al.* 1987). However, thrust wedges moving over rocks with a high shear strength, such as crystalline basement gneisses or granites, will require a higher wedge taper and hence a steeper mountain slope.

The frontal ranges of the Himalayas illustrate this principle. Along the main ranges in India and Nepal, the mountain front is steep with a vertical elevation change of 5 km in 100 km horizontally (figure 2). In this region, the basal thrusts lie in foreland basin molassic sediments, passing back into older basement beneath the main Himalayan mountains. This region shows active seismicity, which, from local depth determinations and first motion studies, suggests displacements on thrust faults inclined at about 30° to the north (Seeber *et al.* 1981).

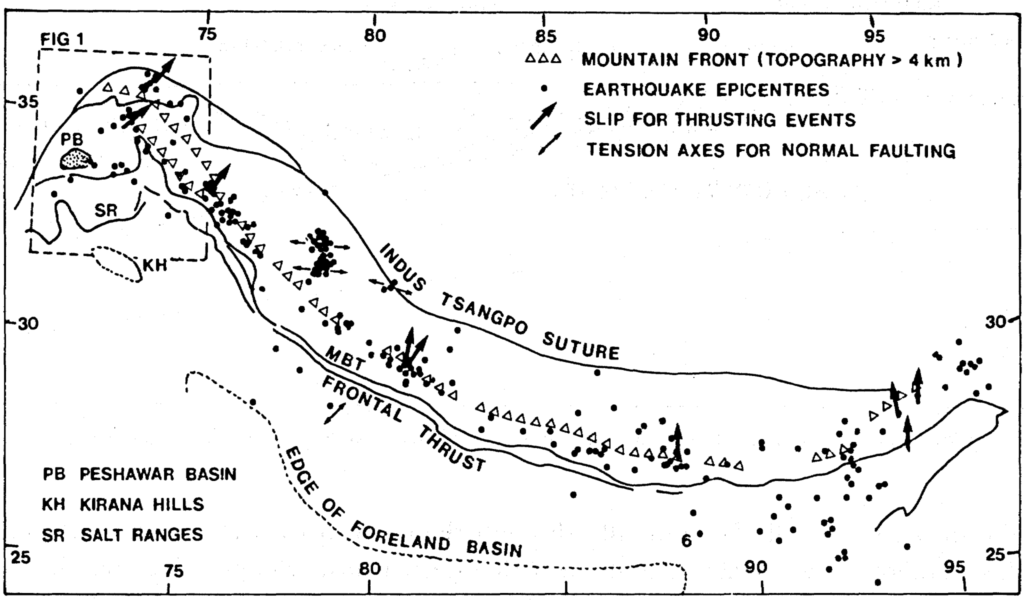

Figure 2. Map of the Himalayan mountain front throughout India, Nepal and Pakistan, showing the position of the main topographic slope, the associated sedimentary basins and the zones of seismic activity (partly after Seeber *et al.* (1981)). Earthquake epicentres are shown only for the Indian Plate.

In northern Pakistan, however, there is a much lower critical taper, with a change in elevation from the Kohistan ranges to the foothills of up to 4 km in 200 km horizontally. Indeed, there is an anomalous topographic low, occupied by Plio-Pleistocene sediments of the Peshawar Basin (figure 2). This area of low flat ground is in the same structural position, north of the MBT, as the major mountain front in Nepal. A possible reason for the preservation of this low ground in northern Pakistan during latest thrust movements, is that the thrust wedge probably had low basal shear strength. South of Peshawar, the thrusts detach in Cambrian salt

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and the very gentle taper to the wedge is probably allowed by displacement on this weak salt layer. We note that deep lithospheric processes, related to crustal loading and subsequent flexure may partly control the origin of the Peshawar depression, as is discussed later. Seeber *et al.* (1981) point out that the frontal regions of the mountain belt in North Pakistan are aseismic; presumably displacement occurs by ductile creep in the weak sediments. The dominant seismic activity in Pakistan occurs in NW–SE trending zones, N and NW of the Hazara syntaxis (figure 2), which from first motion studies, dominantly indicate thrusting to the SW, with a local depth range of between 35 and 70 km (Jackson & McKenzie 1984; Seeber *et al.* 1981). This activity probably represents displacement on the lateral continuation of the main Himalayan thrusts and will be discussed in more detail later.

Exploring the notion further, the critical taper of a thrust wedge can be changed by deformation within the wedge, by accreting material as thrust slices to the front of the wedge, or by the accretion of fault-bounded packages of material from beneath the wedge (figure 3). As erosion removes material from the surface, more internal deformation is needed, or more material must be added to the wedge, to maintain its critical taper (Davis *et al.* 1983).

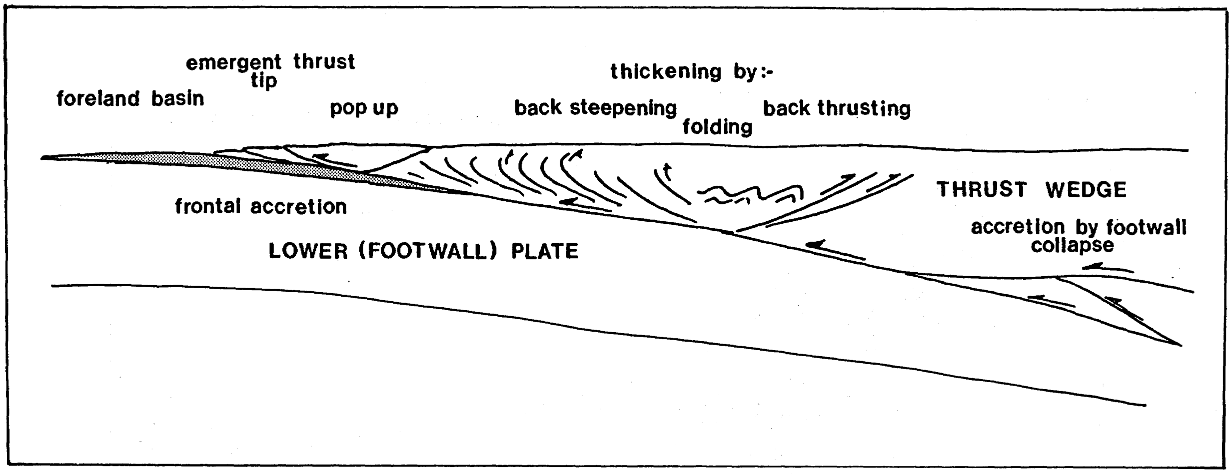

FIGURE 3. (*a*) Methods of accretion of material to a thrust wedge (after Davis *et al.* 1983).

As the thrust wedge climbs gradually through the crust, it overrides rocks with different strengths. A more pronounced wedge shape with a steeper surface slope will be required where the thrust climbs through the stronger middle crust. At the frontal region, where the wedge overthrusts uncompacted sediments, the taper may be too large; that is, the surface slope may be too steep (figure 4). The slope may be reduced by erosion, by the addition of frontal thrust packages or sometimes by collapse in a series of foreland-directed extensional faults, similar to large landslides (cf. Coward 1982).

In the deeper parts of the thrust wedge, the basal shear strength may decrease as the thickened crust heats up. In the Himalayas, the internal zone also shows major extensional structures, where the large-scale normal faults dip down in the same direction as the thrusts and may link with the zone of weakened lower crust at depth. Large-scale extensional faults have been recognized around much of the Himalayan belt, with large normal faults mapped along the northern edge of the Crystalline Zone, north of Everest (Burg & Chen 1984; Royden &

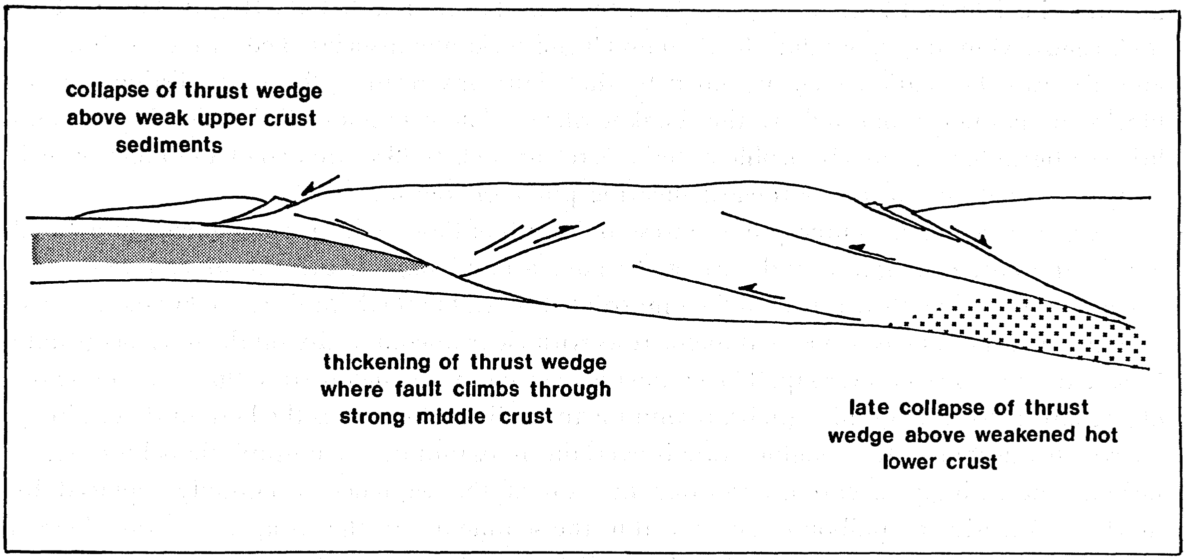

FIGURE 4. Showing how extensional structures may develop in a major thrust wedge (see text for discussion).

Burchfiel 1987) and in Kashmir (Herren 1987). However, these heating processes will weaken the supporting lithosphere, generating steeper gradients that could cause the thrust wedge to lock up, generating breakback structures and refolding earlier thrust sheets (cf. Butler 1987).

Because of the problems in evaluating rigidity decay during lithospheric flexing, in the next section we will continue exploring the simple concept that structural developments, including fault kinematics and geometries, can be related to progressive wedge shape.

INTERNAL THRUST ZONES

Stratigraphy

The crystalline rocks of the internal zones can be divided into several different basement sequences, metamorphosed and intruded by granites during the Precambrian or lowermost Palaeozoic, overlain by a cover sequence of uncertain, but probably Phanerozoic, age. Basement rocks include quartzo-feldspathic gneisses, termed the Besham Group (Treloar *et al.* 1988*a*) (figure 5*a*), which consist of metamorphosed granitoid rocks and metasediments, including psammites, pelites, often sulfidic and/or graphitic, and minor marble horizons. They are of unknown age and are confined to the lower thrust sheets that have been uplifted in a broad, dome-like, late fold at Besham.

To the east, the Besham Group is bounded by a major steep ductile shear zone (the Thakot Shear), which shows now a dextral sense of displacement, but is interpreted as a tilted thrust. Above this, to the east, the Tanawal Formation (Treloar *et al.* 1988*a*) is a sequence of dominantly semi-pelitic and psammitic metasediments, possibly correlatable with a series of lowgrade metasediments, the Hazara slates, south of Mansehra (Calkins *et al.* 1975). The stratigraphic relationship between the Tanawal Formation and the metasediments of the Besham Group is unknown, although both form a basement to the Phanerozoic cover. A sheared biotite granite with large orthoclase porphyroclasts (the Swat or Mansehra Granite) intrudes the Tanawal Formation and near Mansehra has been dated at 516 ± 16 Ma (Le Fort *et al.* 1980). Mapping shows that the Besham Group rocks and associated cover metasediments, and Tanawal Formation rocks intruded by the Mansehra Granite, form two distinct crustal blocks, or nappes, separated by the Thakot Shear. These nappes, distinguishable in both lithostratigraphic and metamorphic criteria (Treloar *et al.* 1988*b*) are two of a number of such nappes stacked late in the southward shearing phase of collision.

Cover metasediments outcrop to the west and south of Besham as parallel inliers imbricated within the basement gneiss and east of Besham, around Banna, they occur as dominantly calcareous rocks in a thrust sheet in the immediate footwall to the MMT. Seven kilometres west of Besham, a slice of cover metasediments rests with clear unconformity on the gneissic-granite basement of the Besham Group. The contact is marked by a conglomerate that contains clasts of pegmatite, foliated granite gneiss, psammite and pelite. This slice is the best for determining a cover stratigraphy; the conglomerate is overlain by psammite, then graphitic pelites, which become increasingly calcareous towards the top of the sequence, eventually replaced by marbles. Intrusive amphibolites occur within the sediments. In the west, near Swat, there is another group of cover sediments, the Alpurai Schists with a more pelitic stratigraphy than the Besham cover sequences.

Structure

A polyphase deformation history (table 1) affects the basement gneisses and cover metasediments. There is an early schistosity (S1) forming event which is sub-parallel to bedding. This tectonic fabric is crenulated by second phase structures on a mesoscopic and macroscopic scale, deforming lithological layering and S1 fabric into tight folds whose axes are curvilinear, varying in plunge from 60° to the SW to 30° to the NE (Coward *et al.* 1982). These sheath-like folds and the mineral lineations that plunge to the N, suggest S-directed movements during development of the F2 structures (Treloar *et al.* 1988*a*). The second deformation phase culminated in, or was followed by, a discrete SSE-directed thrusting event that stacked the crustal nappes along shears such as the Thakot Shear and also internally imbricated them.

TABLE 1. DEFORMATION CHRONOLOGY FOR THE INTERIOR ZONES OF THE NORTHERN MARGIN OF THE INDIAN PLATE

	Structures that post-date the main southward obduction of Kohistan
post-D3	N–S striking brittle steep reverse faults. E side up.
D3	NW- and NNW-verging backfolds and backthrusts which locally breach the MMT. Large-scale NNE-plunging WNW-verging (syntaxial) upright folds. These structures are probably coeval with the thrusts in the external zone.
pre-D3	Top-side E- or NE-directed shears that re-activated D2*a* surfaces.
	Structures generated in the footwall of the MMT during southward obduction of Kohistan
D2*a*	Thrusts with southerly transport which stack and internally imbricate crustal scale nappes.
D2	Crenulations and folds, through S-facing, although strongly sheath-like in the N. Probably a diachronous continuation of D1.
D1	Main fabric forming event related to southward overthrusting of Kohistan over India. Ductile blastomylonites, thickened by small-scale thrust-related folds in the N. Becoming more brittle to the S, where the fabric is increasingly typical of a shortening rather than shearing deformation, with shear strains increasingly accommodated in narrow mylonite zones.

Fabric porphyroblast relations show that the main metamorphism was largely synchronous with the early stages of deformation. A metamorphic map of the internal zones, from Treloar *et al.* (1988*b*) is shown in figure 5*b*. There are metamorphic breaks across the shears that stack the crustal nappes and within each nappe there is an overall upward increase in metamorphic grade. Within the highest grade rocks of the Besham nappe, the Alpurai schists, the metamorphic peak (600 ± 50 °C at 9 ± 2 kbar†) was synchronous with the D1 ductile shearing event. Thermobarometry and garnet inclusion studies (Treloar *et al.* 1988*a*) imply that this metamorphism accompanied a steep pressure increase, interpreted as involving subduction and thickening of the leading edge of the Indian Plate beneath Kohistan. The early cessation of the metamorphism here reflects a rapid crustal rebound. Within the Hazara nappe (figure 5), however, metamorphism was at lower pressures (about 5–8 kbar) (Treloar *et al.* 1988*b*) and continued for longer, until after development of D2 crenulations. The metamorphism of this zone is more typically characteristic of thermal relaxation following crustal thickening.

West of Besham the lowest-grade rocks occur in the core of the late large Besham antiform and the grade generally increases upwards on a gross scale, suggesting some form of inverted metamorphism (cf. Le Fort 1986). There are sharp metamorphic breaks across the late thrusts that imbricate basement and cover slices west of Besham although there is no direct evidence as to whether metamorphic grade within individual sheets increased upwards or not. As the rocks immediately beneath the MMT near Swat contain low-temperature blueschist assemblages, this suggests that the uppermost part of the thrust stack was cold. Therefore, we suggest a model for the inverted metamorphism in the Besham area including the following.

(i) Overthrusting of the Indian Plate by the Kohistan arc with a zone of blueschists preserved locally beneath the footwall to the suture. This deformation presumably produced the first fabric, possibly locally stacking the basement-cover sequence and metamorphosing them to give a normal metamorphic gradient. The original metamorphic gradient presumably decreased towards the south, away from the overthrust island arc.

(ii) This package was then re-imbricated during or following the second phase of deformation, slicing and restacking the metamorphic sequence, placing originally deeply buried high-grade rocks on top of more shallowly buried low-grade rocks.

Within the other crustal nappes, such as the Hazara and Kaghan Valley nappes, metamorphic rocks were also imbricated by late thrusts that have higher-grade rocks on their hanging walls than on their footwalls. This late imbrication gives an overall sense of metamorphic inversion resulting from a post-metamorphic disruption of the metamorphic pile, rather than from an originally inverted thermal gradient. This is a fundamentally different model to that proposed for the metamorphic inversion along the MCT in India and Nepal, where a hot slab is interpreted as having been emplaced above colder rocks (Le Fort 1986), with the immediate imposition of a saw-tooth geothermal profile, subsequently modified by a downward heat flux.

A map of the main shears and ductile thrusts is shown in figure 5, based on detailed mapping in the Besham–Swat–Mansehra region, plus reconnaissance mapping to the east. The N–S trending Thakot shear zone either slices through, or is joined by, E–W trending shears in the Hazara basement nappe. It can be interpreted as the western lateral ramp to the Hazara nappe, the Balakot Shear Zone (BSZ) forming the eastern lateral ramp boundary. This Balakot shear is the same structure as the mylonite belt mapped NW of the Hazara syntaxis by Bossart

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† 1 kbar = 10^8 Pa.

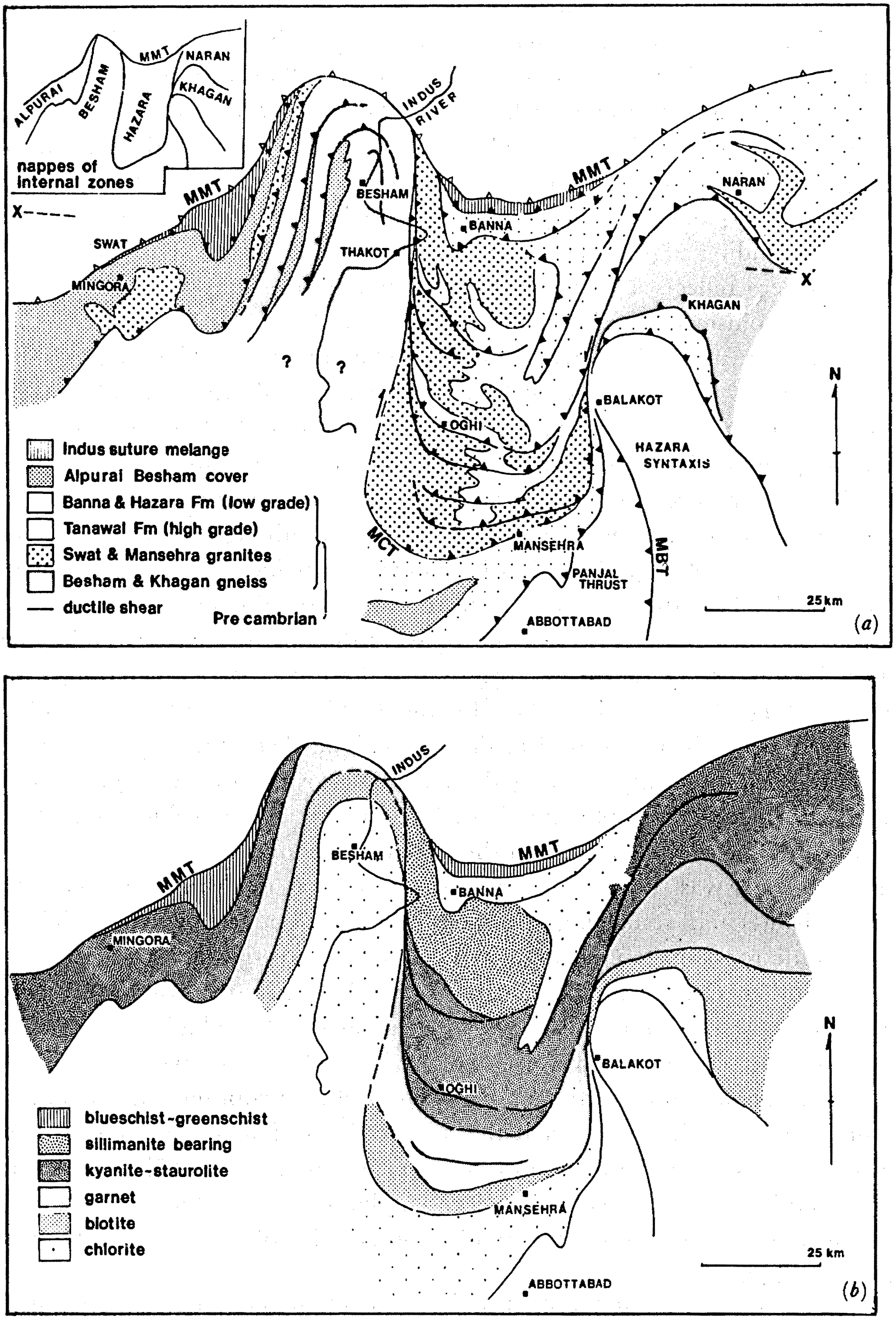

Figure 5. (*a*) Map of the internal zones in the Besham–Mansehra region, showing the distribution of metasediments and gneisses. Tentative correlations are made between metasediments and granites of the Naran nappe and those of the Hazara nappe and between gneisses of the Khazan and Besham nappes. (*b*) Simplified map showing variations in metamorphic grade (after Treloar *et al.* 1988*a*, *b*).

et al. (1984). If the imbricate ductile thrusts within the Hazara nappes, such as the Oghi shear (figure 5) (Coward *et al.* 1982), are the same age as the major shears that bound and separate the nappes, they may be modelled as hanging wall splays off a major ductile thrust system. Figure 6 shows an E–W cross section through the thrust stack roughly perpendicular to the thrust transport. The trend of the lateral ramps suggests a N–S overthrust direction.

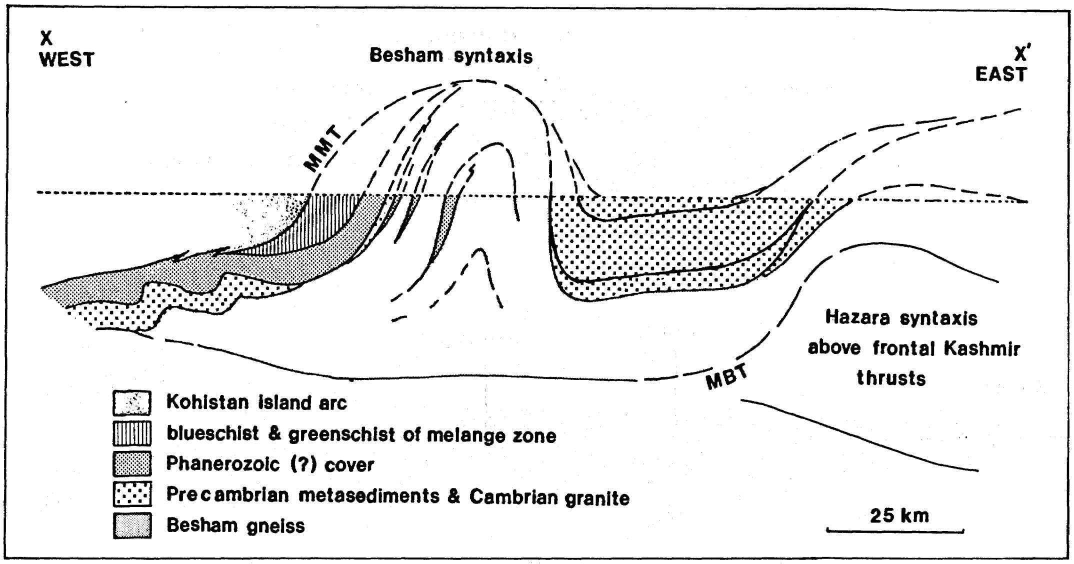

FIGURE 6. East–west simplified section through the main thrust packages of the internal zone; for section line see figure 5*a*).

This relatively straightforward package of ductile shears in metamorphic rocks is modified by at least three later tectonic events. The Banna sediments form a low-grade package above the Hazara nappe. From the sense of the small-scale folds and thrusts and the trend of mineral lineations, they would appear to have been transported from the south as a backthrust sheet. Figure 7 shows our interpretation of the Banna sediments thrust as a wedge between the Hazara nappe and the MMT.

The gneisses and cover sediments near Besham show several shear zones, locally occurring as 5–10 m wide zones of low-grade fault rock, with kinematic movement indicators which suggest a displacement of top to the east or northeast. These shears are folded round the later Besham antiform, so that in the west they are upward and eastward verging, in the east they are downward verging. They may be related to an eastward-directed low-angle thrust, subsequently folded round the Besham antiform or to a low-angle extensional fault, similar to the NE-directed extensional fault in Kashmir (Herren 1987), and generated by the collapse of the more ductile thickened crust.

The Besham antiform is part of a series of N–W trending upright to westward verging folds which occur south of the MMT between the Indus River and the Afghanistan border (figures 5 and 8). North of Besham, these upright structures fold the MMT into a syntaxial zone similar to that of Nanga Parbat. To the west, however, the MMT appears planar and hence these late structures must decouple up onto the MMT. Their origin is unknown (cf. Coward *et al.* 1986).

They may be related to deformation around the western tip of the main Himalayan thrust belt, that is, they may be unrelated to the Kohistan thrust sequence. Alternatively, they may be oblique back thrusts, developed during Kohistan thrusting.

Figure 7*b* shows a sketch restoration of the rocks of the internal zone. It suggests that the high-grade rocks of the Hazara nappes formed originally the northernmost part of the Indian Plate in southern Kohistan.

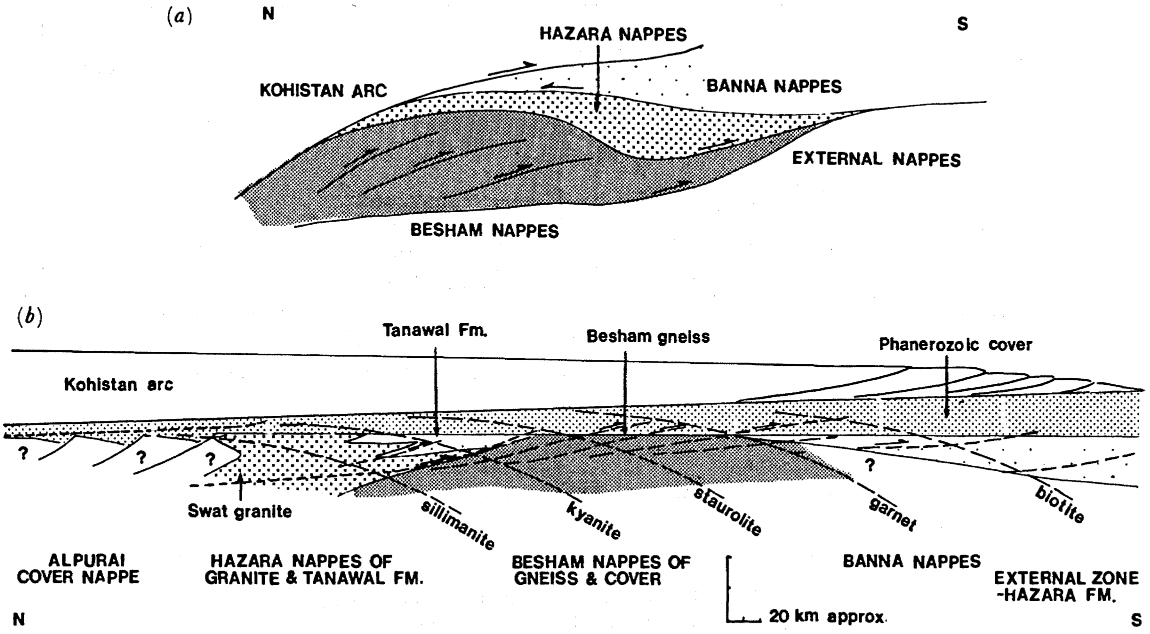

FIGURE 7. (*a*) Simplified cross section through the internal zone to show the distribution of the major nappe packages. (*b*) Simplified restored cross section to show the original distribution of the nappe packages; see text for discussion.

The early Himalayan metamorphism (S1 to post-S1) is assumed to be related to crustal thickening during the initial stages of overthrusting by the Kohistan arc. That the arc did overthrust the Indian Plate a considerable distance, in excess of 100 km, is shown by the Nanga Parbat syntaxis (figure 1), where the suture is folded and thrust by structures in the underlying Indian Plate and then eroded to leave a long thin half-window.

The Hazara nappe package shows Precambrian to Cambrian deformation and metamorphism in the Tanawal sediments, largely overprinted by Himalayan effects and intrusion of the Swat–Mansehra granites. Similar high-grade metasediments and coarse porphyritic granites occur in NE Kohistan and form much of the Indian Plate gneisses of the Nanga Parbat syntaxis. The basement metamorphism probably represents part of the widespread late Precambrian–early Palaeozoic tectonic event that affected much of Gondwanaland, i.e. it may represent the local equivalent of the 'Pan African' event. This tectonic event is absent over much of the north Indian craton, occurring mainly in the Himalayan thrust sheets (Le Fort *et al.* 1980). A late Precambrian–early Palaeozoic event is also recognized in the basement rocks of the Lhasa Block, north of the Indus Suture (Chang Chengfa *et al.* 1986).

The Besham thrust package originated south of the Hazara package. The origin of the Besham gneisses is unknown, although they may be basement to the Tanawal Formation to the north and Hazara slates to the south. The Banna nappe is considered to be the originally southernmost of the internal thrust sheets, back-thrust as a wedge between the Hazara nappe package and the MMT. This back-thrust and the upright to west-verging folds at Besham probably developed to maintain critical taper to the overall thrust wedge as it over-rode the Indian Plate (figure 8). The Himalayan leucogranites are confined to the Hazara and Besham packages and probably formed by melting of the thickened crust at depth, and were then intruded after the F1/F2 deformation.

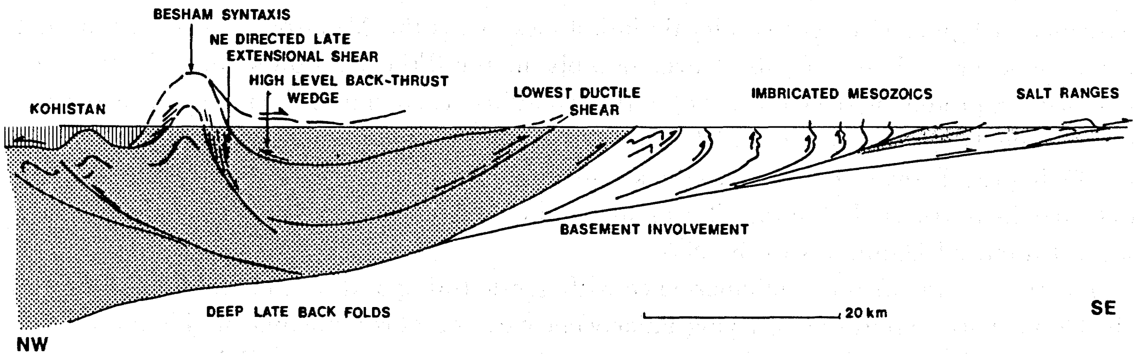

Figure 8. Simplified section to show the distribution of late shears, thrusts and folds near Besham and the relation of internal (stippled) and external (blank) zones. Foreland basin sediments shown by fine stipple.

The external thrust zones

Stratigraphy

The Precambrian mudstones and greywackes of the external zones show little of the late Precambrian–early Palaeozoic tectonics of the internal zones. Near Abbottabad (figure 1), the older sediments were tilted before deposition of the Cambrian(?) Abbottabad Formation. However, only a Himalayan-age cleavage has been recognized in this area, common to the Precambrian and Phanerozoic sediments. The exact age of the Abbottabad Formation is uncertain; a Cambrian age is suggested on the basis of acretarchs from the upper limestones (Latif 1974). In the frontal part of the thrust zone, south of Islamabad, reviewed by Butler *et al.* (1987), Eocambrian–Lower Cambrian rocks form the Salt Range Formation, overlain by Lower to Middle Cambrian clastic sediments (Schindewolf & Seilacher 1955; Teichert 1964; Butler *et al.* 1987). The Salt Range Formation is a major evaporite-bearing sequence, locally over 1 km thick, of red marls, gypsum and dolomite passing up into thick beds of halite with thinner marls and some poor-grade oil shales. It represents a thick series of playa and distal alluvial fan evaporites, with palaeocurrent directions indicating transport from the south (Asrarullah 1967). The relation between the Abbottabad Formation and the Cambrian rocks of the Salt Ranges is unknown; no Cambrian rocks occur in the intervening thrust sheets and the two regions must have been several hundred kilometres apart before Himalayan-age thrusting.

In northern Pakistan the region formed a high throughout most of the Palaeozoic and in the Salt Ranges, Permian sediments overlie the Cambrian formations with only a slight angular unconformity. Permian sediments comprise a basal group of tillites, with diamicrites, grading upwards into massive sandstones. These presumably reflect the widespread Gondwanaland

Permian glacial event. The overlying Permian sediments record a change to warmer conditions with a good marine fossil fauna and upper limestones and dolomites. Elsewhere Mesozoic carbonates rest directly on the Precambrian or Cambrian sediments. They are mainly shallow marine to non-marine carbonates, essentially dolomites and dolomitic limestones, with minor shales and sandstones (Shah 1977). There were phases of emergence with local disconformities, notably at the end of Triassic times and in the Upper Jurassic. The Lower Cretaceous consists of glauconitic and iron-rich sandstones with probable non-sequences, indicative of a change to a deeper-water environment, passing up into sandstone and shale horizons and then to a thick sequence of Upper Cretaceous micritic limestones. Thus the Mesozoic can be interpreted in terms of several phases of subsidence, notably in the Triassic, Lower Jurassic and Lower Cretaceous, producing over 1 km of essentially platform carbonates. We interpret these as post-rift sediments, probably deposited during thermal subsidence following phases of rifting producing the Tethyan margin. No thick syn-rift sediment packages and graben-fill have been detected in northern Pakistan. The main region of extension was on the Tethyan margin, several hundred kilometres to the NW.

There was a major phase of emergence with gentle tilting and possibly folding at the end of the Cretaceous, so that the overlying Palaeocene carbonates rest unconformably on the eroded Mesozoic sediments. Figure 9 shows a simplified sub-crop map for the Palaeocene. The trend of the gentle end-Cretaceous folds is N–S to NE–SW, highly oblique to the trend of Himalayan-age thrusts, but approximately parallel to the Tethyan margin of NW Pakistan. This phase of basin inversion coincides with the commencement of rapid spreading of the Indian Ocean as India moved northwards away from the rest of Gondwanaland. It also coincides with the emplacement of ophiolites on to the northern margin of the Indian Plate, in Zanskar (Searle 1983, 1986) and on to the Arabian Plate in Oman (Searle 1985).

The lowest Palaeogene sediments are local deltaic sandstones and shales with some coals, overlain by a thick sequence of foraminiferal limestones, recording continued subsidence. During the Eocene there was a gradual influx of red clastic sediments. Evaporites occur in the Eocene of the Kohat region and in the northern part of the Hazara syntaxis there is an interleaving of molassic deposits and Eocene limestones (Bossart & Ottiger 1988) recording the onset of Himalayan-derived sedimentation.

The transgressive package of molassic sediments has been divided into a lower Rawalpindi Group and an upper Siwalik Group. In general, the sediments coarsen upwards, so that the Siwaliks have a much greater sandstone content with conglomerates. The groups thin towards the SW; in the northern Potwar the Rawalpindi Group attains a thickness of over 3 km, but in the SW Salt Ranges it is only 200 m thick. Similarly, the Siwaliks thin from about 4 km in the east, to zero south of the Salt Ranges, where basement rocks are uplifted along the Kirana Hills. This change in sediment thickness is also reflected in the Bouguer gravity-anomaly map (figure 10), which shows contours trending WNW–ESE. The Kirana Hills coincide with the ridge of positive Bouguer anomalies and may represent a low amplitude peripheral bulge at the edge of the main Himalayan flexural basin, though they are also the site of a pre-existing basement high during Mesozoic sedimentation.

Note that this flexural basin is oblique to the trends of thrusts in northern Pakistan and hence causes important lateral changes in thrust geometry.

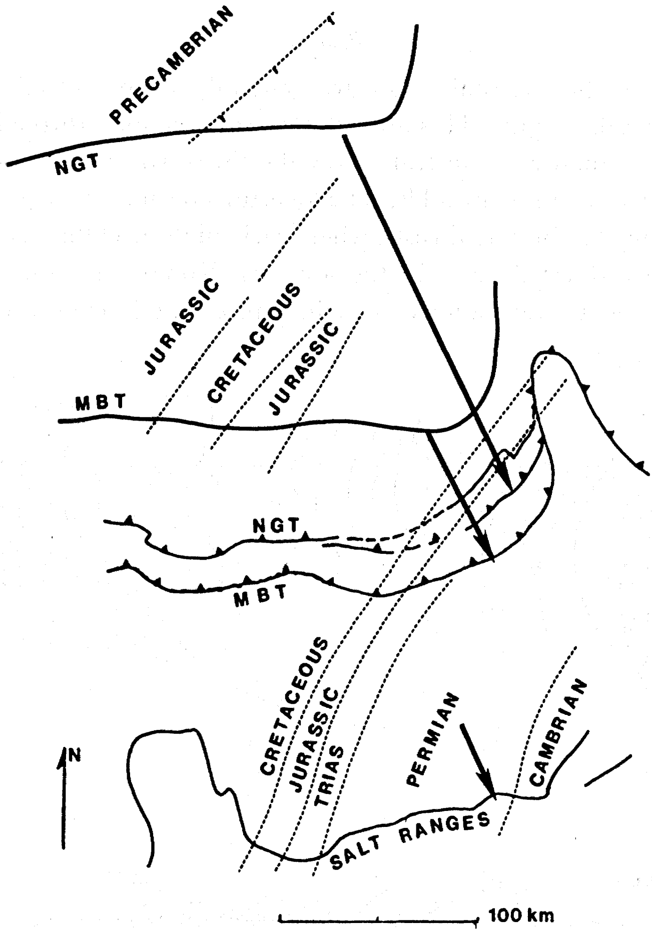

FIGURE 9. Sub-crop map of the Palaeocene, restored for Himalayan thrusts following the model of Coward and Butler (1985). NGT, Nathia Gali Thrust; MBT, Main Boundary Thrust. Data from Latif (1977). Stratigraphic data are compiled from Gee (1980), Shah (1977), Meissner *et al.* (1974) and Yeats & Hussain (1987).

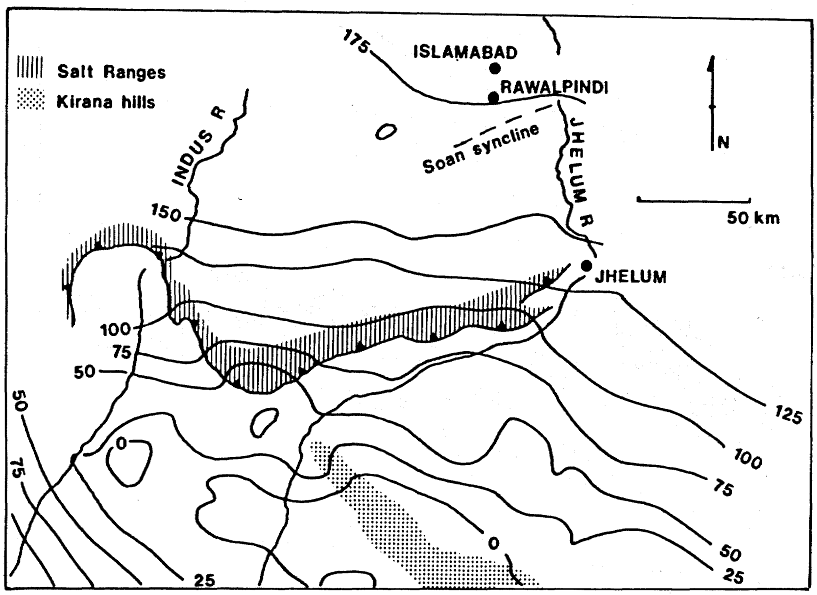

FIGURE 10. Bouguer gravity map of northern Pakistan (after Farah *et al.* 1977). The units of the contours are milligal (1 mGal = 10^{-3} cm s^{-2}).

Structure

The thrust sheets of the external zones are generally steep and often overturned to dip moderately to the south. Figure 11 shows three cross sections through the frontal ranges between Murree and Kohat and illustrates how the thrust stacks have been reorientated into north-facing inclined to recumbent folds. This overturning may be caused by the following.

(i) Back-steepening of imbricate thrusts, where early high-level thrusts are back-tilted by the accretion of later lower-level thrusts. In the southern Kohat area, the development of local duplex zones in Jurassic–Lower Cretaceous sediments certainly causes some back-steepening.

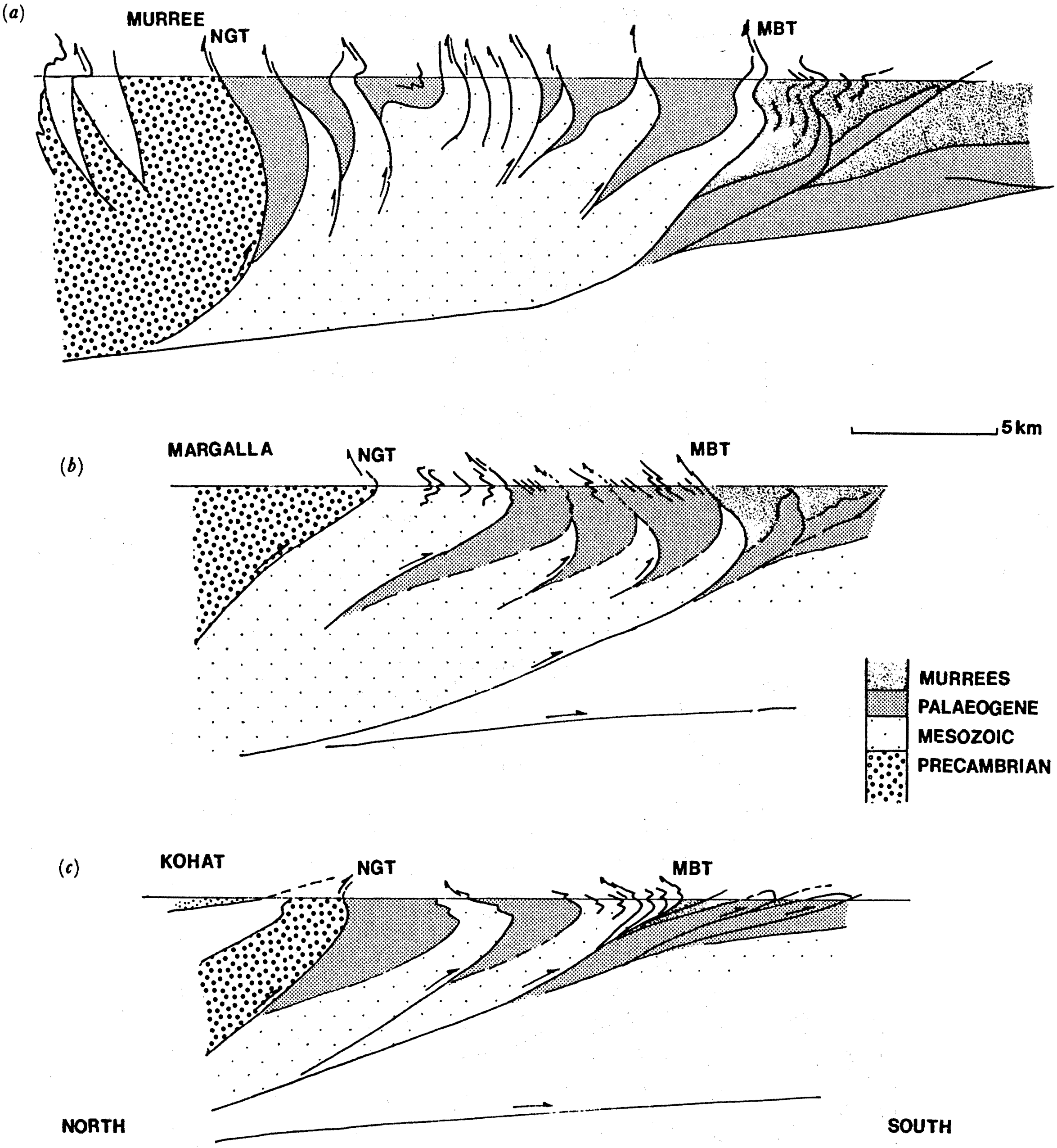

Figure 11. Cross section through the frontal parts of the external thrust zones; for section lines see figure 1.

(ii) Refolding by a later phase of back-folds, developed above the later low-level thrusts. This is considered to be the principle mechanism and produces several orders of folding; macroscopic parasitic folds occur on the overturned limb of the major fold.

This major back-folding event, close to the thrust front, is probably related to the change in critical thrust wedge taper as the basal detachment climbs into the sands and conglomerates of the Rawalpindi–Siwalik Groups.

South of Kohat, later thrusts form above a detachment in Eocene evaporites (figure 12). Here the fault wedge had a much lower basal shear strength. The thrusts show less evidence of back-steepening; many dip at moderate angles to the north and many of the folds can be considered as simple ramp anticlines. There are several zones of south-dipping normal faults along the Kohat–Margalla Hills north of this zone, suggesting that there may have been changes in wedge shape by extensional collapse of the relatively steep mountain front. Further south, near the Surghar Ranges, the southern Kohat thrusts also become back-steepened, suggesting local loss of easy basal slip in the Eocene sediments.

During the latest movements, slip has transferred down into Cambrian salt. Throughout much of the western Potwar Plateau displacement occurred by easy slip beneath the previously formed high level thrusts, to form thrust ramps at the Surghar and Salt Ranges, where the easy slip was disturbed by salt diapirism, local loss of salt, or earlier normal faults (Baker *et al.* 1988). The geometry of the Salt Range décollement is described at length by Butler *et al.* (1987). The progressive changes in style of thrust front structures and their variations along strike seem to record the changes in basal shear strength of the thrust wedge as it climbs from Mesozoic limestones to Cainozoic molasse deposits and subsequently locally back down to Eocene and then to Cambrian easy-slip horizons by major footwall collapse (figure 12).

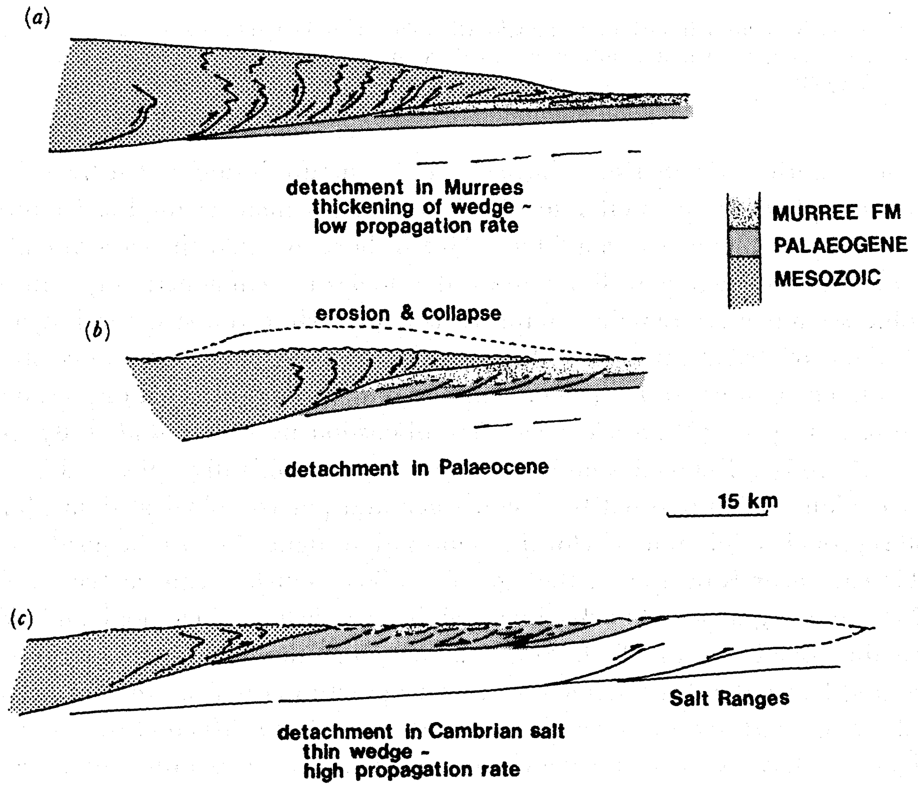

FIGURE 12. Model for thrust belt evolution in the external zones; see text for discussion.

In plan form, the Salt Ranges have a markedly irregular pattern (figure 1) and show pronounced change in structural style along strike. In the west, on the eastern side of the Surghar re-entrant, thrusts and folds detach within, or at the base of, the Salt Range Formation evaporites, so that a full stratigraphic section is involved in the deformation. The westernmost section (figure 13) shows a simple fold train, underlain by a greatly thickened sequence of evaporites. Further east, however, the structure is dominated by a simple ramp-type uplift, morphologically similar to the classic Appalachian examples. Restored sections through the ranges suggest between 20 and 30 km shortening. At the eastern end of the Salt Ranges the basal detachment lies within the molassic sediments; any salt within the stratigraphic section must remain untapped at depth. Here the structural style involves a complex series of backthrusts, forethrusts and related folds, suggesting about 30 km displacement. The gradual transfer of foreland- and hinterland-directed displacements caused local rotations of up to 30° anticlockwise (see discussion by Butler *et al.* 1987 from data of Opdyke *et al.* 1982). Detailed studies of reversal magnetostratigraphy, calibrated against known successions and supported by fission track and palaeontological data (Johnson *et al.* 1979, 1982) provide minimum ages for the deformation (figure 14). In the northern part of the Potwar Plateau, near Rawalpindi, the age of the Soan syncline can be accurately dated at 2.1–1.9 Ma, from ages of sediments involved in the thrust-related fold and of sediments unconformably overlying the fold. Since 2.0 Ma, the main Salt Range structures have developed and hence the thrust detachment propagated rapidly from the northern Potwar to the Salt Ranges, a restored distance of about 120 km in 2 Ma. Much of the shortening in the Salt Ranges must have occurred during this time, that is, there was a time-averaged shortening

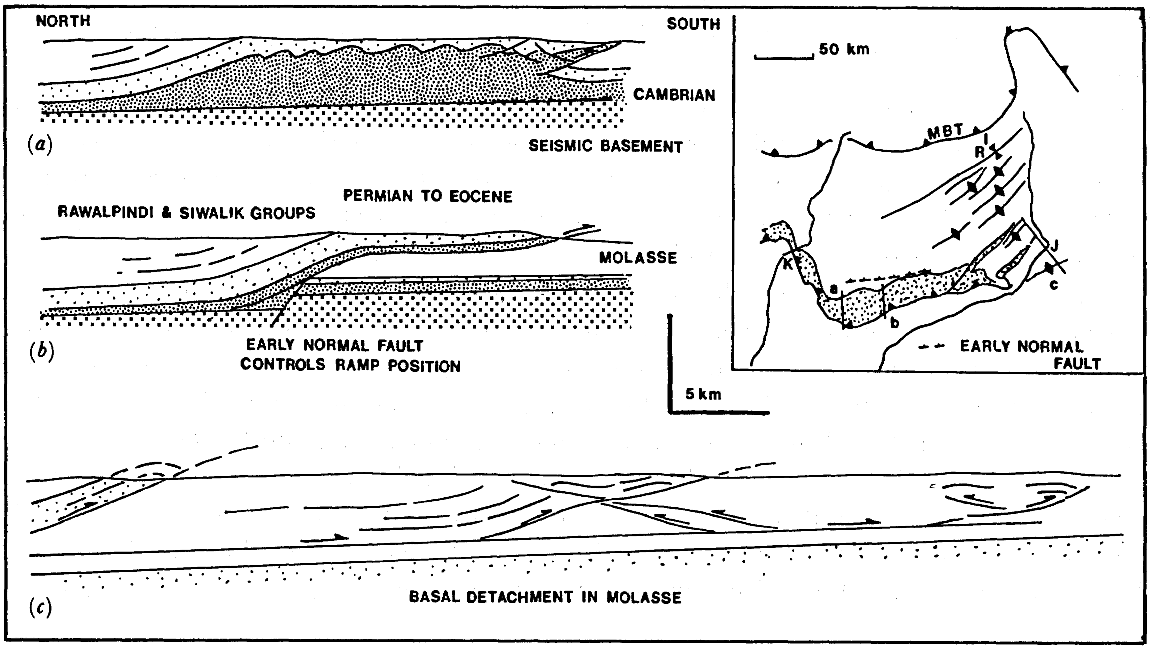

FIGURE 13. Cross sections through the Salt Ranges, location shown on the inset map (I, Islamabad; R, Rawalpindi; J, Jhelum; K, Kalabagh) based mainly on surface data plus an interpretation of seismic data (see, for example, Baker *et al.* 1988).

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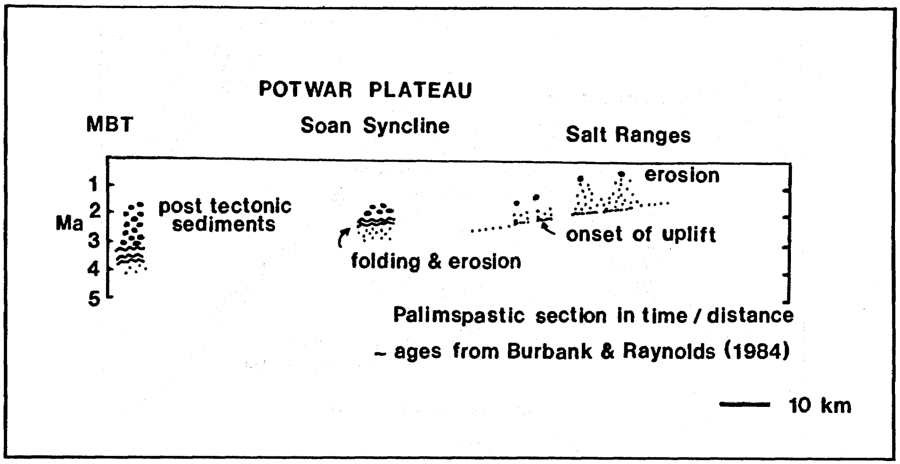

Figure 14. Schematic profile through the Potwar Plateau–Salt Ranges, to show the timing of folding (coarse wavy lines), local uplift (fine wavy lines), coarse sedimentation at final uplift and erosion (circles); data from Burbank & Raynolds (1984).

rate of 1.0–1.5 cm a^{-1}. This matches the migration rate of the foredeep basin in India (Lyon-Caen & Molnar 1985), although direct comparisons are unwise in view of the uncertainties in flexural rigidity, local morphology and crustal structures in these areas.

Interferences of Himalayan and Kohistan movements

Northern Pakistan shows the effects of interference between two thrust transport directions, i.e. the S–SSE directed transport of the Kohistan system and the SW–W directed thrusts of the western Himalayan arc. The thickness variations of the Rawalpindi and Siwalik Groups and the Bouguer anomaly map show that the foreland basin south of the Salt Ranges has been controlled by flexure related to thickening along the NW–SE trending Himalayan arc and not in the Kohistan mountains.

The Kohistan thrust direction can be obtained from the maps of cut-offs and lateral ramps as well as lineation data and axes of sheath folds in the internal zones (figure 16). The lateral ramps that bound the Salt Ranges and Surghar Ranges suggest a clear 160° direction for thrust transport, although there is evidence for Recent anticlockwise rotation at the eastern lateral tips to the larger thrusts in the Salt Ranges (Opdyke *et al.* 1982; Butler *et al.* 1987).

At the eastern end of the Salt Ranges there is interference between Himalayan and Kohistan thrust movements. The most outlying structure of the Himalayan mountains is the Mangla–Samwali anticline (figure 15), which deforms alluvium with reversal stratigraphies indicative of deposition between 2.7 and 1.5 Ma (Johnson *et al.* 1979). This anticline immediately predates the eastern folds of the Salt Range and probably inhibited the lateral propagation of the Salt Range detachment. Thus the lateral termination of the Salt Range system may reflect either the proximity of the main Himalayan belts or the associated flexural depression and its thicker pile of molassic sediments to the NE. This lateral pinning of Salt Range structures may cause the local obliquity of the thrusts in the eastern Salt Ranges.

Slickensides and other shear criteria in the fault rocks of the Kohat, Kala Chitta Ranges and Margalla Hills (figure 1) also suggest a dominant SSE thrust direction, although in the east,

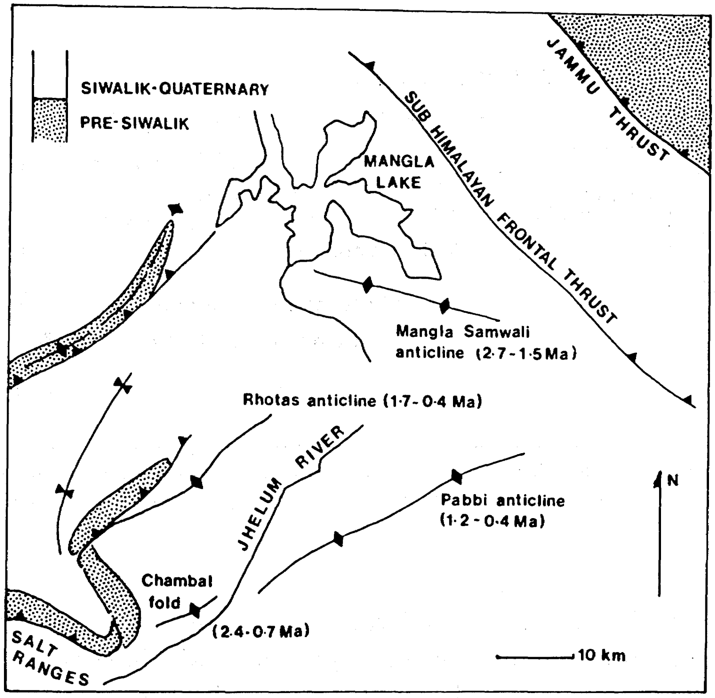

Figure 15. Simplified map of the distribution of folds and thrusts at the eastern termination of the Salt Range in the Jhelam district (see figure 1 for location), modified after Gee (1980) and Johnson *et al.* (1979), illustrating the ages of folding for various structures determined by magnetic reversal stratigraphy in the Siwalik Group of molasse.

near Murree, some of the thrusts carry large folds with steeply plunging but curvilinear hinges, which suggest a strike-slip movement (figure 16). These could be SW-directed folds and thrusts of the Himalayan system, tilted to give an apparent strike-slip attitude during subsequent SSE-directed thrusting. The Hazara syntaxis is an uplifted zone of Palaeogene sediments beneath the Hazara thrust system (Bossart *et al.* 1984). The trend of the syntaxis suggests it originated from a complex strain pattern and uplift in SW-directed structures at depth (see also Seeber *et al.* 1981; Coward 1983), though in detail the bedding-cleavage intersection directions and incremental strain indicators show that the uplift has been variable and connected with pronounced rotation (Bossart *et al.* 1984).

In the internal thrust zones of N Pakistan, the transport direction may be estimated from lineation data (figure 16). In the Mansehra–Besham region and NE of Nanga Parbat the majority of mineral lineations and hinges of large scale sheath folds have a NW–SE trend (Coward *et al.* 1986, 1987). North of Besham and near Swat, however, lineations are more variable; figure 17 shows the range in the Besham–Alpurai/Swat area, from N45E to N45W. Perhaps a more accurate indicator of thrust transport is given by the trends of major lateral structures of the Thakot and Balakot shears (figures 5 and 6), indicating N–S transport.

The Nanga Parbat syntaxis is a zone of recent uplift as shown by K–Ar cooling ages (Coward *et al.* 1986) and fission track data (Zeitler *et al.* 1982; Zeitler 1985). It is dominantly a large antiformal fold, buckling the MMT and underlying sheared gneisses of the Indian Plate. A structural cross section is given in Coward *et al.* (1986). The gneisses have been intensely re-deformed during the uplift and two dominant shear senses can be recognized: of ductile thrust

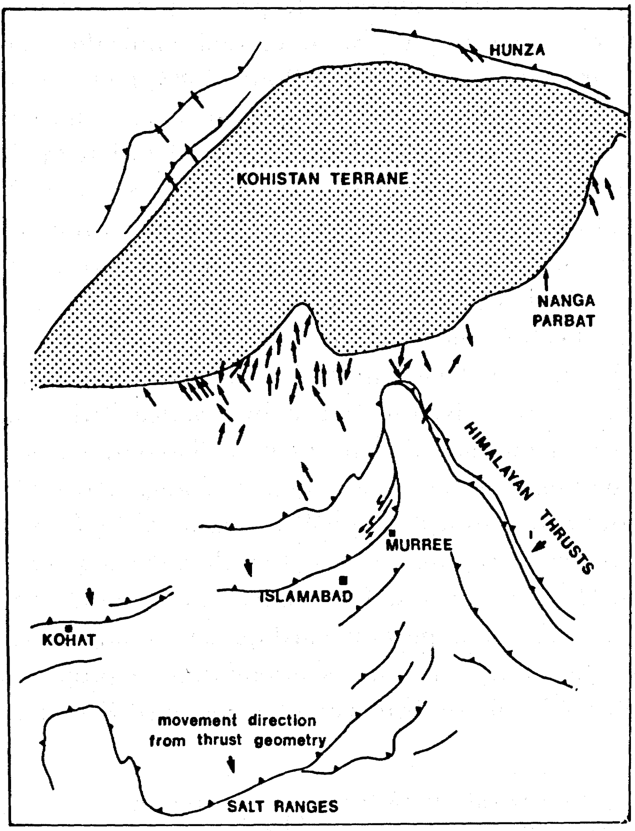

FIGURE 16. Simplified map of Kohistan showing the orientations of mineral lineations and early fold hinges for the internal zones of the Indian Plate, and from the Himalayan age shears and thrusts of the Asian Plate to the north. (Data on Asian Plate from Coward *et al.* 1986; Pudsey *et al.* 1986.)

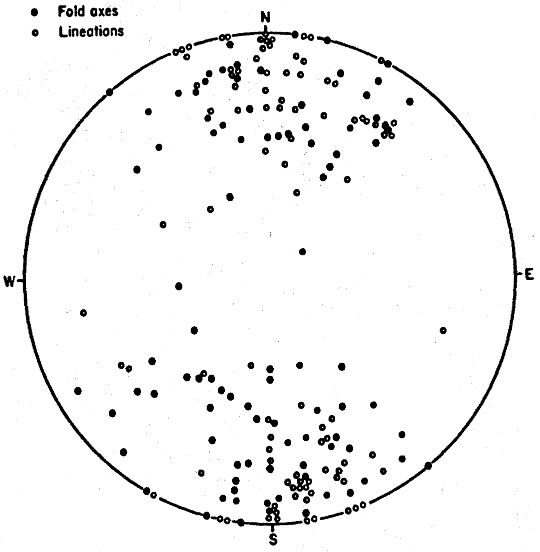

FIGURE 17. Stereoplot of stretching lineations and fold axes from the imbricated sequence west of Besham (MPW in Treloar *et al.* 1988*a*).

sense to the NW and of dextral strike-slip on a steeper shear zone (Butler & Prior 1988*b*). The amphibolite facies ductile shear zones were carried onto the sediments by continued movements. The Liachar thrust zone (Butler & Prior 1988*b*) moved to the NW, parallel to the shear direction in the earlier ductile zone and emplaced gneisses on to river gravels and glacial deposits (50000 years BP) (Gansser 1981; Lawrence & Ghauri 1983; Butler & Prior 1988*b*). It has historical seismic activity. Small-scale faults in the gravels trend NE–SW and have both thrust sense and dextral strike-slip sense. The strike-slip zone terminates in zones of shattering towards the south that weakly overprint small-scale structures associated with the NW-directed thrust. Thus, the Nanga Parbat syntaxis may be considered as the NW tip of the Himalayan arc with some uplift to the NW and associated SW-directed shearing. Detailed discussion of these structures will be presented elsewhere. Dating of pebbles from the deformed Indus gravels, suggest that they were derived from a cooling Nanga Parbat mass at only 2 Ma, that is Nanga Parbat was eroded and the sediments then tilted and overthrust within the past 2 Ma.

Earthquake fault solutions for the region west of Nanga Parbat also suggest dominant present-day thrust movements towards the SW (Jackson & McKenzie 1984; Coward *et al.* 1987). Figure 18 shows the distribution of recent earthquake activity related to the uplifts of the Nanga Parbat and Hazara syntaxes. The syntaxes may be linked by a NE-trending zone of uplift. However, the zone of important earthquakes trending NNW from the Hazara syntaxis suggests that the Himalayan arc is attempting to propagate along strike but is hindered by the complex of Kohistan thrusts and the obducted Kohistan island arc. The initial

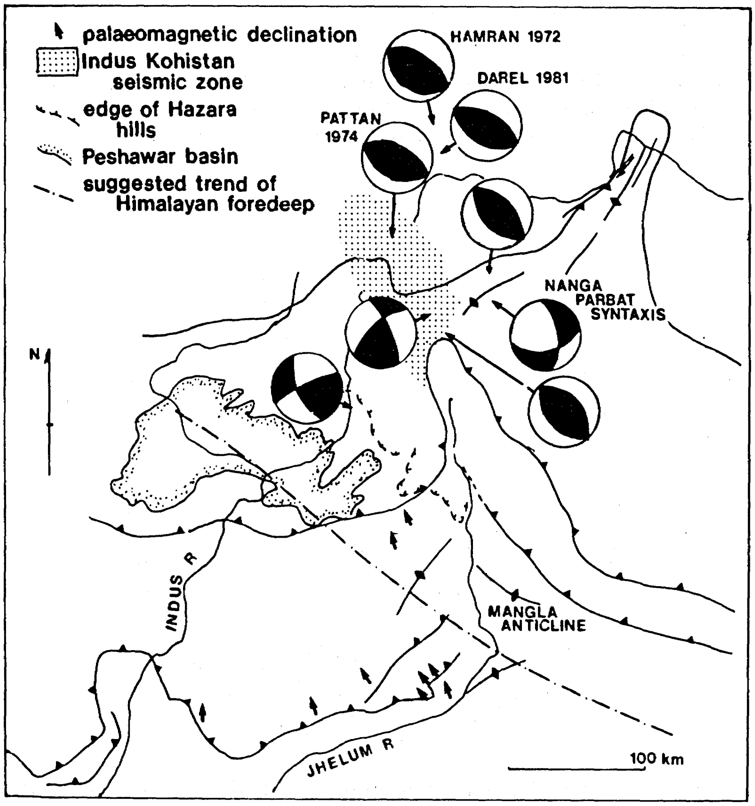

FIGURE 18. Distribution of the main neotectonic structures of the western Himalayan arc.

age of the Nanga Parbat and Hazara syntaxes is unknown. However, the later thrust movements in the southern part of the Hazara syntaxis uplifted the Mangla Samwali hills 2.7–1.5 Ma ago and presumably uplifted the Murree to Nathia Gali hills to their present altitude of over 2 km at this time (see figure 18). Some of this uplift was transferred on to the Nanga Parbat syntaxis causing overthrusting of Indus sediments. This late uplift and crustal thickening presumably modified the foreland basin. The Peshawar Basin (figure 18) may be partially a flexural basin ahead of the Himalayan thrusts, superimposed on and depressing the earlier Hazara thrusts. Sediments in the Peshawar basin date from about 2.8 Ma to the present day, fitting closely the timing of uplift in the Mangla Samwali hills and Nanga Parbat.

The tectonics of northern Pakistan therefore, cannot be considered accurately in simple two-dimensional sections. Accurate restorations require a three-dimensional thrust analysis. Furthermore, any modelling of lithospheric flexure (cf. Duroy 1986) needs to consider three-dimensional data before values for the effective elastic thickness or rates of shortening from the migration of the foreland basin can be calculated. Duroy (1986) and Duroy *et al.* (1988) consider the flexure in terms of a NNW–SSE section, perpendicular to the Kohistan thrusting. However, as argued above, the flexural basin is probably largely developed by the load of the main Himalayan arc, but to estimate effective elastic parameters for Northern Pakistan, the loads of Kohistan and the Himalayas need to be taken into account.

CONCLUSIONS

1. Large displacements of Kohistan relative to the Indian Plate took place on detachments within the upper part of the crust. Estimates of about 470 km have been made for shortening within the non-metamorphosed Phanerozoic cover in the external zone, and at least an extra 150 km displacement occurred by shear in the metamorphosed cover sequence in the Nanga Parbat syntaxis. Indian lower crust, therefore, must have been subducted northwards beneath Kohistan. The continental crust beneath the Indian Plate is on average 35–40 km thick (Chaudhury 1965) but beneath Nanga Parbat it may be over 70 km thick (Kaila 1981). Much of this thickening may occur by underplating of Indian crust (see also Malinconico 1988). Certainly the Kohistan arc remained relatively undeformed during Himalayan events, locally shortening by SE-directed shears near the NW margin (Pudsey *et al.* 1986; Searle *et al.* 1987). However, it is unlikely that lower Indian crust extends beneath Kohistan as a rigid sheet; more likely it has been internally folded and imbricated, similar to the gneisses in the Besham area (figure 19).

2. Much of the thrusting involved thin-skinned tectonics in a simple, almost layer-cake, stratigraphy. Very little of the rift margin has been preserved and Tethyan sediments consists of shelf carbonates with several phases of Mesozoic subsidence and emergence. A minor phase of inversion and erosion occurred at the end of the Cretaceous, so that Palaeocene sediments rest unconformably on a range of Phanerozoic rocks.

3. The northernmost Tethyan sediments form the cover sequence to the basement rocks in the internal zones. The Nanga Parbat and Hazara nappe units are the more distal, the Besham nappes more proximal. Collision involved subduction of the basement gneisses and some cover rocks beneath Kohistan, associated with locally high-grade metamorphism. Generally, the more distal rocks of the Hazara nappe show a higher metamorphic grade than those of the

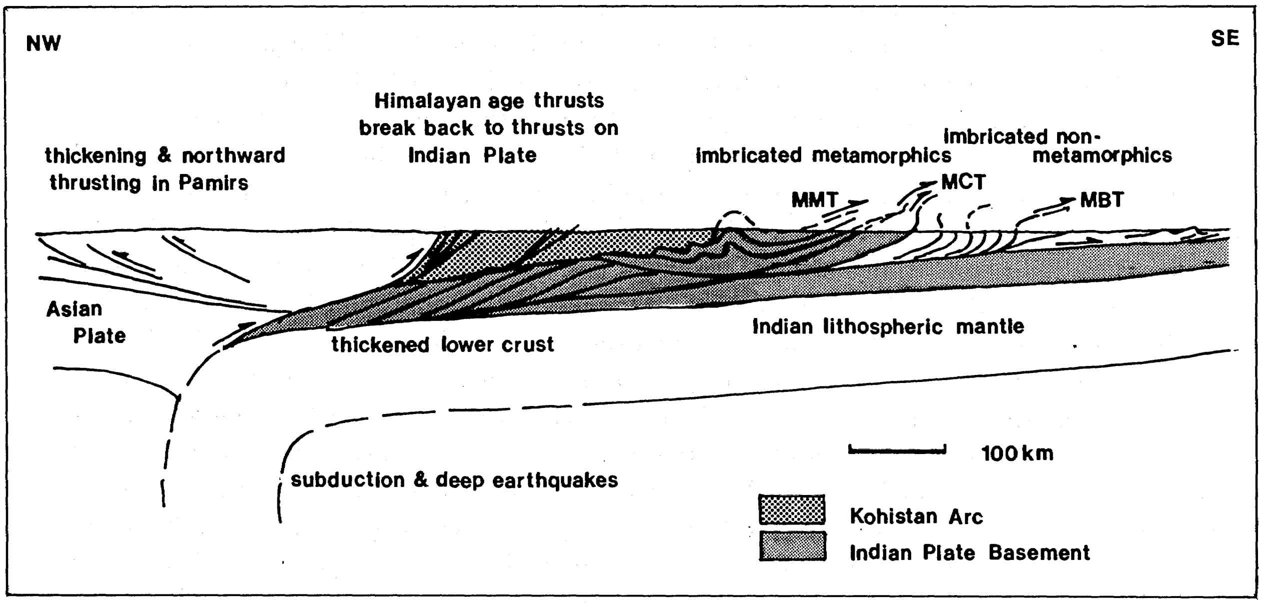

FIGURE 19. Simplified section through Kohistan and Pamirs showing how the Indian continental crust must be subducted partially beneath the Asian Plate, hence causing some thickening and uplift. Some Himalayan age deformation of the Asian Plate occurs by SE-directed thrusts, which are break-back to the main deformation on the Indian Plate.

Besham nappes, suggesting deeper subduction. However, there may be east–west lateral variations in metamorphic grade associated with lateral changes in thrust structure and associated crustal thickening. This metamorphic sequence was subsequently imbricated during later stages of collision, so that high-grade rocks were stacked above rocks preserving lower-grade assemblages, producing a form of metamorphic inversion.

4. The thrust package has been modified by several phases of back-folding, back-thrusting and extensional shears, probably largely related to the bulk strain necessary to maintain critical wedge shape, as the internal zone of nappes was thrust onto cover sediments of the Indian Plate. Relatively late structures include those of the Besham syntaxis and associated folds to the west, some of which detach onto the MMT and may link with the Himalayan thrusts which affect NW Kohistan (figure 20).

5. Within the external zones there are complex variations in thrust geometry and dramatic zones of back-steepening and large-scale back-folds that also are probably related to bulk strains maintaining wedge shape. Eocene salt horizons in the Kohat area and Cambrian evaporites beneath the Potwar Plateau and Salt Ranges have allowed late easy slip. The basal detachment has propagated rapidly through the salt, at a time-averaged rate of over 6 cm a^{-1} and thrust movement has been possible even though the critical taper of the thrust zone was low.

6. Time averaged displacement rates for the Potwar Plateau–Salt Ranges are in the order of 1–1.5 cm a^{-1}, comparable with those estimated for the Indian foothill thrusts (Lyon-Caen & Molnar 1984). A similar time-averaged displacement rate can be estimated for Kohistan tectonics as a whole, with over 600 km shortening in the 50 Ma since collision. At present, the Indian Plate is moving northwards at a rate of between 3.5 cm a^{-1} in the west and 5.0 cm a^{-1} in the east, relative to a fixed Asian Plate (cf. Molnar & Tapponnier 1975). The difference

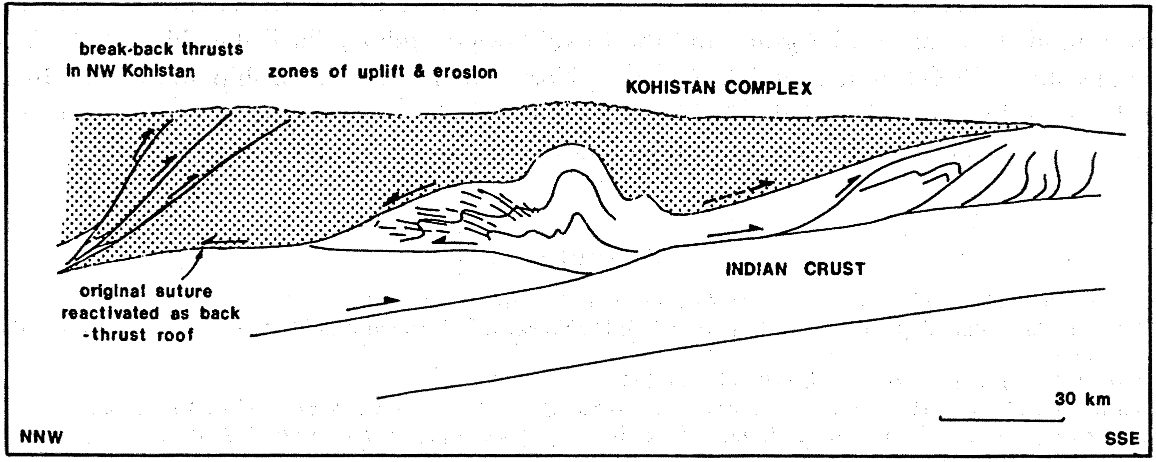

FIGURE 20. Suggested links between the break-back thrusts in the Kohistan arc and the back-thrusts and back-folds at Besham.

in shortening rate between that measured from field studies and that estimated from plate reconstruction must be accommodated by extra strains north of the MMT, within the Pamirs, Tibet and west China–central Asia.

7. The Himalayas show a range in overthrust directions, particularly around the western Himalayan arc. Reasons for these variations, whether they are caused by rotation around lateral tips to the thrust system or to spreading of thickened Tibetan–Himalayan lithosphere, are discussed by Coward *et al.* (1987). The Kohistan thrust system involved tectonic transport to the S or SSE as determined from minor structures and larger-scale thrust fault geometries. There is major interference between the western Himalayan and Kohistan thrust directions, whereby both thrust systems hinder lateral propagation of the other set. Hence accurate restorations and models of lithospheric flexing require more detailed three-dimensional surveys of the region. Such work is in progress.

8. The most recent Kohistan thrust movements involved above 30 km displacement on the Salt Range thrusts. These structures terminate laterally at the frontal ranges of the Himalayan arc, at the Mangla Samwali hills, formed at about 2.7–1.5 Ma. The zone of Himalayan uplift, folding and thickening can be traced northwards, to the west of the Hazara syntaxis, to form a zone of active seismicity (the Indus–Kohistan Seismic Zone of Seeber *et al.* (1981)). This probably links with uplift of the Nanga Parbat mountains, where paired strike-slip and thrust movements on the western margin of the massif affect Recent river gravels and appear to have stepped southwestward with time. This probably reflects the SW migration of the lateral tip to the Himalayan system. The foreland basin seems to be related to crustal thickening in the Himalayan arc rather than in Kohistan, where younger Cainozoic deformation is thin skinned. Hence the foreland basin trends WNW, or NW, oblique to Kohistan structures and the Peshawar Basin may be a foreland depression superimposed on top of Hazara thrusts by the excessive crustal thickening in the western Himalayan arc, in particular in the Nanga Parbat region. Presumably, only the presence of salt beneath the frontal Kohistan thrusts has allowed continued movement without the necessary build up of wedge shape.

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Discussion

A. BARNICOAT (*Department of Geology, University College of Wales, U.K.*). The metamorphism seen imbricated within the thrust sheets in the Besham area is of Barrovian type, and hence presumably caused by thermal relaxation following crustal thickening. Would one of the authors care to speculate on the nature and geometry of that thickening?

P. J. TRELOAR. We welcome Dr Barnicoat's offer to speculate about metamorphism and crustal thickening in North Pakistan, but would rather follow our established practice and confine ourselves to a description of the facts and their implications. Himalayan age metamorphism at Besham accompanied a rapid pressure increase with the peak synchronous with the main D1 ductile shearing event. We equate this syn-tectonic metamorphism to thickening of the Indian Plate during its subduction underneath the over-riding Kohistan complex, rather than to metamorphism during thermal relaxation after crustal thickening. The imbrication of the metamorphic pile during thrusting late in the period of southward shearing in the footwall of the MMT generated an overall 'inverted' metamorphic profile in that it stacked higher-grade rocks on top of lower-grade ones. Such a tectonic inversion is the norm in the Indian Plate rocks south of the MMT in North Pakistan where the late thrusting stacked a number of internally imbricated metamorphic blocks on top of each other. Unfortunately, either individual slices are too thin, or errors on the thermobarometry too large, to state whether or not the metamorphism was originally the right way up (temperature increasing with depth), although over the region as a whole that is what we would expect to have been the case. What is noticeable is that metamorphism was diachronous with the syn-D1 metamorphic peak at Besham pre-dating the syn- to post-D2 peak in the Hazara region where textural relations imply a more normal post or late thickening thermal relaxation. Perhaps part of the reason for the difference is that the rocks at Besham actually underwent some subduction under Kohistan whereas those in Hazara saw nothing more than normal orogenic thickening in the footwall of the MMT.