Journal of Structural Geology, Vol. 13, No. 3, pp. 319 to 327, 1991
Printed in Great Britain

0191-8141/91 $03.00+0.00
Pergamon Press plc

Thrust kinematics in the Kohat Plateau, Trans Indus Range, Pakistan

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(*Received* 5 *October* 1988; *accepted in revised form* 10 *June* 1990)

Abstract—The Kohat Plateau consists of a heavily deformed and structurally elevated thrust sheet. Pop-ups, broad synclines and narrow fault- and evaporite-cored anticlines record high-level translation of a large thrust mass along Eocene evaporites. A lower detachment level is also inferred, located at the base of the Mesozoic–Palaeozoic section. This lower detachment is common to both the Kohat and the adjacent Potwar Plateaux whereas the upper level is restricted to the Kohat. Beneath the Kohat, a blind imbricate stack of pre-Tertiary rocks is developed. Above their roof thrust, the foreland basin-fill of Kohat records greater internal deformation compared to that of the adjacent Potwar Plateau. In contrast, the Potwar thrust belt displays a greater amount of overthrusting on its basal surface, this displacement emerging in the Salt Range. Total shortening across the two plateaux is comparable, but is accommodated in an areally smaller thrust belt with a higher structural relief in the Kohat as compared to the Potwar structural province. The resultant geographical offset of the thrust front is denoted by the Hukni–Kalabagh lateral ramp. The differences in the thrust kinematics are tentatively suggested to be caused by the mechanical response of the orogenic wedge to different imposed geometries of the wedge laterally within the basin. The Kohat Plateau appears to have a lower basal dip than does the western Potwar, and thus shows greater internal deformation.

INTRODUCTION AND REGIONAL SETTING

THE Kohat–Potwar foreland fold–thrust belt on the southern fringes of the Himalayan orogenic belt is a product of ongoing collision of the Indian and Eurasian plates (Fig. 1). Surface and subsurface information in the foreland fold–thrust belt have provided valuable insights into the sedimentary history and deformation of the foreland basin (Powell 1979, Coward & Butler 1985, Johnson *et al.* 1985, Banks & Warburton 1986, Lillie *et al.* 1987, Baker *et al.* 1988, Jaume & Lillie 1988). A portion of the active fold–thrust belt, the Kohat Plateau of Pakistan, exhibits a distinctive thrust sheet geometry (Figs. 1 and 2).

This area constitutes the westernmost part of the Himalayan foreland-basin (Fig. 1). It is bounded to the north by the Main Boundary Thrust (MBT) and to the south by the Surghar Range Thrust. The Kalabagh Fault is a prominent N–S structural feature which forms the eastern boundary to the Plateau and compartmentalizes the foreland thrust belt. It was described as a N15°W dextral fault by McDougal (1985), and as a lateral ramp structure by Butler *et al.* (1987). A number of E–W-trending thrusts branch from this lateral ramp in the vicinity of Shakadarra. This contribution addresses the contrasting styles of deformation and thrust propagation in the Kohat portion of the foreland-basin and compares it with that of the adjacent western Potwar Plateau (Figs. 2 and 3), and considers the lateral ramp that forms their common boundary.

To examine the nature of deformation and amount of shortening in the Kohat Plateau, an area around Shakardarra town was selected for detailed investigation. The area was mapped at 1:50,000 scale during two field seasons with the help of topographic maps and aerial photographs, which provide a good coverage of the area (Figs. 5 and 6). Detailed field observations such as the strike and dip of thrusts, the orientations of slickensides on thrust surfaces, bedding and fold envelopes were recorded in conjunction with measured stratigraphic thicknesses. The interpretation of subsurface geology and depth to detachment level calculations were extrapolated from the detailed surface geological database, constrained by a limited amount of subsurface information (fig. 10 of Khan *et al.* 1986). Standard section construction techniques were used in generating the new profiles presented here.

STRATIGRAPHY

No rocks older than the early Eocene age are exposed in the Kohat Plateau (Meissner *et al.* 1974), but an at least 1 km thick Mesozoic–Palaeozoic succession is exposed in the Surghar Range to the south, and in the hinterland to the north. These deposits are therefore inferred to underlie the Eocene succession in the intervening Kohat area (Fatmi 1973, Meissner *et al.* 1974, Khan *et al.* 1986). Eocambrian evaporites with a thin veneer of Palaeozoic sediments were extrapolated by Khan *et al.* (1986) under the Kohat and Bannu areas, but are not exposed anywhere in the Trans Indus Ranges. This suggests that these deposits are autochthonous beneath the study area and that the range front thrusts cut upsection from the evaporites to the base of the Palaeozoic–Mesozoic succession to the north of Kohat (Butler *et al.* 1987). The Potwar Plateau, however, was translated along these Eocambrian evaporites. This resulted in the broader, more open and less internally deformed style of the Potwar foreland belt (Khan *et al.* 1986, Leathers 1987, Lillie *et al.* 1987, Baker *et al.* 1988).

In contrast, the exposed thrusts of the Kohat Plateau emplace Eocene evaporites over Miocene molasse sedi-

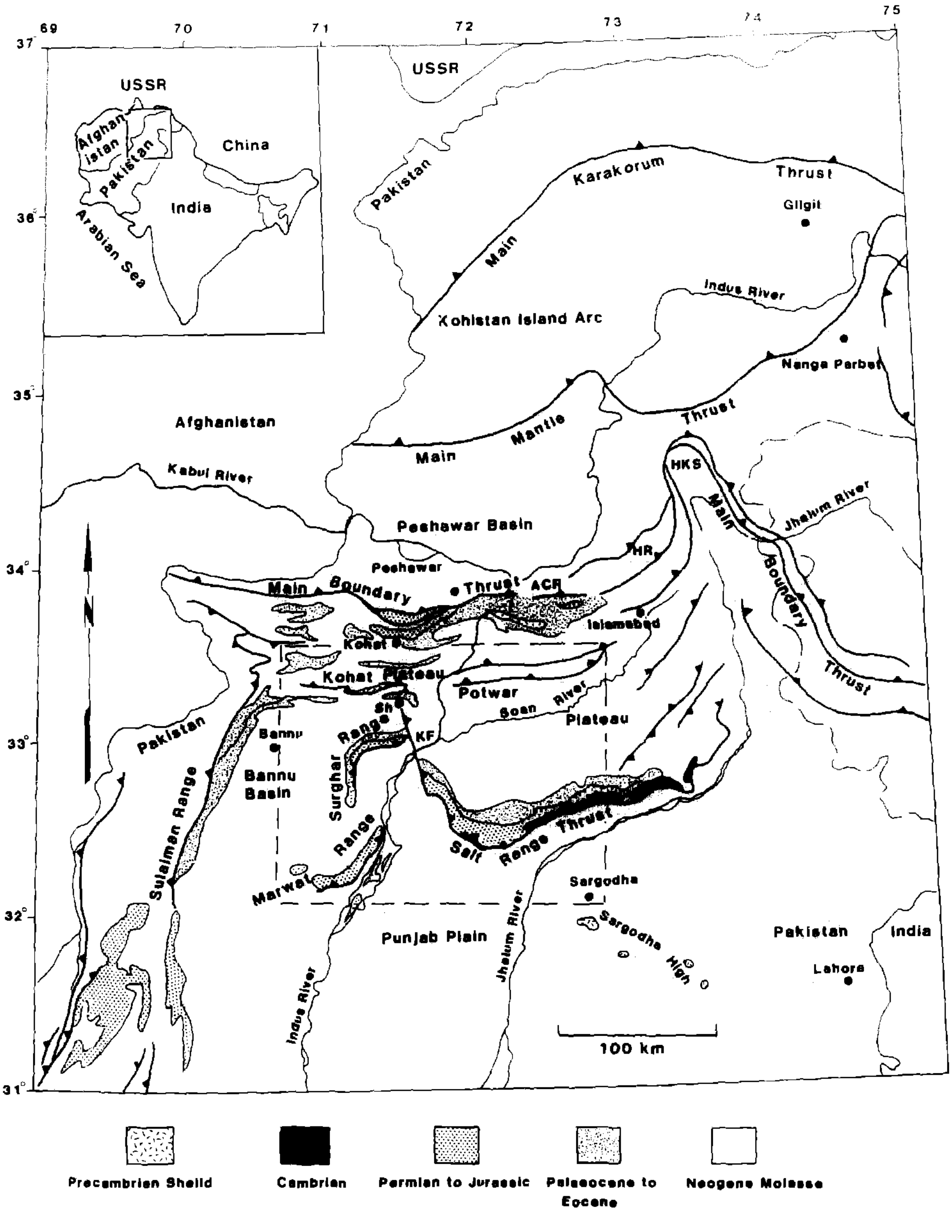

Fig. 1. Sketch map of the western Himalayas, showing the location of the Kohat and Potwar Plateaux (area in rectangle). Modified from Kazmi & Rana (1982). Regional map is in the top left corner.

ments. The distribution of these evaporites (the Bahadurkhel Salt and Jatta Gypsum of Meissner *et al.* 1974) is confined to the central Kohat Plateau where they are exposed in a narrow elongated belt termed the Kohat Salt Zone (Khan *et al.* 1986). The Eocene evaporite sequence is overlain by Eocene shelf sediments of the Kuldana Formation (siltstone) and the Kohat Formation (limestone, see Fig. 4). The shelf sediments are themselves unconformably overlain by 5 km of molasse deposits. Figure 4 is a simplified summary of the Kohat Plateau stratigraphy.

DEFORMATION IN THE KOHAT AND POTWAR PLATEAUX

Figures 2 and 3 show the difference in the style of deformation of the Kohat and Potwar Plateaux. The Potwar Plateau is approximately 150 km wide (Fig. 3a), with most of its internal deformation concentrated in the north, where at least 45 km of shortening in the imbricates in the footwall to the MBT is estimated (Leathers 1987, Baker *et al.* 1988). An additional 20 km of shortening is proposed for the central and western Salt Ranges along the range fronts. There is very little or almost no internal shortening recorded in the allochthon between the northern Potwar Plateau and the Salt Ranges (a distance of 80 km), preserving a thick pile of largely undeformed molasse sediments (Fig. 3a) (Leathers 1987).

The internal shortening in the Kohat Plateau (between the MBT and the Surghar Thrust) is estimated to be about 55 ± 5 km (Fig. 3b) which is comparable to that recorded in the Potwar Plateau. This is accommodated in a much smaller area (in a distance of about 75 km), mainly to the north of Shakardarra. Two detachment levels exist beneath the Kohat Plateau. The upper

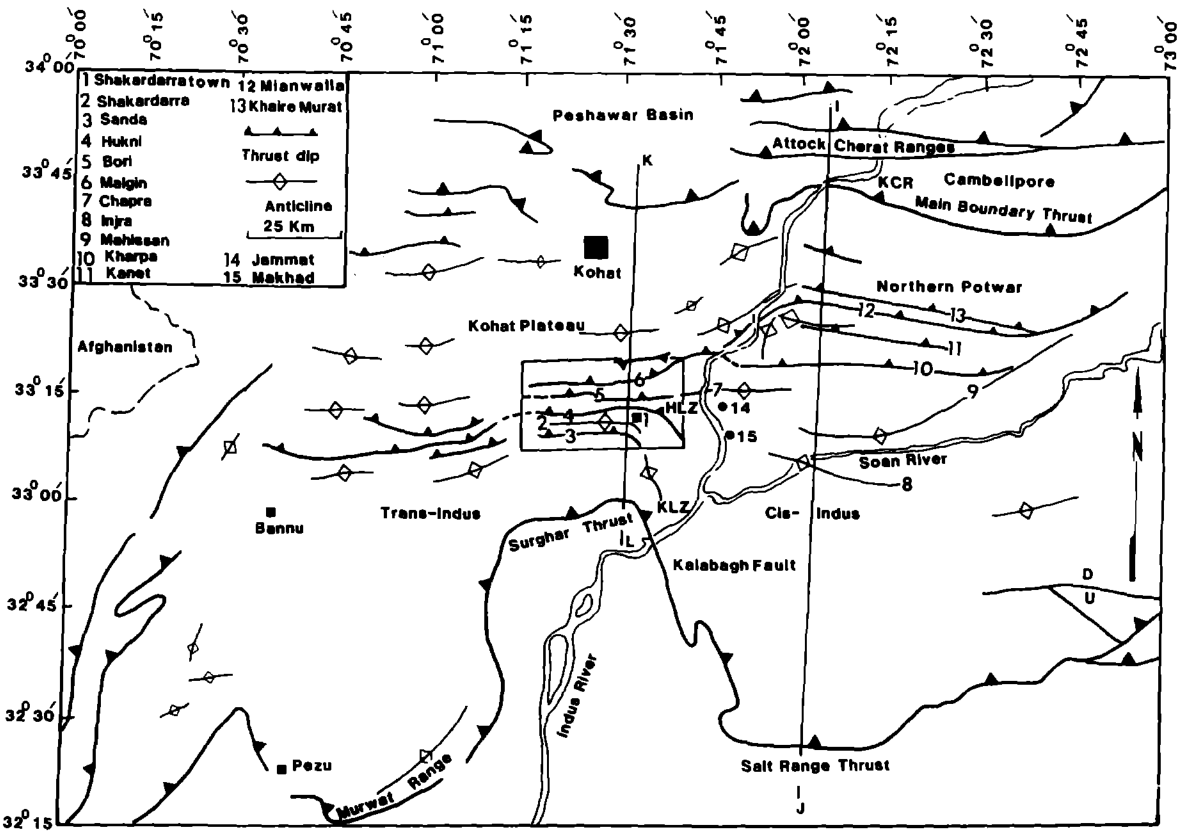

Fig. 2. Structural map of Kohat and Potwar Plateaux. Modified (mainly in Kohat area) from Leathers (1987). Area in rectangle marks the study area. Section K–L and I–J are represented in Figs. 3(a) & (b), respectively. Numbers refer to surface structures.

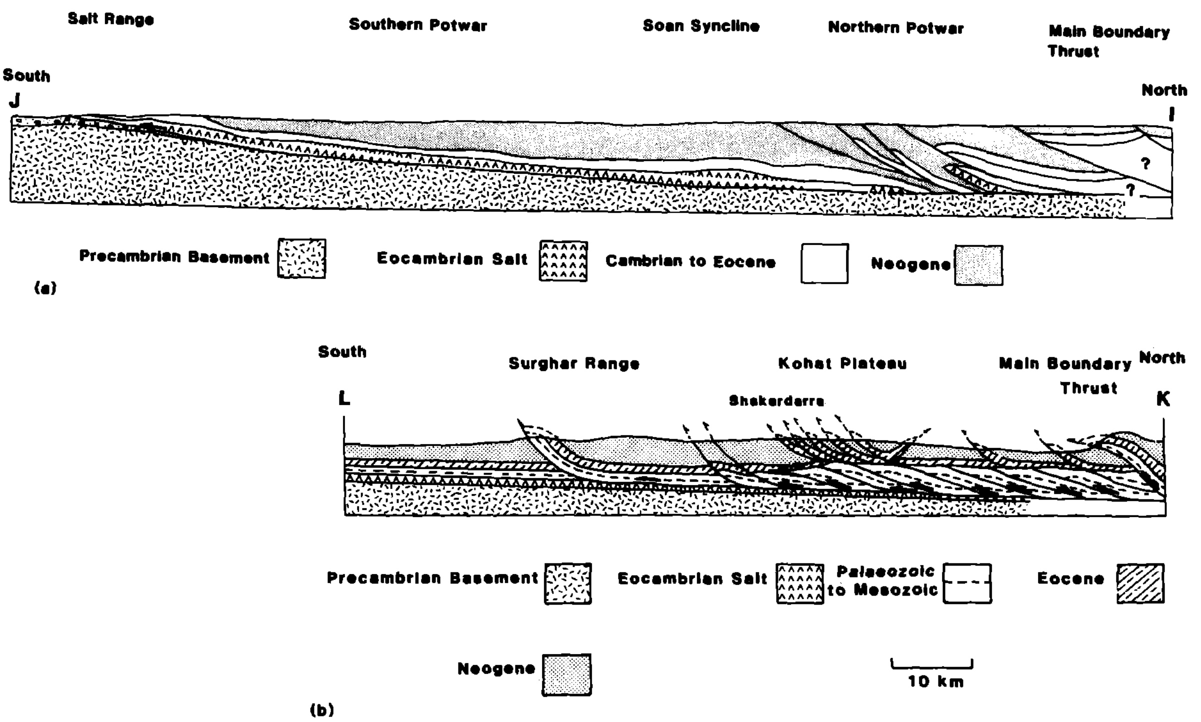

Fig. 3. (a) Cross-section I–J (Fig. 2) from Attock Cherat Ranges in the north through western Potwar to western Salt Range (after Leathers 1987) (b) Cross-section L–K (Fig. 2) from MBT through Kohat Plateau to Surghar Range, exhibiting style of deformation in the Kohat Plateau. Note increased amount of internal shortening of the Kohat foreland thrust sheet compared to the Potwar Plateau.

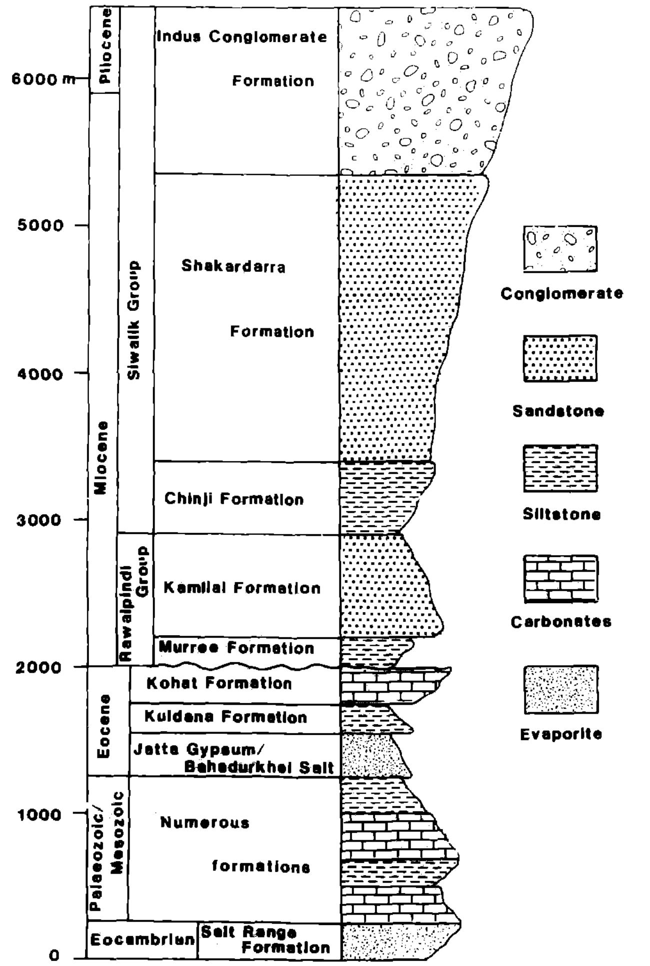

Fig. 4. Stratigraphy of the Kohat Plateau (after Fatmi 1973, Meissner *et al.* 1974, Shah 1977).

detachment level (the regionally confined Bahadurkhel Salt and Jatta Gypsum peculiar to the Kohat Plateau) is estimated to be at about 1.5–2 km depth as determined from the kilometric-scale faults and folds exposed at the surface. The resultant elevation change of the calculated level of the Eocene datum along the N–S profile was attributed to the presence of a postulated blind stack of thrust slices composed of the stratigraphy intervening between the two detachment levels. The elevation of the lower detachment level was calculated from the known stratigraphic thickness, and is assumed to be a regional flat across the area at about 6–7 km depth, located along the contact between the Mesozoic–Palaeozoic platform sediments and the Eocambrian Salt Range Formation.

South of Kohat, deformation of the foreland basin is limited in intensity, and relates to the slip along the basal detachment. This displacement emerges at the thrust front, where the thrust at the base of the Mesozoic cuts up-section to the surface in the Surghar Ranges. This generated open structures behind the thrust front, and preserved over 5 km of molasse deposits.

IMBRICATE FAN AND DUPLEX GEOMETRY

Figure 3(b) is a vertical cross-section across the Kohat Plateau, and Fig. 7(a) is a detailed section across the central Kohat Plateau, where most of the deformation is concentrated. Detailed field and aerial photograph studies around Shakardarra area (Figs. 5 and 6) are the basis of these interpretations. North of Shakardarra town, thrusts A–E (named on captions of Fig. 6, see also Fig. 7), dipping north, have emplaced the Eocene evaporites (Meissner *et al.* 1974) over the Chinji Formation (Miocene, Shah 1977) of the Siwalik Group and form an imbricate fan (terminology of Butler 1982, Morley 1986). The intervening folds between these thrusts are usually asymmetric, have steep limbs and short wavelengths (Figs. 6 and 7a). The high angle of imbricate thrusts, intervening fold envelopes and measured stratigraphic thicknesses suggest a shallow (1.5–2 km deep) detachment level running along the Eocene evaporites present only in the Kohat Plateau. This is compatible with seismic information (fig. 10 of Khan *et al.* 1986, R. Graham personal communication).

The Chinji Formation in the Siwalik Group is relatively incompetent due to its higher silt content and thrusts exploit this stratigraphic level. This formation is characteristically tightly folded and faulted in the immediate footwall of major thrusts (e.g. thrusts A and E, Fig. 7).

Thrusts A, B and D, with an average shortening of 3–4 km on each thrust, can be traced from the Kohat Plateau into the western Potwar area (Fig. 2) where they are represented by thrusts and/or tip-line anticlines. Displacement across thrust A in the Kohat is accommodated by the Mianwalla and Kharpa thrusts (Fig. 2), and the shortening recorded by thrusts B and D is represented by the Chapra and Injra anticlines in the western Potwar. The displacement accommodated across these tip-line structures is of about the same magnitude as shortening along thrusts B and D. Thrust C, however, is truncated to the north of Braghdi village, and is not represented in the Potwar area. A series of N–S-trending normal faults, extensional features developed over the Nandrakka Salt Dome, downdrop and preserve the closure of this halotectonic anticline. The geometry of all these structures (A–E) suggests a shallow evaporite detachment from which thrusts branch.

This shallow detachment level forms the roof thrust to a blind duplex which imbricates the Mesozoic and Palaeozoic formations. An imbricate stack of horses is interpreted to underlie the roof thrust as the floor thrust (the lower detachment level) is located about 4–5 km below the roof thrust. The imbricates in between are represented schematically, as there is no constraint on the internal geometry of the stack. The blind tip-line of the passive roof-thrust to the duplex (Banks & Warburton 1986) lies below and in advance of thrust E. This roof thrust has a backthrust sense of displacement, and dips towards the foreland at very low angle. Hinterland dipping thrusts splay from this detachment into the upper plate, which consists of the Tertiary stratigraphy.

The alternative interpretation of the structure of the area, with the upper thrust plate overriding an undeformed footwall, and having been generated from a

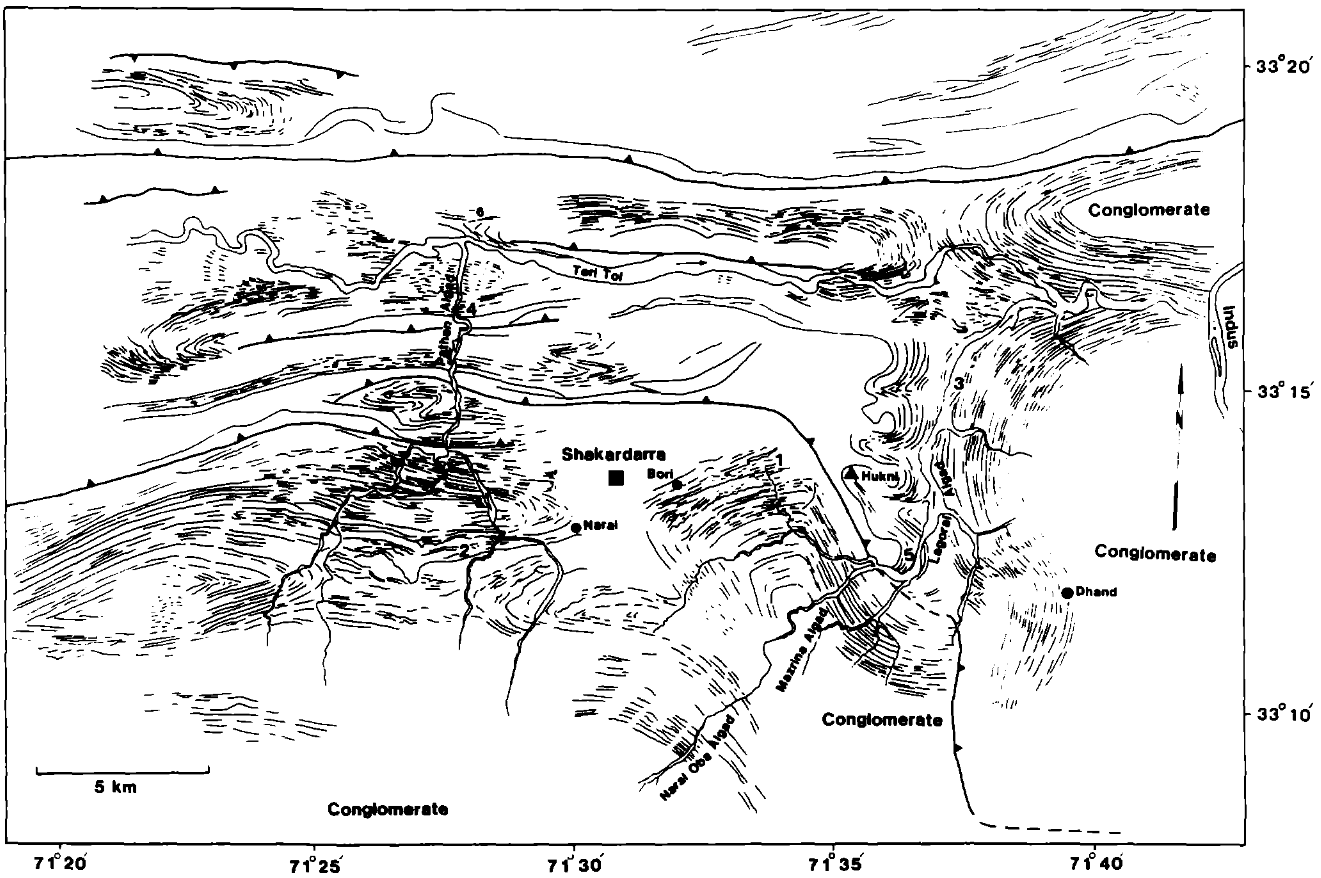

Fig. 5. Line drawing map of the Shakardarra area (Fig. 2) based on the aerial photographic mosaic. Major surface structural features are shown in thick lines.

footwall ramp at the northern end of the section line, is permissible in the study area. However, this model implies about 40 km of shortening across such a fault. This displacement is absent in the Potwar Plateau, and thus does not support such an interpretation (Fig. 2).

To the south of the passive-roof duplex, thrusts F and G branch directly from the basal detachment below Mesozoic–Palaeozoic formations, and the Shakardarra and Mattukhel anticlines are developed due to folding and emergence of these thrusts (Figs. 6 and 7a).

LATERAL RAMP STRUCTURES

The thrusts to the south of, and including, thrust D transfer their displacement onto the N–S-trending Hukni Lateral Zone (HLZ). Detailed surface study (Figs. 5, 6) and cross-sections constructed along (Fig. 7b) and across thrust D (Figs. 7c & d) in this area allow detailed description of the thrust geometries typical of the lateral ramp.

Thrust D, trending E–W in the western part of the study area, changes its orientation near the village of Nandrakka to N–S above the lateral ramp, as does the trend of bedding strike lines of the hanging wall rock sequence. Movement along the lateral ramp (Fig. 7d) was possibly located by structures developed during the Eocene evolution of the area, and is associated with diapirism of the Eocene evaporites (Fig. 6). The lateral ramp in the area trends almost parallel to the thrust transport direction and the rock sequence exposed above this structure dips towards the ENE, quite similar to the geometry of the eastern limb of the Kalabagh re-entrant described by Butler *et al.* (1987).

One further point of significance of thrust D is that all the structures north of it trend E–W, and major thrusts pass into the western Potwar either as thrusts or as tipline anticlines, whereas all the structures south of it change their orientation from E–W to N–S, in a 'concentric pattern', recording progressive collapse of the blind lateral and frontal ramp complexes at depth.

The rock sequence of the Hukni section (Figs. 6 and 7b), including the Jatta, Kuldana, Kohat, Murree and Kamlial Formations, is folded in a number of E-plunging anticlines and synclines above the lateral ramp. Similar eastward plunges of anticlines also occur to the north of the study area. The rock sequence in the Hukni section may have undergone a component of N–S strike-slip bulk deformation as reflected by the rotation of the fold axes from E–W to NW–SE (Fig. 6). Dextral shear in this zone across the vertical N–S sidewall is implied. The slip sense along the trace of the fault thus varies from that of reverse slip in the west to strike slip in the east (Figs. 5 and 6), and thus the fault has characteristics of both fault-group types. A westward-verging fold style related to the accommodation of the hanging wall lateral ramp is

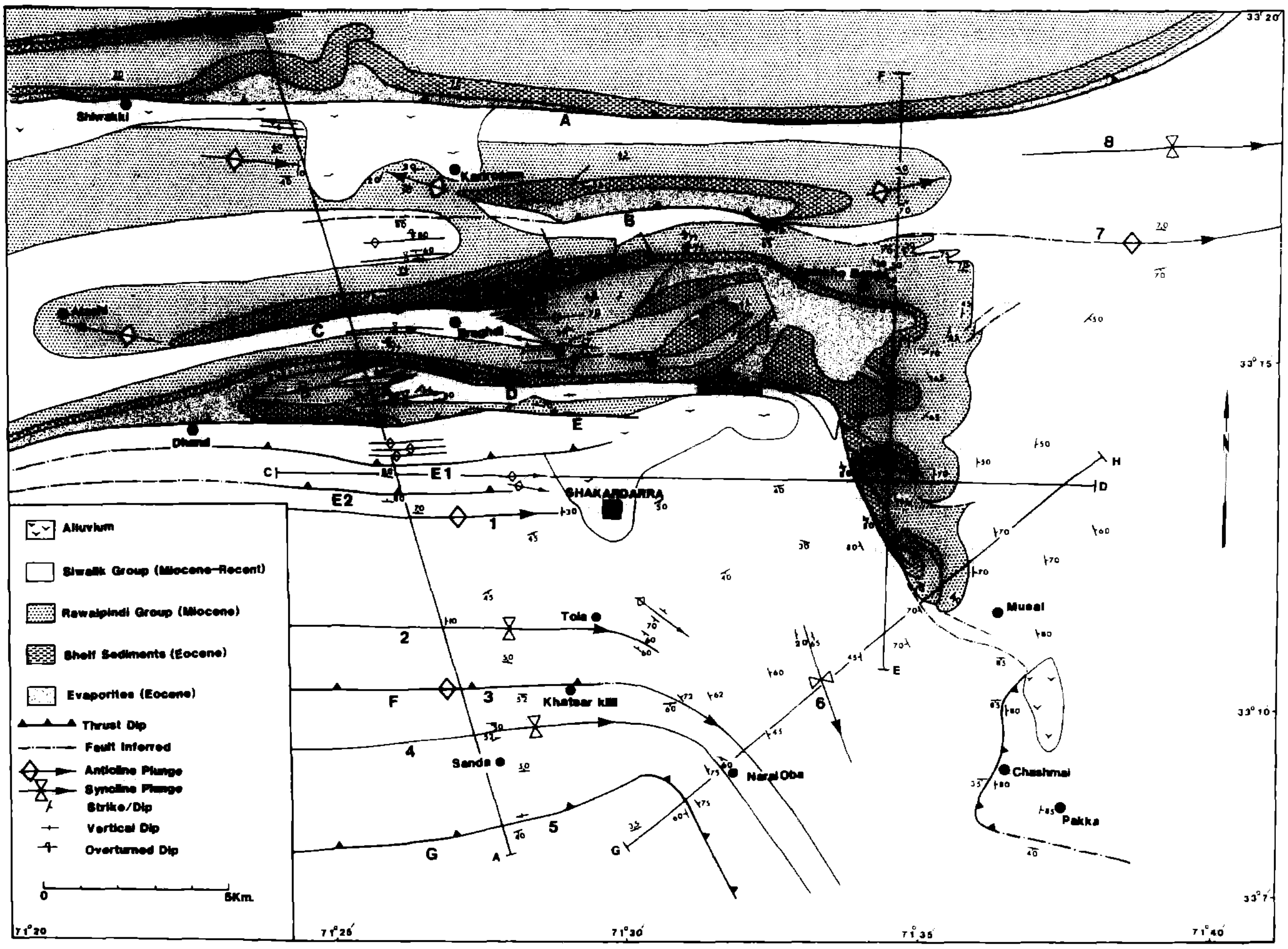

Fig. 6. Detailed structural map of Shakardarra area constructed from the field work undertaken in this study. Thrust A—Malgin Thrust, B—Bori Thrust, C—Braghdi Thrust, D—Hukni Thrust, E—Dhand Thrust, F—Matukhel Thrust, G—Sanda Thrust. 1—Shakardarra antiacline, 2—Mainji syncline, 3—Mattukhel anticline, 4—Sanda syncline, 5—Sanda anticline, 6—Badasam syncline, 7—Chapra anticline, 8—Ziarat syncline.

present (Fig. 7d), and signifies an additional limited amount of shortening perpendicular to the main shortening direction.

A cross-section (E–F, Fig. 7b) across the folded rock sequence along the lateral ramp shows that the area is underlain by a thickened sequence of salt and gypsum. The elongation of diapirs or the salt-coring of anticlines can be considered as a combined geometrical response to the action of gravitational overturn in a compressive tectonic stress regime.

It is apparent from the interpretation of the Hukni lateral ramp that deformation at higher structural levels was directly influenced by the behaviour of the Mesozoic–Palaeozoic platform sediments at depth. This resulted in passive hanging wall folding (albeit modified), above terminations of ramp anticlines generated between the upper and lower detachment levels. The limited displacement below such ramp anticlines (and also frontal ramps, Figs. 7a & b) transfers to the surface onto tip-line anticlines and weakly emergent thrusts out in the continental succession. Failure of the core of the Hukni passive hanging wall ramp anticline has resulted in limited slip of the eastern limb of the anticline over its western counterpart. Diapiric effects are intimately associated with this feature. There is no conclusive evidence to suggest that the limb-slip post-dates (deforms) the passive hanging wall anticline, or pre-dates it (and has been translated over the lateral ramp). Certainly, section E–F implies the lower ramp to be later, such that the passive roof duplex post-dates the imbricate fan.

DISCUSSION

Our structural interpretation for the Kohat Plateau implies a blind duplex between the Main Boundary Thrust (MBT) and Shakardarra. The roof thrust of the duplex is interpreted as a backthrust passively accommodating shortening beneath it. The deformation in the sequence above the roof thrust is not necessarily related to the structure of the underlying duplex (Banks & Warburton 1986).

The minimum shortening estimate of 55 ± 5 km in the Kohat Plateau is consistent with shortening estimates across the Potwar Plateau e.g. 65 ± 5 km (Baker *et al.* 1988), but is accommodated in a smaller area than the Potwar Plateau. The Potwar Plateau is an areally large

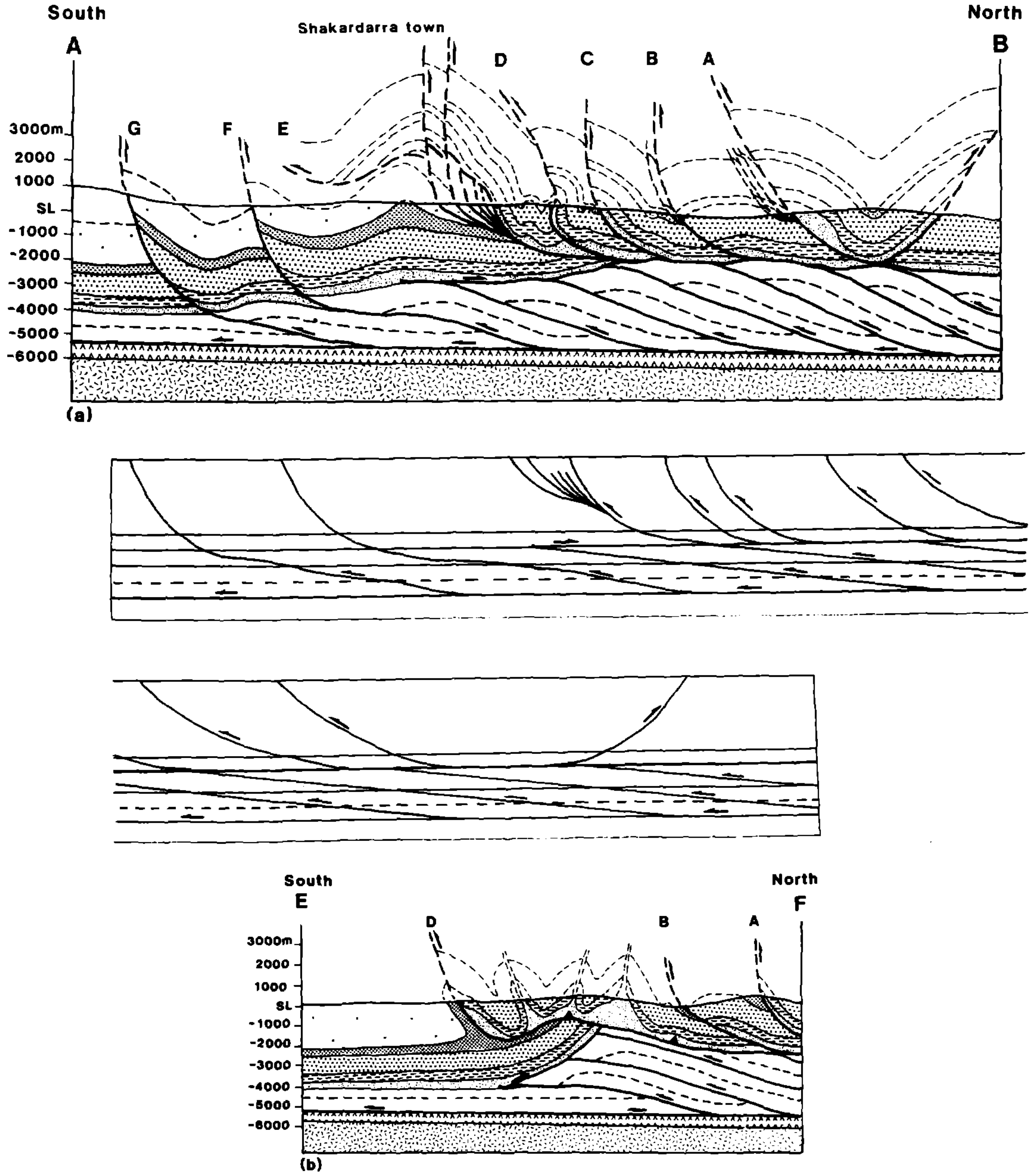

Fig. 7. (a)–(b). *(Continued overleaf)*

thrust sheet which moved coherently (seismic profiles in Lillie *et al.* 1987). This contrasts with the Kohat allochthon which is much more heavily faulted and has a correspondingly narrow outcrop width and higher structural relief.

The causes of this differing kinematic behaviour are suggested to relate to differing mechanical behaviour of the two deforming orogenic wedges. The eastern Potwar is deformed both by foreland and hinterland directed thrusts (Johnson *et al.* 1986, Pennock *et al.* 1989). The basal detachment is along the Eocambrian Salt. The critical taper of the thrust wedge is <1°, estimated to be only 0.8° by Jaume & Lillie (1988). Due to this low critical taper, the thrust wedge had to deform internally to create sufficient topographic slope to assist basal sliding. The western Potwar, in contrast, was shown to have been a super-critically tapered wedge ($\alpha + \beta$ larger than necessary for thrust wedge to propagate without any internal deformation) during thrusting (Lillie *et al.* 1987, Jaume & Lillie 1988).

The gravity map (fig. 2 of Farah *et al.* 1977) shows an abrupt negative anomaly (at 32°45′–33°0′ and 71°45′) whose eastern margin lies below the Kalabagh lateral ramp. The map shows that the basement to the west of the Kalabagh re-entrant is downdropped at least 2 km (Leathers 1987) with respect to the western Potwar. The basal detachment is subsequently deeper to the west, beneath the Kohat Plateau, and is overlain by a thick cover carapace. This suggests, firstly, a greater effective normal stress on the basal detachment, and hence a greater resistance to sliding. This would tend to favour increased internal deformation of the overlying wedge compared to the thinner wedge of the Potwar.

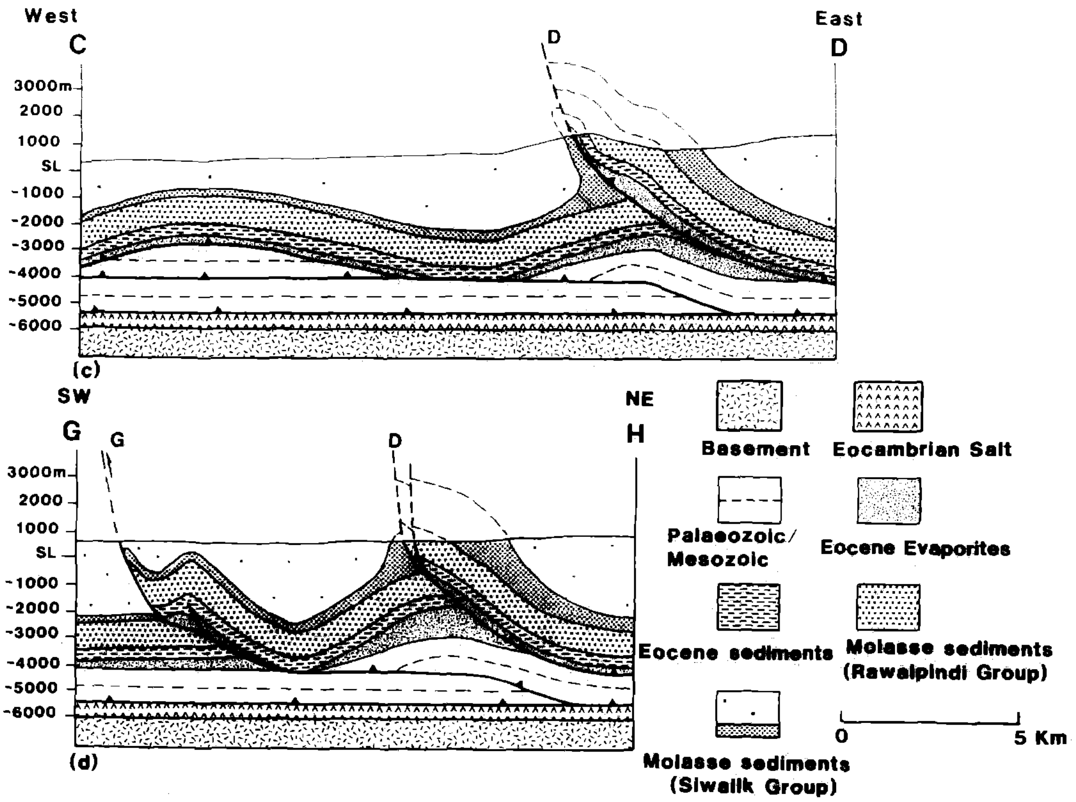

Fig. 7. *(Continued)* Cross-sections through the Kohat Plateau, based on detailed surface data and measured thicknesses. For location of all sections see Fig. 6. V = H throughout. (a) N–S section showing a blind duplex structure between the MBT and Shakardarra area. The roof sequence to the duplex is heavily deformed along a back thrust which is dissected by a number of foreland verging imbricate thrusts. South of Shakardarra, the deformation is mainly along the floor thrust. (b) Salt tectonics (at Eocene evaporite level) disrupt the upper thrust plate in the eastern part of the study area. (c) Blind culmination of the Mesozoic–Palaeozoic rocks below shakardarra area generates structural relief in the footwall to the Hukni lateral ramp. Movement sense, out of the page (thrust D shows strike-slip at surface). (d) Displacement of a blind hanging wall lateral ramp anticline at the level of the Mesozoic–Palaeozoic sequence accommodated at the surface by a second ramp anticline out in the molasse succession.

Secondly, the contours of the gravity map are less closely spaced beneath the Kohat than beneath the Potwar. If these contours do reflect the geometry of the basement–cover contact, a lower dip (β) of the basal detachment is implied under the Kohat Plateau, as compared to the western and central Potwar Plateau which was estimated between 1 and 4° (Lillie *et al.* 1987, Jaume & Lillie 1988). Internal shortening in the Kohat Plateau is thus mechanically likely during deformation in order to build a sufficient topographic slope (α) for slip (Davis *et al.* 1983). Absolute values for α and β are not possible to measure due to lack of subsurface data.

A comparatively higher (1–4°) dip of the basal detachment (β) in the central and western Potwar is probably due to the topographic slope of the Sargodha–Delhi High, an uplifted basement ridge beneath the foreland basin formed by flexure of the Indian Craton during the continent–continent collision. The Sargodha–Delhi High is a NW–SE-trending ridge which has a variable slope. Its higher slope proximal to the central and western Salt Ranges provided the necessary critical taper to the overlying wedge to propagate without much internal deformation, whereas the lower slope in front of the eastern Salt Range and the Surghar Range resulted in a low-angle basal detachment, and subsequently higher internal deformation of the overlying wedge. The narrow width of the Kohat Plateau as compared to the Potwar Plateau is thus a kinematic response to differing mechanical conditions imposed by the varying geometry of the two deforming wedges (Davies *et al.* 1983), as suggested for the Eastern Salt Range (Jaume & Lillie 1988).

CONCLUSIONS

(1) Kohat has a distinct passive roof duplex geometry, formed of thrust slices of pre-Tertiary stratigraphy. This is overlain by a high-level thin-skinned imbricate system within the Eocene evaporite formations. This contrasts with the single thrust sheet characteristic of the Potwar Plateau.

(2) The Hukni lateral ramp overlies the branch point between the two levels of detachment of the Kohat and the single basal level underneath the Potwar.

(3) The amount of shortening (55 ± 5 km in the Kohat and 65 ± 5 in the Potwar) across both portions of the compartmentalized thrust belt is similar, despite the distinct geometries. Kinematic compatibility across the Hukni lateral ramp results from the greater elevation of a narrower thrust wedge to the west (Kohat Plateau), and a wider thrust belt of lower structural relief to the east.

Acknowledgements—We are very grateful to many individuals who have helped in completing this paper, especially Drs Peter Friend and Nigel Woodcock from Cambridge University. Dr R. W. H. Butler of the Open University and Chris Izatt from Imperial College are thanked for their helpful and open discussion about the geology of the Salt Range and Potwar area. Rod Graham of British Petroleum is thanked for showing us some of his unpublished seismic data. Discussions with Bob Lillie from Oregon University, U.S.A., greatly improved the manuscript. Iftikhar Ahmed Abbasi acknowledges receipt of a grant from the Government of Pakistan and the Cambridge Commonwealth Trust, and Ronan McElroy is grateful for a N.E.R.C. studentship.

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