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Thrust geometries and evolution of the eastern North Potwar Deformed Zone, Pakistan

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ABSTRACT: *The North Potwar Deformed Zone is part of the active Himalayan foreland fold-and-thrust belt in northern Pakistan. Field work have been carried out mostly along a profile in the eastern North Potwar Deformed Zone, to gain an insight into this complexly deformed area of hydrocarbons interest. The results show a triangle zone geometry and a set of imbricates between the Soan Syncline and the Main Boundary Thrust. The preserved triangle zone below the Soan Syncline is characterized by a floor thrust located at depth of 6 km in the Eocambrian evaporites. The floor thrust propagates upsection and merges in a roof thrust at depth of about 3 km in the Rawalpindi Group strata. The roof thrust has a hinterland vergence similar to backthrusts of the triangle zones in other fold-and-thrust belts. Integration of structural and timing data for consideration of kinematics suggests that thrust imbricate north of the preserved triangle zone is exposed due to increasing uplift and erosion of a duplex.*

A structural cross-section indicates that approximately 42 km of shortening has occurred across the NPDZ. The rate of shortening is 16 mm/yr considering deformation that has occurred between 4.5–1.9 Ma in the North Potwar Deformed Zone.

INTRODUCTION

The Himalaya, the world's youngest and highest orogenic belt is evolution due to continent-continent collision. This collision between Indian and Eurasian plates occurred during the Eocene time along the Indus Suture Zone (Molnar & Tapponier, 1975). Subsequently, thrusting shifted southward, along the Main Central Thrust and the Main Boundary Thrust (MBT), respectively. South of the MBT, the Salt Range/Potwar Plateau (SR/PP) represent the Himalayan foreland fold-and-thrust belt in Pakistan (Fig. 1).

The SR/PP manifests itself as a broad (about 100 km) thrust sheet that is relatively undeformed towards foreland (Lillie et al., 1987; Baker et al., 1988) and is strongly deformed towards hinterland in the footwall of the MBT (Jaswal, 1990; Kemal, 1991). The northern part called as the North Potwar Deformed Zone (NPDZ) is pro-

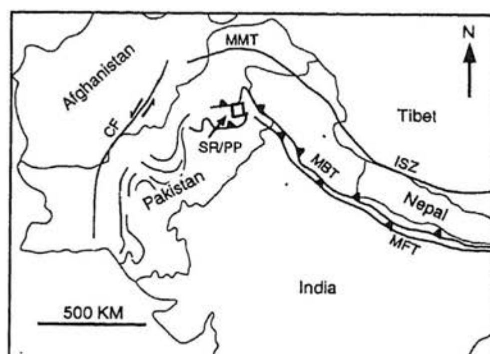

Fig. 1. A simplified tectonic map of the Himalayas. Box shows the location of Figure 2. Abbreviations: ISZ = Indus Suture Zone, MBT = Main Boundary Thrust, MFT = Main Frontal Thrust, MKT = Main Karakoram Thrust.

ducing moderate amount of hydrocarbons (Khan et al., 1986; Raza et al., 1989). It is critical to resolve the structural geometry of this region for successful drilling and an insight into the evolution of the NPDZ. This article provides a preliminary report on geology of the eastern NPDZ adjacent to the Dhurnal oil field (Fig. 2).

TECTONIC SETTING

Indus suture zone between Indian and Eurasian plates is divided into the Main Karakoram Thrust (MKT) and the Main Mantle Thrust (MMT) in Pakistan (Tahirkheli et al., 1979). These faults bound the Ladakh and Kohistan Arc terranes which were sandwitched between Eurasian and

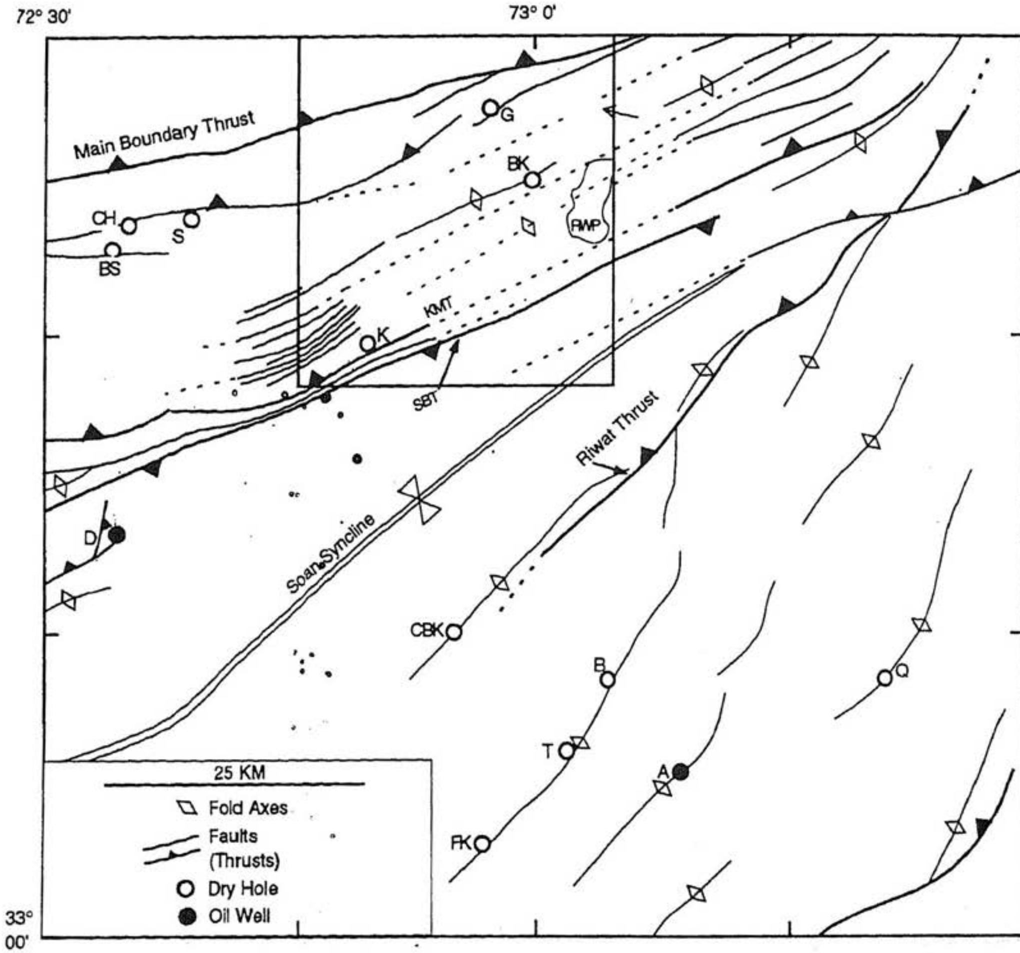

Fig. 2. Structural map of the eastern NPDZ modified from Pennock et al. (1989), Jaswal (1990), unpublished maps of the Geological Survey of Pakistan, Oil and Gas Development Corporation of Pakistan (1:2,50,000) and Pakistan Petroleum Limited (1:50,000). Box shows the location of Figure 3. Faults: KMT = Khairi-Murat Thrust, SBT = Soan Backthrust. Wells: A = Adhi, B = Bains, BK = Bokra, BS = Basal, CBK = Chak Beli Khan, CH = Chirrat, D = Dhurnal, FK = Fim Kasar, G = Golra, K = Khairi Murat, Q = Qazian, S = Sadkal, T = Tanwin, RWP = Rawalpindi.

Indian plates to the north and south, respectively. In northern Pakistan, the Himalayas have four major tectonic subdivisions (Yeats & Lawrence, 1984). These, from north to south, are the Karakoram Ranges and Hindu Kush Ranges of Gondwana affinity sutured to Eurasia (the Turan Block) in Late Triassic to the middle Jurassic time (Sengor, 1979). The Kohistan Island Arc located between the MKT and the MMT was docked with Eurasia in late Cretaceous to early Eocene time (Jan & Asif, 1981; Tahirkheli, 1982; Pudsey, 1986; Searle et al., 1987; Treloare et al., 1989). The low ranges of Swat, Hazara and Kashmir in Pakistan located between the MMT and the MBT represent the marginal foreland fold-and-thrust belt in Pakistan equivalent to the sub-Himalaya in India. Zeitler et al. (1982) suggested that the MMT locked approximately 15 Ma, subsequent to rapid uplift north of the fault between 30 and 15 Ma (Zeitler et al., 1980). Following the cessation of movement along the MMT, deformation propagated southward to the MBT. Along MBT unmetamorphosed Mesozoic and Lower Tertiary rocks are thrust over Neogene molasse strata.

The Neogene molasse strata in the footwall of the MBT can be divided into two age groups based on its outcrop pattern. Middle to upper Miocene Rawalpindi Group strata is mostly exposed in the NPDZ north of the Soan Syncline. Middle Miocene to Quaternary strata is exposed south of the Soan Syncline (Figs. 2, 3). Thickness of molasse strata is about 5 km below the Soan Syncline (Lillie et al., 1987; Baker et al., 1988). However, mostly Rawalpindi group strata of moderate to steep dips is exposed in a wide zone of over 20 km north of the Soan Syncline (Fig. 3). Apparently this strata is repeated involving platform strata but not involving Siwaliks. How is outcrop pattern controlled by tectonics and sedimentation? The problem is considered in this article as an effort to resolve the structure of the NPDZ. The SR/PP south of the MBT represents broad Himalayan foreland in northern Pakistan. Yeats et al. (1984) observe that the Siwalik strata of Upper Miocene to Pleistocene age is fully involved in deformation in the Salt Range. The Salt Range constitutes a narrow zone of localized strong folding, faulting and uplift at the mountain front in contrast to the thrust imbricates of the Potwar Plateau. The two structural domains are separated by the asymmetrical Soan Syncline, the south limb of which is much gentler than the north limb. Complex deformation of the North Potwar is discussed in this article.

STRATIGRAPHY

A stratigraphic column based mostly on lithological log in Dhurnal oil field is shown in Figure 4. The Rawalpindi and Siwalik Group strata have variable thicknesses from one to the other location (Jaswal, 1990; Pennock et al., 1989). The rationale for thickness calculations is to have a better idea about the estimated stratigraphic thickness for extrapolation of stratigraphy during construction of geological cross-sections. The oldest formation known to lie on top of the basement is the Eocambrian Salt Range Formation. The overlying Paleozoic to Eocene strata is about 1051 m thick. In Dhurnal the base of this sequence is marked by pelitic to arenaceous Paleozoic Tobra, Dandot, Warchha, Sardhai and Amb Formations. This group is disconformably overlain by pelitic to calcareous strata of Jurassic to Eocene age. The upper part of stratigraphic section in the vicinity of Soan syncline comprises the Miocene Rawalpindi Group (~ 2106 m thick) and the Upper Miocene-Pleistocene Siwalik Group (~ 2881 m thick). The Rawalpindi Group consists of Murree and Kamlial formations of dominantly pelitic and arenaceous strata of the Chinji, Nagri, Dhok Pathan and Soan formations (Fig. 4). The Siwalik have been deposited during the last 13 Ma (Johnson et al.,

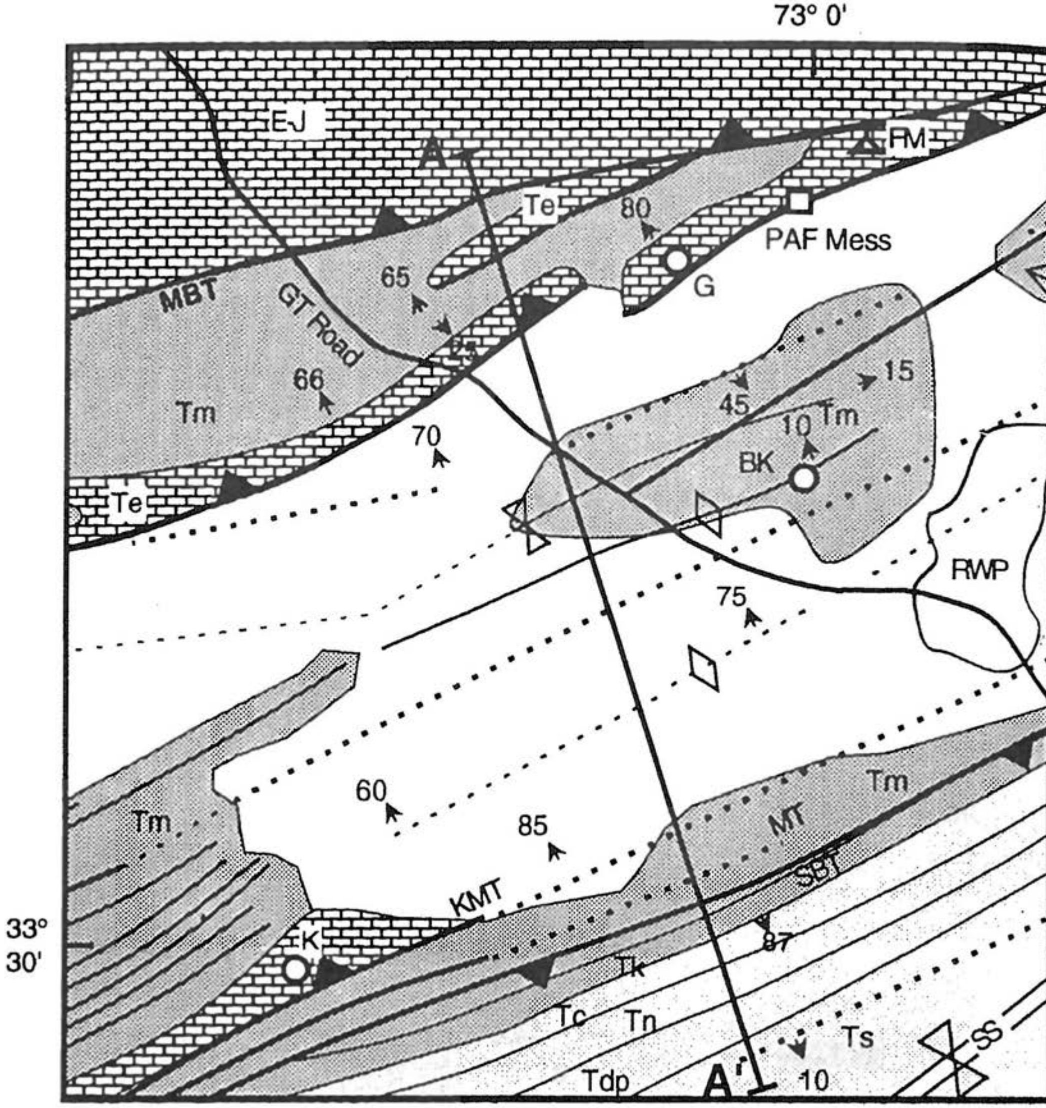

Fig. 3. Geological map of the eastern NPDZ. AA' locates the structural cross-section shown in Figure 7. Structures: KMT = Khairi-Murat Thrust, MBT = Main Boundary Thrust, MT = Murat Thrust, SBT = Soan Backthrust, SS = Soan Syncline. Strata from younger to older: Ts = Soan Formation, Tdp = Dhok Pathan Formation, Tn = Nagri Formation, Tc = Chinji Formation, Tk = Kamlial Formation, Tm = Murree Formation, Te = Eocene, E-J = Eocene to Jurassic. Wells: BK = Bokra, G = Golra, K = Khairi Murat, FM = Faisal Mosque, RWP = Rawalpindi. Arrows with numbers show dip of beddings. Other structures are similar as shown in Figure 2.

1979, 1982). Top of the Murree Formation is dated at 17 Ma. These strata are non-marine time transgressive molassic facies that represent the erosional products of southward advancing Himalayan thrust front. Johnson et al. (1979) suggest that the fluvial and fluvio-deltaic Rawalpindi

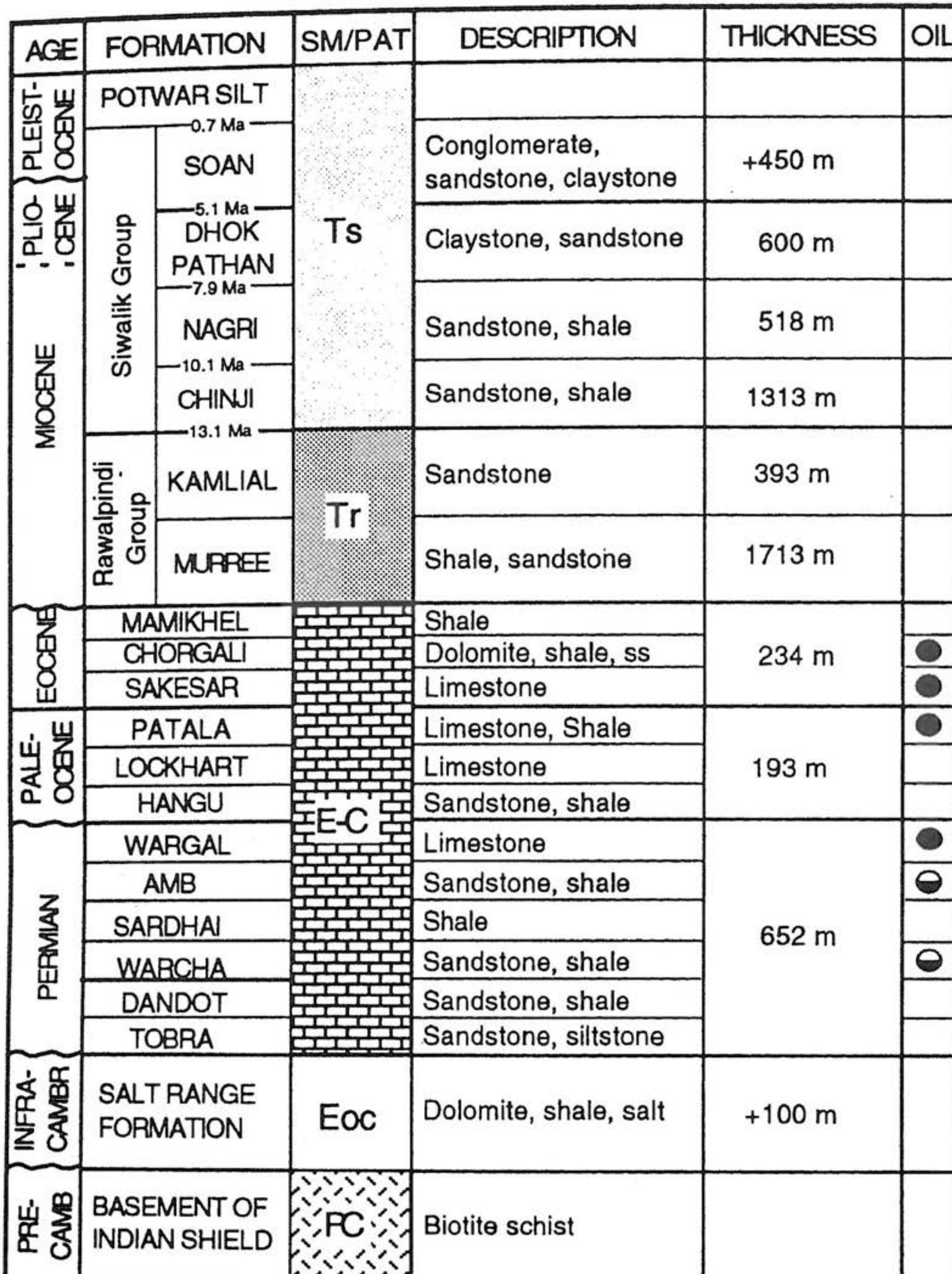

Fig. 4. Stratigraphic column of the NPDZ based on Dhurnal–3 well (after Kamran & Rake, 1987; Jaswal, 1990; Ahmed et al., 1993). Age dating of Siwaliks is based on chronostratigraphy (Johnson et al., 1979; 1982).

Group strata indicate the initiation of significant Himalayan uplift. The Siwalik Group records continued uplift of the Himalayas. However, where lower Siwalik strata are derived from the crystalline and metamorphic terrains of the Higher Himalaya; upper Siwalik strata consists of recycled Lower and Middle Siwalik debris due to continuous southward migration of the deformation front (Keller et al., 1977; Acid et al., 1983). Magnetostrati-graphy combined with sedimentation and tectonics provides useful details of dynamic processes in the Himalayan foreland of Pakistan (Raynolds & Johnson, 1985; Johnson et al., 1986; Burbank & Raynolds, 1988).

STRUCTURE

A structural map of the study area is shown in Figure 3. This is modified from unpublished maps of the Geological Survey of Pakistan, Oil and Gas Development Corporation of Pakistan (1:2,50,000) and of Pakistan Petroleum Limited (1:50,000). In the study area, the Murree Formation is predominantly exposed with sporadic outcrops of the Eocene along faults (Khairi Murat, Golra in Figs. 2 & 3). The general trend of bedding and faults is ENE and WSW. Upper Miocene to Quaternary Siwalik strata is exposed to the south along the Soan Syncline (Fig. 3). North of the Soan Syncline, mostly Rawalpindi Group strata is exposed. Either Siwalik Group was not deposited that far north or have been removed by erosion during deformation and uplift of the NPDZ. The main structures of the eastern NPDZ are briefly described below for simplification and future qualitative work along each structure. These from south to north are as follows:

A) Soan Syncline: The Soan Syncline with a half wavelength of about 20 km is a major structural feature of the SR/PP. It separates moderately deformed strata to the south from highly deformed strata to the north (Fig. 2). The northern limb of the syncline is much steeper than the southern limb. Along northern limb, Siwalik strata i.e., Chinji, Nagri, Dhok Pathan and Soan Formations with increasing degree of dip towards north are exposed. Chronostratigraphy provides tight age constraints on the development of the Soan Syncline (Raynolds, 1980; Burbank and Raynolds, 1984; Raynolds & Johnson, 1985; Johnson et al., 1986). Sequential development of the Soan Syncline is illustrated in Fig. 5 (Jadoon & Frisch, 1995). It shows that the southern limb of the Soan Syncline was formed prior to the northern limb; thus, the development of the Soan syncline records an out-of-sequence event. The development of the southern limb is related to the Riwat thrust that was active between 3.4-2.7 Ma. Magnetostratigraphic control shows that the pre 3.4 Ma strata is tilted and deformed due to uplift along the Riwat thrust. The uplift is manifested by the non-deposition marked by 0.7 Ma interval unconformity along southern limb of the Riwat thrust (Burbank & Beck, 1991). The deposition continued after 2.7 Ma. The strata over the unconformity remains generally flat which suggests the cessation of movement along the Riwat thrust. Subsequently, northern limb of the Soan Syncline was deformed. Along the northern limb, nearly vertical strata of Siwalik molasse sediments are truncated and overlain by generally undeformed Lei Conglomerate (Fig. 5). The youngest preserved Siwalik strata is dated at about 2.1 Ma. The base of the overlying Lei Conglomerate is interpreted as 1.9 Ma (Burbank and Raynolds, 1984), supported by a 1.6 ± 0.2 Ma date of an ash bed in the Lei Conglomerate (Johnson et al., 1982). Thus, the Soan Syncline was evolved between 3.4 to 1.9 Ma in the eastern NPDZ.

B) Soan Backthrust: In thin-skinned tectonics, fold-and-faults are related to each other. Faults are not always a planar structure. Bending of a fault results into flats and ramps. Flats being

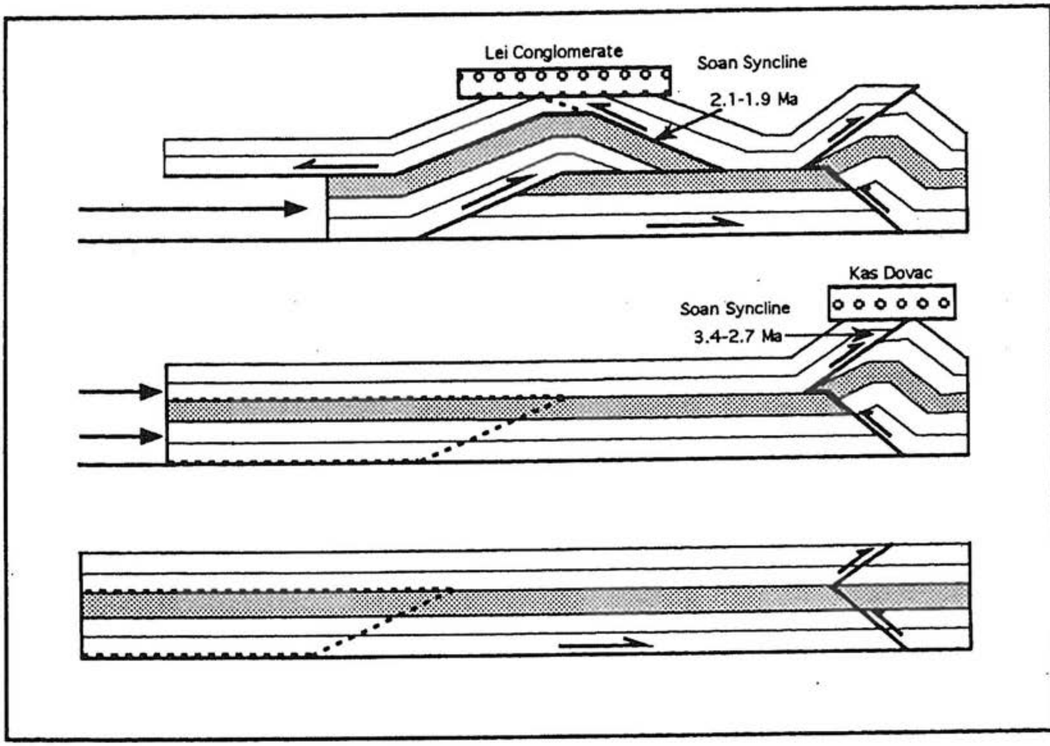

Fig. 5. Sequential evolution of the Soan Syncline (from Jadoon & Frisch, 1995). Timing constrains are based on magnetostratigraphy by Raynolds (1980), Raynolds and Johnson (1985) and Johnson et al. (1986).

a part where a fault is parallel to a stratigraphic horizon and ramps where the fault cuts across the stratigraphic horizon at a high angle. The movement along a fault may result in bending of hanging wall over the footwall to produce fault-bend (Suppe, 1983), fault-propagation folds (Suppe & Medwedeff, 1984; Suppe & Shaw, 1994), and thrust imbricates (Figs. 6, 7). In other cases, bedding of hanging wall strata between a lower and an upper detachment results in duplex structures. In duplex geometry, strata above and below an upper detachment may be called as roof and duplex sequence, respectively.

The roof sequence may propagate towards the foreland or the hinterland (Fig. 7). When roof sequence propagates passively towards the hinterland compared to the underlying duplexes, the resultant geometry is called as a passive-roof duplex (Banks & Warburton, 1986). In a passive-roof duplex, the roof sequence remains passive with respect to the underlying duplex. In this case, shortening in the roof sequence may be accommodated along a set of passive-backthrusts. The passive-backthrusts ideally evolve from the tip of each duplex in order to accommodate comparable shortening that occurs due to movement of duplex horses. Thus, evolution of a passive-backthrust involves tilting and final emergence of the roof sequence over the duplexes (Fig. 6, 7Dii). Such a similar fault has evolved below the northern limb of the Soan Syncline, herein called as the Soan-backthrust (Figs. 2, 3).

The Soan-backthrust is one prominent feature of the eastern NPDZ (Fig. 2). Along this

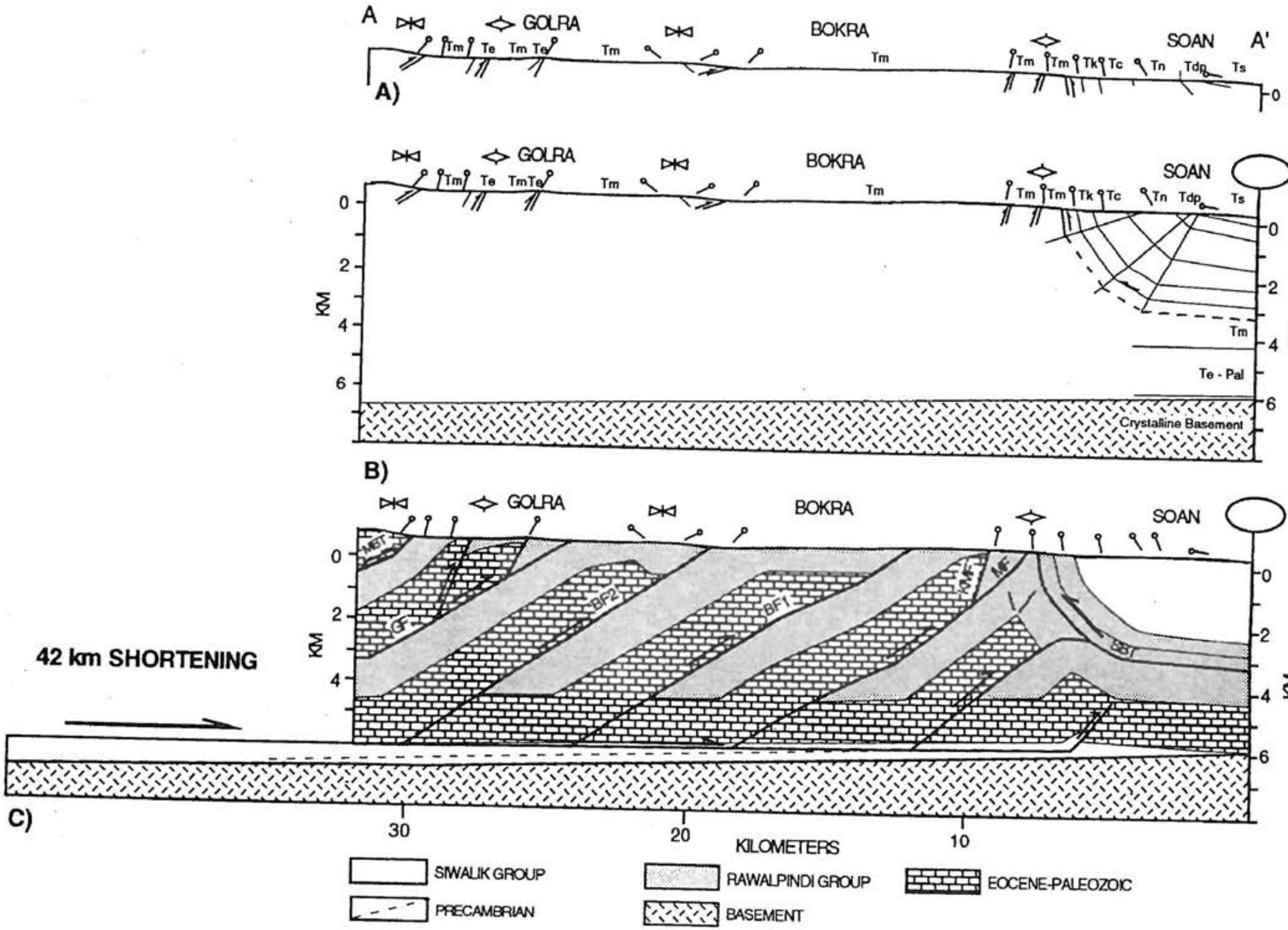

Fig. 6. Step-wise construction of cross-section AA' shown in Figure 3. The cross-section shows thin-skinned features of the eastern NPDZ with a triangle zone geometry and imbricates. Some imbricates show breakback thrusting. 42 km of shortening is estimated along the section. Text for discussion.

structure, surface dips vary drastically from near horizontal along axis of the Soan Syncline to vertical near the passive-backthrust. The backthrust is located near the top of the Rawalpindi Group strata and involves 90° of rotation and uplift of about 3 km (Jaswal, 1990; Raynolds & Johnson, 1985). As deformation along the northern limb of the Soan Syncline occurred between 2.1 to 1.9 Ma, uplift rates of about 15 mm/yr can be calculated.

C) Khairi-Murat and Golra Imbricate Zone: The Khairi Murat and Golra set of south-vergent imbricates are dominant structures between the Soan Syncline and the MBT (Figs. 2, 3). They are named after the Khairi Murat Range and the Golra village. Generally lower to middle Miocene Murree Formation (molasse) of erratic trends is exposed in this zone of over 20 km across strike. However, along Khairi Murat and Golra thrust linear outcrop of Eocene strata are extensively exposed. The dips are moderate to vertical and even overturned. Thus, substantial repetition of strata can be envisaged. Presently low relief of the area suggests cessation of activity and substantial erosion. Deposition of almost horizontal Lei Conglomerate represents end of the tectonic activity. The base of the Lei Conglomerate is dated at 1.9 Ma (Raynolds, 1980). Since then, erosion and resultant thick cover of alluvium concealed outcrops, particularly in synclinal areas and footwall of the faults. However, faults can be traced laterally based on structural trends, along strike ridges, stratigraphy, and steps in topography. Gouge, calcite veins, fault breccia, steps in relief, and springs are typically related to the faults. Established faults can be traced laterally in Islamabad due to steps in roads i.e., Golra fault south of the Faisal Mosque (Fig. 3). The surface exposure of the Khairi Murat Fault is prominent due to thrusting of the Eocene (Chorgali) strata over the Murrees. Similar structural and stratigraphic relationship is observed to the west along the Khairi Murat Fault (Jaswal, 1990).

North of the Khairi Murat Fault, an extensive exposure of Murree Formation is exposed along the Kashmir Highway (Islamabad). The structure here is of a broad Bokra syncline (Fig. 3). Along the axis of the syncline shallow dips upto 15° are encountered. A dry hole was drilled to a depth of 1939 m on the adjacent Bokra anticline (Kamran & Ranki, 1987). Bokra anticline and syncline allow to locate a ramp and a flat of a thrust sheet. Towards SW in the Khairi Murat ranges, moderate to steep dipping Murree Formation (Fig. 3) is mapped to be imbricated (Jaswal, 1990). This set of imbricates may represent small bedding-parallel slip and related splays.

The south-vergent Golra fault merges into the MBT towards NE (Fig. 3). Along this fault Eocene strata is exposed on the hanging wall of the fault. Fault is very well exposed near the Pakistan Air Force Mess (PAF) in Islamabad and along Grand Trunk Road. In Islamabad, PAF Mess is constructed over the fault escarpment and the Pleistocene conglomerate. The fault can be traced laterally, by the emplacement of Eocene strata against Murree strata/alluvium and the features described above. Hanging wall strata records moderate to steep dips between 65° to 80°. North of the Golra fault, another south-verging fault, herein called as Shah Allah Ditta juxtaposes Eocene and Miocene strata.

Both Golra and Shah Allah Ditta faults are splays of the MBT. They merge eastwards in the latter. The Margalla Hill Range with Mesozoic and Lower Tertiary strata is located along the hanging wall of the MBT. In the study area, the MBT may consist of several relatively smaller faults at concurrent positions instead of being a

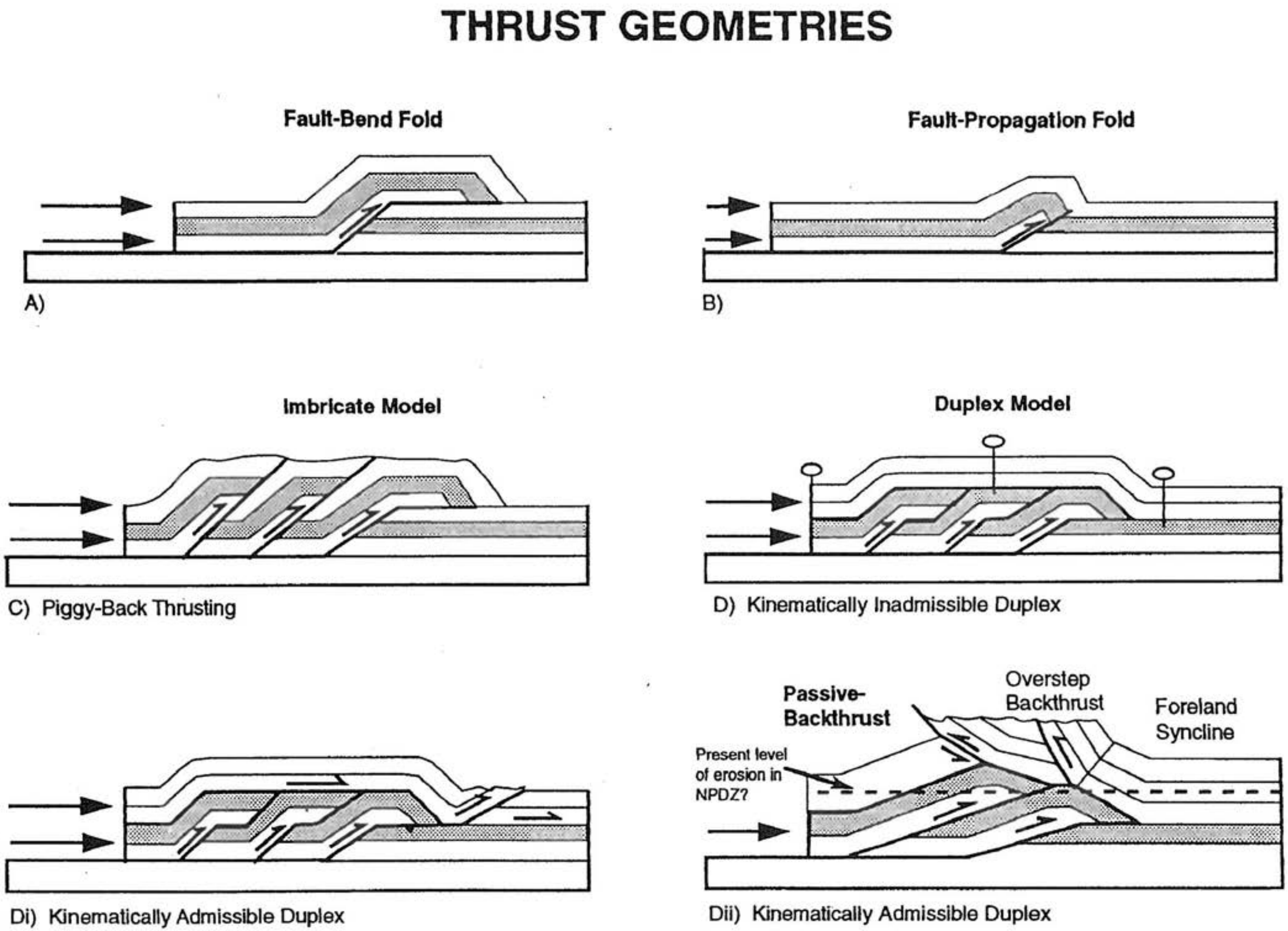

Fig. 7. Fold-and-thrust geometries applicable to eastern NPDZ. Text for discussion.

single continuous fault. This hypothesis can be tested in future.

CONSTRUCTION OF STRUCTURAL CROSS-SECTION

A representative structural cross-section has been constructed using concepts of balanced sections (Dahlstrom, 1969; Woodwards et al., 1989; Jadoon, 1992) according to the following steps:

Assembly and projection of basic data
The data discussed above was projected on the profile AA' in Figure 6. The profile is selected parallel to the direction of tectonic transport for its usefulness to reflect a true picture of subsurface structural geometry and calculation of shortening. Generally, direction of tectonic transport remains perpendicular to bedding, fold axes, and cleavages. Subsequently stratigraphy, fold axes, faults, and dips were projected on the profile in Figure 6A.

Basement depth and sedimentary thicknesses
After projection of basic data, it was important to locate basement with consideration of the main decollement and any deformation above. Besides, thickness of sedimentary strata was critical for structural geometry and balancing purpose. Basement was located on the profile at depth of about 6 km along the axis of the Soan Syncline and at about 7 km along the MBT (Fig. 6B) based on seismic reflection data (Pennock et al., 1989; Jaswal, 1990). The 1° dip of basement towards north is based on reflection interpretations (Lillie et al., 1987). Plot of the basement provided a space, above, for extrapolation and interpolation of structures and stratigraphy. Figure 4 based on Dhurnal-3 well provides details of Precambrian to Neogene strata. About 1 km of Eocene to Paleozoic platform and 3776 m of molasse strata was encountered in the Dhurnal well. Paleozoic to Eocene platform strata does not show much variation in thicknesses in the SR/PP (Lillie et al., 1987; Baker, et al., 1988; Pennock et al., 1989).

Following basement, an important step was to locate the main decollement. The decollement is well established in the Eocambrian evaporites throughout the Salt Range (Lillie et al., 1987; Pennock et al., 1989). It remains in the same horizon in the eastern NPDZ (Jaswal, 1990).

Hereon, structures were interpolated and extrapolated using geometrical techniques of balanced cross-sections. Line-length balancing and kink method is used for the construction of cross-section AA' in Figure 6. The resultant cross-section shows thin-skinned features related to the Himalayan collision in eastern NPDZ.

INTERPRETATION

Structural style
Figure 6C shows some details of the complex structural geometry in the NPDZ. During present stage of evolution, most prominent structure between the Soan Syncline and the MBT is a triangle zone and a set of imbricates. A triangle zone is formed by wedging of competent strata between a floor and a roof thrust. The roof thrusts in a triangle zone generally show hinterland vergence (Jones, 1982; Price, 1986) and are termed as passive-backthrusts (Banks & Warburton, 1986). As prograde deformation occurs from hinterland toward foreland, the most proximal thrust located hinterland side of the backthrust reaches the erosional surface in the regular triangle zones (Fig. 8). Such a similar structural geometry is interpreted below the northern limb of the Soan Syncline in eastern NPDZ. The basal decollement (floor thrust) and the Soan backthrust (roof thrust) represent the two faults that bound a wedge of Rawalpindi and older strata below the northern limb of the Soan Syncline (Fig. 6).

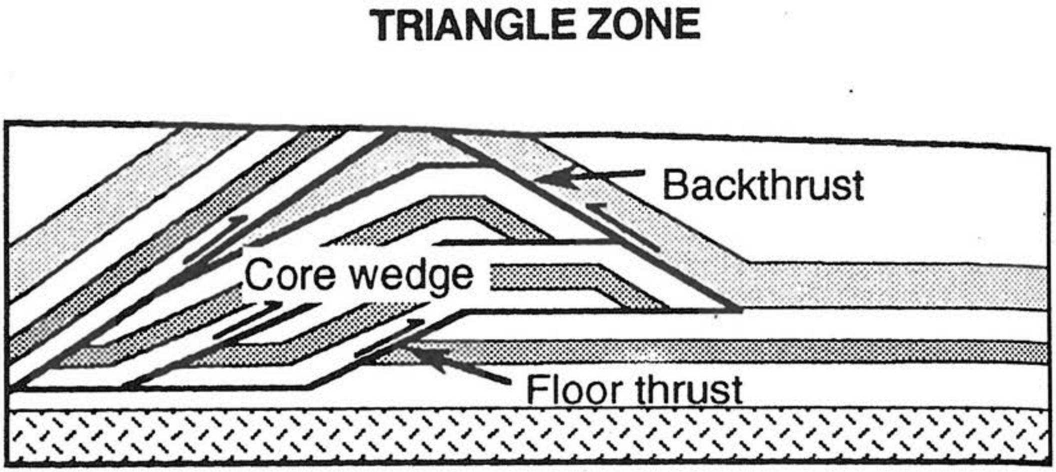

Fig. 8. Model of a triangle zone geometry with a core wedge bounded between a floor and a roof (back) thrust.

Khairi Murat/Murat faults represent the proximal thrusts located hinterland side of the backthrust. This interpretation is consistent with seismic reflection observations in the Dhurnal oil field (Jaswal, 1990).

Figure 6 predicts the presence of a fault-bend and a fault-propagation fold in the triangle zone. Along the fault-bend fold the floor thrust makes a ramp across the competent platform and Rawalpindi Group strata and merges in the roof thrust at a depth of about 3 km. About 2.3 km of displacement along the duplex and the overlying accommodating fault resulted in about 90° clockwise rotation of the roof sequence, exposing the passive-backthrust. The fault-propagation fold shows a slip of about 200 m and an amplitude of 300–400 m. The propagating fault dies out in the core of the fold. So, it does not merge in the roof thrust. To the west, a similar structure, the Dhurnal pop-up (Fig. 2) is producing hydrocarbons (Jaswal, 1990; Kemal, 1991; Ahmed et al., 1993).

The cross-section AA' (Fig. 6) shows that the fault-propagation fold under the northern edge of the Soan Syncline is a salt cored anticline, recognized as a pop-up within the triangle zone (Jaswal, 1990; Kemal, 1991). The triangle zones have been reported in the frontal portions of the Sulaiman and Kirthar ranges of Pakistan (Banks & Warburton, 1986; Humayon et al., 1991; Jadoon et al., 1992), the eastern Rocky Mountain foothills of Canada (Price, 1981; Jones, 1982; Price, 1986) and Magallenes Foreland Fold-and-Thrust Belt, Southern Chile (Alvarez-Marron et al., 1993), and seems to be major structures of the mountain fronts.

North of the triangle zone, Figure 6 predicts the presence of a set of imbricates (during present stage of evolution) which splays off from the basal decollement. Present structural geometry is of piggy-back thrusting. Each splay involves a displacement of about 6 to 10 m. Of these, Khairi Murat and Golra show further imbrication near their tips. The secondary splays merge in the main thrust at depth of about 2 km. It is probable, that Murat is the main thrust whereas Khairi Murat represents a splay suggesting breakback thrusting along the Khairi Murat and the Golra faults. This is consistent with observation of Dahlstrom (1970) from the Canadian Rockies. He suggests that imbrication near the surface may produce a breakback sequence unlike a breakforward sequence at depth. However, Jones (1987) consider that the hanging or footwall imbricates (terminology after Butler, 1982) can develop in any order depending upon when major fault of the sequence has developed.

Thrust geometries and kinematics

The structural cross-section AA' (Fig. 6C) reflects some characteristic features of the foreland fold-and-thrust belts. It shows deformation in the sedimentary strata above the decollement. Deformation in the sedimentary strata is dominated by a set of imbricate fan with thrust sheets consisting of platform and Rawalpindi Group (Murrees) strata. Siwalik strata is not observed in the thrust sheets. It is critical to differentiate if Siwalik strata was not deposited at the time of thrusting in the NPDZ (Fig. 7C) or if thrusting occurred as duplexes below the Siwalik strata (Fig. 7D). Chronostratigraphic control on the Siwalik strata is available (Johnson et al., 1979; Johnson et al., 1982) that constraints deposition of the Siwaliks (Chinji, Nagri, Dhok Pathan) between 13.1-5.1 Ma (Fig. 4). Thus, an imbricate model would suggest that deformation in the NPDZ has occurred prior to the 13.1 Ma. However, as Siwalik strata is not involved in the imbrication and as much of deformation in the eastern Potwar Plateau may have occurred after 4.5 Ma (Johnson et al., 1986) with major movement along MBT at 1.8 Ma (Burbank & Raynolds, 1988); it is most likely that deformation in the North Potwar has occurred after deposition of the Siwalik strata. This would suggest a duplex style of deformation between a floor and a roof thrust according to a duplex model (Fig. 7D). In this model, roof thrust can be located in the Rawalpindi Group strata. Thus, absence of the Siwalik strata in the NPDZ may be related to the thrust geometries.

The duplex geometry in Figure 7D presents an inadmissible section because it does not show similar length of the stratigraphic horizons below and above the roof thrust. Figure 7Di shows as admissible geometry by introducing an emergent fault in the roof sequence similar to as suggested by Treloar et al. (1992). Baig (1995) presents a similar solution considering Riwat thrust (Fig. 2) as the emergent thrust. However, Jadoon and Frisch (1995) demonstrate that the Riwat thrust is genetically related to a hinterland-vergent tectonic wedge (Fig. 5). Moreover, the Riwat thrust with a displacement of about 5 km cannot accommodate shortening of duplexes in the Figures 6 and 7Di. Alternately the roof thrust must show a passive northwards translation (Fig. 7Dii) similar to a passive-backthrust of a triangle zone (Gordy, 1977; Jones, 1982) or a passive-roof duplex geometry (Banks & Warburton, 1986). The triangle zone geometry is being increasingly recognized as the foreland structure of the several fold-and-thrust belts such as the Canadian Rockies (Jones, 1982; Price, 1986; Lawton et al., 1994); the Andies (Ramos, 1989); the Carpathians (Jones, 1982) and the Sulaiman lobe of Pakistan (Humayon et al., 1991; Jadoon et al., 1992; 1994). The backthrusts in the passive-roof duplex may accommodate comparable shortening in the roof-sequence. This interpretation is consistent with the presence of a extensive passive-backthrust along northern limb of the Soan Syncline (Jaswal, 1990; Jamshed, 1995; Baig, 1995). Backthrusting is also shown in some preliminary sections across the Kala Chitta Range towards west (Qureshi et al., 1994).

The presence of basal decollement and termination of faults in the decollement is a regular features in thin-skinned deformation of fold-and-thrust belts (Chapple, 1978; Jones, 1987). The NPDZ has a floor and a roof thrust in the Eocambrian Salt Range Formation and Rawalpindi Group strata respectively. Multiple faults bounded between the floor and roof thrust has stacked a hinterland dipping duplex. During NPDZ evolution, the roof sequence of Siwalik strata has been uplifted and eroded, probably along multiple backthrusts similar to the Soan-backthrust (Figs. 2, 3). Figure 7Dii shows the possible structural geometry before and after erosion of the roof sequence in the NPDZ.

Shortening, timing and rate of deformation

Balancing of Figure 6 shows about 42 km horizontal contraction between the Soan Syncline and the MBT. The total minimum shortening calculated near Indus River (western Potwar) is over 40 km (McDougall et al., 1993). Thus, our estimate of shortening from eastern Potwar are closer to that of western Potwar. However, it is in disagreement with Jaswal, (1990) and Treloar et al. (1992) who have calculated shortening of about 69 km and 80 km, respectively, in the NPDZ. The difference may represent error or lateral variation in the amount of shortening.

Known the shortening and timing of deformation, one can estimate the rate of orogenic contraction. If 42 km of shortening in the NPDZ has occurred between 4.5 and 1.9 Ma, as discussed above, the rate of shortening is 16 mm/yr. This number compares with shortening estimates of 9–14 mm/yr in the SR/PP (Leather, 1987; Baker et al., 1988) and 1–15 mm/yr in the Sub-Himalaya in India (Lyon-Caen & Molnar, 1985).

Our shortening estimates of 42 km along cross-section AA' (Fig. 6) represent orogenic contraction between the Soan Syncline and the MBT. An orogenic contraction of 23 km is calculated by Pennock et al. (1989) along a balanced cross-section in the eastern Salt Range (between thrust front and the Soan Syncline). Thus, a total shortening of 65 km can be predicted south of the MBT in the eastern SR/PP in Pakistan.

CONCLUSION

Structural interpretation of the NPDZ shows a triangle zone geometry below the northern limb of the Soan Syncline and a set of imbricates below the footwall of the MBT. The triangle zone geometry is characterized by a core wedge bounded between a floor thrust in the Eocambrian evaporites and a roof thrust in the Rawalpindi Group strata. The floor thrust propagates upsection from a depth of about 7 km and merges in the roof thrust at a depth of about 3 km. The roof thrust has a hinterland vergence similar to backthrusts of the triangle zones in other fold-and-thrust belts. A fault-bend and a fault-propagation fold occupy the position of the core wedge in the triangle zone. These structures may have accumulated sufficient quantities of hydrocarbons for drilling.

The imbricate set north of the triangle zone consists of thrust sheets of Murree Formation (molass) and older platform sequence. As deformation is apparently younger than deposition of most of the molasse strata, absence of the Siwalik strata in thrust imbricates is attributed to the duplex style of deformation in the NPDZ. Besides, absence of a foreland vergent fault suggests a hinterland-vergence to the roof sequence. This is consistent with the exposed backthrust and triangle zone geometry to the south.

Total shortening in the NPDZ is about 42 km between 4.5 and 1.9 Ma. This data provides a shortening rate of about 16 mm/yr. The 16 mm/yr shortening estimate in the NPDZ is comparable with 9–14 mm/yr in the SR/PP (Leather, 1987; Baker et al., 1988) and 10–15 mm/yr in the Sub-Himalayas in I ndia (Lyon-Caen & Molnar, 1985). Total shortening of 65 km can be predicted south of the MBT in northern Pakistan combining 42 km in the NPDZ with 23 km south of the Soan Syncline in the eastern SR/PP (Pennock et al., 1989).

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