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Title: Geology and Geophysics of the Foreland Fold-Thrust Belt of Northwestern Pakistan

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Himalayan collision produced frontal and lateral ramps and associated Pliocene to Quaternary tectonic geomorphic features in the foreland fold-thrust belt of northwestern Pakistan. The transpressional right-lateral Kalabagh tear fault zone displaced the emergent Surghar Range frontal thrust from the western Salt Range by 16-19 km since 1.9-2.1 Ma: the age of youngest Siwalik molasse strata erosionally truncated during the southward advance of decollement thrusting. Folds and fanglomerate deposits resulting from decollement thrusting were also cut by the Kalabagh fault. North of the eastern Surghar Range, the N15W-trending Kalabagh fault bends to the west

into north-dipping thrust faults that sole out beneath the southern Kohat Plateau. Foreland subsidence associated with the southward advance of thrusting controlled the distribution of Indus River conglomerates during the late Pliocene and Quaternary. Uplift in the northern Kalabagh fault zone diverted the Indus river eastward to its present course.

South of the Main Boundary thrust (MBT) and west of the Indus River, decollement thrusting dominated by layer-parallel slip of as much as 32 km on a single thrust fault emplaced blind thrust sheets and fault-bend folds. Balanced cross sections show over 50% line-length shortening in sedimentary strata between the top of the basement and the base of the clastic wedge of the Murree and Kamlial formations and the Siwalik Group. A NNW-trending basement ridge modeled from Bouguer gravity data may have nucleated the similarly-oriented Kalabagh fault lateral ramp along the western Salt Range. A basement fault may have produced the frontal ramp at the Surghar Range. Low friction along the basal decollement thrust, with rapid underthrusting and internal thickening, produced a subcritical wedge tapering approximately 2° across the 70-km-wide Kohat foreland fold-thrust belt between the MBT and the Surghar Range thrust.

Geology and Geophysics of the Foreland Fold-Thrust Belt of Northwestern Pakistan

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The work producing the manuscripts in this thesis and related material concentrated on structural analysis of primarily macroscopic geological structures. However, observations of geological features at all scales were used. Interpretations required extensive geological mapping, seismic reflection data, Bouguer gravity data, and well data. Fields of geology represented in the thesis include structural geology, tectonics, neotectonics, sedimentology, geomorphology, and geophysics. Each of the manuscripts contains more specific background material.

Field work by the author was undertaken in Pakistan in successive field seasons during 1982-85. An appendix includes a 1:50,000-scale tectonic map that has been an important data base for the thesis project.

II. STRIKE-SLIP FAULTING IN A FORELAND FOLD-THRUST BELT: THE KALABAGH FAULT AND WESTERN SALT RANGE, PAKISTAN

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Abstract

The 120-km-long Kalabagh fault zone is formed by transpressive right-lateral strike-slip along the western Salt Range-Potwar Plateau allochthon in northern Pakistan. Lateral ramping from a decollement thrust along an Eocambrian evaporite layer produced NNW- to NW-oriented folds and NE- to N-dipping thrust faults in a topographically emergent zone up to 5 km wide. Piercing points along the main Kalabagh fault indicate 12-14 km of middle to late Quaternary right-lateral offset. The older right-lateral Surghar fault displaced axes of frontal folds of the eastern Surghar Range by 4-5 km. Total displacement is reduced northward in the Kalabagh fault zone where north-dipping thrust faults splay to the west. Cumulative right-slip offset in the Kalabagh fault zone compares with displacement along the Salt Range frontal thrust, at a minimum average displacement rate of

7-10 mm/year near the Indus River since 2 Ma. A NNW-trending discontinuous ridge in the basement, plunging 2-3° north along the Kalabagh fault, is interpreted from residual Bouguer gravity anomalies. The eastern flank of this basement ridge probably ramped allochthonous strata upward from a depth of over 5 km in the northern Kalabagh fault zone, which shallows to the south. Kalabagh faulting displaced and uplifted Recent terrace deposits and shifted the course of the Indus River eastward. A high slip rate and associated seismicity indicate that the Kalabagh fault zone should be considered active and capable of earthquakes.

Introduction

Shallow subduction of the Indian plate beneath the Himalaya forms a major north-dipping decollement thrust that brings the Salt Range and Trans-Indus Salt Range over the Punjab foreland of Pakistan. Seismicity associated with foreland thrust faulting reaches depths of 10 km or more and suggests that thrusting may extend 150-350 km north of the Salt Range (Seeber and others, 1979, 1981). The N15W-trending Kalabagh tear fault zone terminates the WSW-trending Salt Range thrust front on the west and extends north of the Surghar Range to the southern margin of the Kohat Plateau (Figure 2.1). The Kalabagh fault zone intersects the Indus River near the town of Kalabagh, for which the longest continuous strand of the fault is named.

The Kalabagh fault zone was recognized by Gee (1945, 1947, 1980), whose work was published as a series of geological maps (1:50,000) extending from the eastern Salt Range to the Kalabagh area. Previously unpublished is a geological map of the northern end of the Kalabagh fault begun by Gee and completed by the author. The Kalabagh fault appears on a map of active faults (Kazmi, 1979) on the tectonic map of Pakistan (Kazmi and Rana, eds., 1982), and in the Kohat Landsat scene (De Jong, 1986). Splays of the Kalabagh fault were mapped during site investigation for the proposed Kalabagh dam at the confluence of the Indus and Soan Rivers (John Petrie and George Hallowes, pers. comm., 1983)

Seismicity recorded during six months of 1977 (Seeber and Armbruster, 1979; Seeber and others, 1981) show microearthquakes 0-30 km deep in zones parallel to and south of the Kalabagh fault zone. A correlation between basement seismicity and surface faulting (Seeber and Armbruster, 1979) is ambiguous. Quaternary deformation along the Salt Range thrust and Kalabagh fault was described by Yeats and others (1984).

Present-day convergence of India relative to Eurasia is approximately 40 mm/year in the western Himalaya at longitude 70-75°E (Minster and Jordan, 1978). Displacement on the Salt Range frontal thrust fault and associated Kalabagh fault system reflects only movements of the Indian plate relative to the Himalaya and is comparable to an instantaneous convergence rate of 18±7 mm/year at the frontal fault of the Himalaya in northern India (Molnar and others, 1984, 1987). The rate of shortening at the Salt Range frontal thrust, that connects with the Kalabagh fault, is calculated at 9-14 mm/year (Baker and others, 1988).

Structural and stratigraphic setting of the Kalabagh fault zone

The Kalabagh fault zone extends 120 km from the southwest corner of the Salt Range near Khushab to the southern Kohat Plateau and is characterized by right-lateral transpression (Harland, 1971) (Figures 2.1 and 2.2). Evidence of thin-skinned deformation includes NW- to NNW-trending pressure ridges and thrust faults that indicate relative southward transport of the Salt Range allochthon east of the Kalabagh fault zone. Models of transpression (Harland (1971) predict these fold and fault orientations in a compressional strike-slip environment. The zone of transpression along the Kalabagh fault system is probably confined to the allochthon and decoupled from the basement. A Paleozoic and younger sedimentary sequence 4-5 km thick, underlain by Eocambrian evaporite deposits of the Salt Range Formation, ramps to the surface along the southern three-fourths of the Kalabagh fault zone. The northern Kalabagh fault zone curves to the west into a zone of north-dipping thrust faults and associated compressional folds.

Isostatic loading by southward-advancing thrust sheets of the western Himalaya created a southward-migrating depocenter for late Cenozoic Siwalik synorogenic clastic rocks (G. Johnson and others, 1985).

Time-transgressive lithologic boundaries in the Siwaliks are also younger to the west across the Kalabagh fault zone (Figure 2.3). To the east of the Kalabagh fault zone are Siwalik sections dated as 18.3 Ma to 0.5 Ma, based on magnetic polarity stratigraphy at the Jalalpur, Chakwal-Bhaun, and Chinji-Nagri stratigraphic sections (N. Johnson and others, 1982, 1985). Khan (1983) reported 12.0 Ma to 0.5 Ma paleomagnetic ages of Siwaliks west of the Kalabagh fault zone in the Surghar Range at Chichali gorge and to the northwest. From the Trans-Indus Salt Range, Khan (1983) reported 3.7 Ma to less than 1.0 Ma paleomagnetic ages of Siwaliks and a maximum age of 4.5 Ma for fossils at the base of the Siwaliks. Stratigraphic sections east of Daud Khel (Hussein and others, 1979), near Makhad in the western Soan syncline (Gill, 1952), and in the Kundian well (unpublished data, Geological Survey of Pakistan) are tied by lithologic descriptions to sections with paleomagnetic age control (Figure 2.3). The Chinji, Nagri, and Dhok Pathan Formations of Pilgrim (1913) and Tatrot and Pinjor mammal zones as described by Pilbeam and others (1977) have been correlated across the Kalabagh fault zone. The upper Siwalik section in the Kalabagh fault zone includes a far-derived polymictic conglomerate sequence 1.5-km-thick near Makhad and west of the Indus River. Deposits include well-rounded clasts of crystalline rocks from the Karakoram and Kohistan areas of northern Pakistan.

Possibly similar in age to this Indus River conglomerate, but entirely different in provenance, is the Kalabagh Conglomerate of Gee (1945, 1947, 1980) that overlies tilted lower and middle Siwalik strata near Kalabagh and to the southeast. Kalabagh Conglomerate clasts are predominantly Tertiary limestone and ferruginous sandstone, similar to strata mapped in the local emergent folded and thrusted ridge to the southwest. The unconformity at the base of the Kalabagh Conglomerate, that dates the Kalabagh fault, is 2.1 Ma in age or younger.

Observations

Western Salt Range and Kalabagh area

Where the Kalabagh fault juxtaposes the Indian shelf sequence underlain by Eocambrian evaporites against deposits of the Indus River floodplain, the Indian shelf sequence is deformed by SW-verging folds and NE-dipping reverse and thrust faults. This zone of deformation reaches a width of 9-10 km at the lobate segment of the fault at Ghundi, with thrust faults on its southern margin dipping 20-30°N. The thrust fault east of Ghundi also cuts late Quaternary alluvial fans on its southern end (Yeats and others, 1984).

The linear Kalabagh fault scarp at Khairabad bounds lake deposits that are displaced by a NNW-trending reverse fault (Figure 2.4). These lake deposits fill a sag pond within the strike-slip fault zone (R.S. Yeats, oral commun., 1986). South of Khairabad, the Kalabagh fault displaces older alluvial fan deposits and steepens E-W slope profiles. Youngest alluvial fans along the western Salt Range are not cut by the Kalabagh fault.

North of Khairabad, the Kalabagh fault branches to the east along NNE-trending splay faults. The Salt Range Formation crops out along the Ainwan fault, the westernmost of these splay faults (Figure 2.5). Near Mari village, the Kalabagh fault continues N15W toward the Chisal Algad and branches along the N30W-trending

Surghar fault. Steeply east-dipping strike ridges of the Paleocene and Eocene Lockhart and Sakesar limestones are stacked along high-angle reverse faults near Mari and the junction of the projected Surghar fault and the Kalabagh fault. Jurassic and Triassic sedimentary rocks make up lens-shaped tectonic slices in the fault zone southwest of Mari.

The Kalabagh fault truncates folds and thrust faults in Eocambrian to Quaternary sedimentary rocks cropping out near Kalabagh. A doubly-plunging anticline cored by Paleozoic limestone is overlain on its north limb by deformed Quaternary Kalabagh Conglomerate. This steep anticline and the Kalabagh Conglomerate are displaced 12-14 km in a right-lateral sense along the main strand of the Kalabagh fault (piercing points p-p', Figures 2.5 and 2.6). The Kalabagh Conglomerate progrades over tilted Siwalik strata of the Chinji and Nagri Formations (similar to "toplap" of Mitchum and others, 1977), near Kalabagh and to the south-southeast. The Kalabagh Conglomerate is not in contact with upper Siwalik strata 20 km WNW of Kalabagh that were paleomagnetically dated by Khan (1983) to be 0.5 Ma.

The Surghar fault of the Kalabagh fault zone truncates the emergent Surghar Range thrust front. Right-lateral offset along the Surghar fault of 4-5 km is defined by displaced vertical strike ridges of Eocene Sakesar limestone and an associated sequence of deformed sedimentary strata (piercing points s-s′: Figures 2.5 and 2.6). This displacement essentially predates the deposition of the Kalabagh Conglomerate between s and s′. However, the underlying Siwaliks are deformed by tight folds trending NNW to WNW in the Surghar fault zone. The Kalabagh area is shown with continuous E-W- to NW-trending compressional folds and thrust faults prior to right-lateral translation along the Kalabagh and Surghar faults (Figure 2.6).

The Surghar fault extends beneath Quaternary alluvium to the south and may be overridden by the Cemetery fault, less than 1 km northwest of Kalabagh. The east-dipping Cemetery fault displaces the Eocambrian Salt Range Formation over Quaternary gravels of the Indus River floodplain to the west.

Chisal Algad and northern extension of the Kalabagh fault

North of the Indus River, the Kalabagh fault trends N15W and follows the stream channel of the Chisal Algad. Tectonic slivers of the Salt Range Formation and Permian limestone were noted by Gee (1980 and unpublished mapping) along the Kalabagh fault (Figures 2.5 and 2.7). The fault is nearly vertical north of the Indus River (e.g., figure 8 of Yeats and others, 1984) and cuts a sedimentary section that includes the 3-4 km thick Siwalik clastic wedge. Tectonic lenses of Salt Range evaporite in the Kalabagh fault zone indicate a fault depth of at least 5 km, the thickness of the post-evaporite section.

In the northern Chisal Algad, polymictic conglomerate beds unconformably overlying tilted Siwalik strata are also cut by the Kalabagh fault. These conglomerate deposits contain about 80% igneous and metamorphic rock clasts and are probably recycled conglomerates from the upper Siwalik section to the north and east. Strain in cobbles of these conglomerates near Tabi Sar indicates post-depositional right-slip offset.

On its northern end, the Kalabagh fault bends to the west along several north-dipping thrust faults that repeat the Siwalik sequence (Figure 2.7). The southernmost thrust fault, the Visor fault, dips from 45° N to at least 79°N with more than 1 km of stratigraphic separation within the Siwalik section. The northernmost continuous strand of the N15W-trending Kalabagh fault changes strike to the west near Shakardarra where the Nagri section is repeated along a thrust fault. In the northernmost Kalabagh fault zone, estimated displacement of 2-4 km on surface thrust faults is only 20-30% of right-lateral displacement of 12-14 km near Kalabagh.

The Hukni fault bounds the southern Kohat Plateau and the Nandrakki deformed zone 5 km northeast of the Kalabagh fault bend near Shakardarra (Figure 2.7). Tight box folds in Eocene strata along the Hukni fault die out upsection in Siwalik strata that are not similarly deformed. The Hukni fault dips 35°N where it trends N80W and steepens to the SSE to 75-80°E where it trends S60E. The Hukni fault extends approximately 10 km south of the Nandrakki area in a zone parallel to the Kalabagh fault but does not connect with splay faults of the Kalabagh fault near the Indus River. South of the Nandrakki deformed zone, fluvial terraces of polymictic conglomerate overlie the Hukni fault.

Basement structure and the Kalabagh fault zone

Gravity data:

A NNW-trending discontinuous ridge in the 2-3° northward-sloping top of basement of the Indian plate is interpreted from positive Bouguer gravity anomalies along the Kalabagh fault zone. The regional (low frequency) Bouguer gravity gradient is based on contour lines that extend across the Potwar Plateau and project into the Kalabagh re-entrant (Figure 2.8-A). The higher frequency residual is separated from the regional gradient, giving residual anomalies along the fault exceeding +30 mgal (Figure 2.8-B). The residual anomaly in general increases to the SSE toward the Sargodha high (+100 mgal) where Indian-shield basement crops out in the Kirana Hills (e.g., Farah and others, 1977).

Basement structures are modeled with a minimum relief of 500 meters above surrounding basement, in calculations using symmetrical E-W cross sectional gravity profiles and a basement to sedimentary overburden density contrast of 0.6 gm/cm . The gravity anomaly is predicted by an equation for a horizontal cylinder of excess mass:

$$g_z = \frac{2 G \pi R^2 \sigma}{\sigma} \cdot \frac{1}{(1 + x^2/z^2)}$$

where σ = density, z = depth to center of the anomalous mass, x = horizontal distance from the edge to the center of the gravity anomaly, R = radius, and G = gravity constant (Griffiths and King, 1981). The radius of the cylinder: R = 550 meters, suggests 500-1000 meters of relief on the basement ridge. Two-dimensional modeling using methods of Talwani and others (1959) produces similar basement structures, while not significantly elucidating the cross sectional shape of the ridge. Where E-W cross sections of the ridge are asymmetric, the basement ridge may be asymmetric. Alternatively, an asymmetric gravity anomaly in E-W profiles may indicate repetition of allochthonous strata.

Seismic reflection data:

A seismic reflection profile extending from Kohat city 30 km southward toward the northern right-angle bend in the Kalabagh fault (located on Figure 2.1) shows a nearly flat basal decollement surface at approximately 8 km (4 sec. 2-way travel time). This flat decollement surface projects eastward along strike to the northern Potwar Plateau, where seismic reflection data constrain the basal decollement of the Salt Range-Potwar Plateau allochthon at a similar depth (e.g., Leathers, 1987; Baker, 1987; Lillie and others, 1987; Baker and others, 1988). Southwest of the Kalabagh fault near Mianwali, the Kundian well penetrates the Salt Range Formation that overlies basement. The Kundian well, and an intersecting seismic line that extends southward toward the Sargodha high, constrain the 2-3° northward slope of the basement toward the Surghar Range and the Potwar Plateau.

Implications:

The Kalabagh fault system is formed by a lateral ramp that extends to the base of the Salt Range-Potwar Plateau allochthon (Figure 2.9). The base of the allochthon and top of basement exceed a depth of 5 km in the northern part of the Kalabagh fault and shallow southward. The Kalabagh tear fault is decoupled from basement and propagates over the basement feature. Right-slip separation determined at the surface near Kalabagh town (Figure 2.5) extends to the south.

Residual gravity anomalies derived from the regional gradient indicate a ridge along the Kalabagh fault zone rather than a step in the basement. Wrench faulting along upward-diverging fault splays or "flower" structures (Harding and Lowell, 1979) may uplift the basement blocks to form the ridge independently of the lateral ramp. This may also corroborate earthquake focal mechanisms reported by Seeber and Armbruster (1979) and Seeber and others (1981) that indicates an overall right-lateral sense of shear in basement to the south of the Kalabagh fault zone. Concentrations of earthquake hypocenters southwest of the Kirana Hills in the Kalabagh re-entrant are shown to define fault zones approximately parallel to, but largely west of the trend of the

Kalabagh fault zone (Seeber and others, 1981). The gravity anomaly beneath the Kalabagh fault zone merges with the regional WNW-trending zone of basement seismicity of Menke and Jacob (1976), although trends of these two features vary by 10-15 degrees. The Kalabagh fault probably ramped up over the basement ridge, which follows an older zone of weakness. Wrench faulting in the basement to produce the ridge may also be in part contemporaneous with Kalabagh fault displacement, producing contemporaneous seismicity.

In the Idaho-Wyoming thrust belt, Wiltschko and Eastman (1983) show that faulted basement structures and slope changes in basement control frontal ramping of thrust faults. An E-W-trending upthrown basement fault block is interpreted to control the position of the ENE-trending Salt Range frontal thrust ramp 70 km east of the Kalabagh fault (Baker and others, 1988). An upthrown basement block is a natural deflection line for a lateral ramp involving oblique compression, such as the Kalabagh fault. In addition to the basement ridge, a generally shallowing basement west of the Kalabagh fault is suggested by the Kundian well, which penetrates the Cambrian section. This provides a favorable overall geometry for a lateral ramp to occur here, however, a westward-shallowing basement does not explain the western part of the Kalabagh re-entrant.

Discussion

Comparison with other structures:

In a thin-skinned thrust system, a lateral ramp along a basement structure would be likely to form a tear fault at the toe of the allochthon, as compared with basement control on a frontal ramp (Wiltschko and Eastman, 1983). The Kalabagh fault propagated from the basement along the western Salt Range and extended to the north to conserve slip. Strike-slip offset of 16-19 km along the Kalabagh and Surghar faults decreases northward, in part by transfer of motion to west-trending folds and thrust faults that crop out north of the Surghar Range.

The Kalabagh fault may be compared with the Jacksboro fault that bounds the Pine Mountain thrust sheet in the southern Appalachians (Figure 2.10). Both faults terminate a major thin-skinned decollement thrust along a low strength sedimentary layer, and are oriented similarly, i.e., with respect to the fold-thrust belt. The thickness of the Chattanooga Shale probably controlled the northwestward advance of the Pine Mountain thrust sheet and the related left-lateral Jacksboro fault (Harris, 1970, 1977). In contrast, although the Salt Range evaporites may vary in thickness, the top of the basement was the primary control on lateral ramping of the Kalabagh fault. Folds that trend E-W to NW on either side of the Kalabagh fault were truncated and significantly displaced by strike-slip faulting. In the Pine Mountain thrust sheet, in addition to frontal ramp-related folds such as the Powell Valley anticline, folds are parallel to the Jacksboro fault (Harris, 1970) and were probably contemporaneous with left-lateral displacement. Cambrian strata follow the strike of the fault in the transition zone between the Jacksboro tear fault and the Chattanooga frontal thrust (Figure 2.10). Stratigraphically-controlled decoupling would produce a more gradual transition between the Chattanooga thrust and Jacksboro fault, whereas the comparable bend of the Kalabagh tear fault zone is offset by right-slip faults. Truncation of the eastern Surghar Range by the Surghar fault and truncation in the Kalabagh area by the Kalabagh fault produced segmentation of folds and faults in emergent lower Tertiary and older strata. The Pine Mountain thrust and Jacksboro fault are mapped as more discrete linear zones at the surface when compared with the Salt Range-Potwar Plateau decollement thrust and Kalabagh fault. The Kalabagh fault zone shows a greater compressional component of strike-slip displacement as well as more influence by basement structures when compared with the Jacksboro fault.

Basement structures are associated with large tear faults in the Swiss Jura, such as the Vallorbe-Pontarlier fault, that trend 20-60° to the axes of compressional folds (Rutten, 1969; Anderson, 1978; Trumpy, 1980). Structures that die out or are truncated by these strike-slip faults lack consistent horizontal displacement, i.e., thin-skinned compressional folds typically were developed independently on either side of the major tear faults in the Jura (Rutten, 1969). The Kalabagh fault zone is characterized by consistent right-lateral offset along the western Salt Range, in contrast with tear faults of the Swiss Jura. In the Kalabagh fault segment north of the Indus River, the northward reduction of offset documented at the surface may be comparable with variable offset along tear faults in the Jura.

The 120-km-long (N-S) Kalabagh re-entrant on its eastern side includes 16-19 km of offset in the Kalabagh fault zone. Subsurface data indicate a 2-3°N dip of basement and the base of the allochthon beneath the western Potwar Plateau, east of the Kalabagh fault zone. Similar shallow N-dipping basement to the west of the Kalabagh fault zone may be offset by a down-to-the-north fault at the Surghar Range frontal ramp (McDougall, 1988, in prep.). This limits southward propagation of decollement thrusting at the Surghar Range. The Kalabagh re-entrant may also be controlled by a flexure in the lithosphere with a wavelength of 60-150 km, approximately parallel to the east-southeastern trend of the central Himalaya east of the Hazara syntaxial bend. The re-entrant may be a primary structural feature on which the north-plunging basement ridge and Kalabagh fault lateral ramp have been superimposed.

The compressional component of slip in the Kalabagh fault zone may have increased by syntectonic clockwise rotation of the principal compressive stress axis (σ_1). Separation between hanging-wall and footwall cutoff lines in an E-W cross section of the Ghundi lobe is shown as 8-10 km (Figure 2.9). This indicates transverse shortening that decreases to the north. The east-dipping back limb of the lateral ramp crops out in strike ridges of Sakesar Limestone along the western margin of the Potwar Plateau, that generally dip more steeply to the north. N-S- to N30E-oriented splay faults that diverge from the Kalabagh fault near the Indus River, that include the Dinghot and Ainwan faults, may be Riedel shears (e.g., Tchalenko, 1970).

Structural evolution:

Cumulative strike-slip offset of 16-19 km along the Kalabagh and Surghar faults can be compared with frontal thrust displacement of the central Salt Range, as both measure movement of the Salt Range-Potwar Plateau allochthon with respect to the Punjab foreland. Shortening of 19-23 km in the central Salt Range was determined from seismic reflection profiles and a balanced N-S cross section of the south-central Potwar Plateau (Baker, 1987; Baker and others, 1988). Frontal thrust displacement at the eastern Surghar Range of 3-4 km (McDougall, 1988, in prep.) adds to displacement along the Kalabagh and Surghar strike-slip faults in comparing offset of the frontal Salt Range. The interconnection between the Kalabagh tear fault system and the Salt Range thrust front implies synchroneity of offset. The difference between 5-8 km of cumulative thrust displacement at the surface in the Surghar Range and northern Kalabagh fault zone and 16-19 km along the Kalabagh and Surghar faults suggests that the Kalabagh fault projects into blind thrusts north of the Surghar Range.

Radiometrically-dated volcanic ashes and associated paleomagnetically-dated stratigraphic sections give a 1.9-2.1 Ma time interval for erosional truncation of the northern limb of the Soan syncline 15 km south of Rawalpindi (Raynolds and Johnson, 1985). This indicates southward transfer of active compressional deformation and incipient ramping of the Salt Range front at about 2 Ma (e.g., Baker and others, 1988). The emergent Salt Range front remains active to the present day and continues to step toward the foreland to the south (Yeats and others, 1984). Southward tectonic transport of the Salt Range-Potwar Plateau allochthon probably correlates in time with emergent thrust faulting at the Surghar Range front. The Surghar Range thrust was succeeded by the Surghar right-slip fault, and finally by the Kalabagh right-slip fault.

Slip rates for the Kalabagh fault system average 7.6-10 mm/year, with 16-19 km of offset in the last 1.9-2.1 Ma. If the base of the Kalabagh Conglomerate is significantly younger than 2 Ma, displacement of this unit 12-14 km along the Kalabagh fault would be at a higher rate. The Kalabagh Conglomerate, by association with the basement ridge (Figure 2.2), marks upward ramping of pre-Siwalik rocks along the Kalabagh fault. Deformation and erosional dissection of the Kalabagh Conglomerate indicates a migration of the depositional axis or deceleration of uplift since maximum Kalabagh fanglomerate deposition.

Neotectonics:

The emergence of the western Salt Range front over the Indus River floodplain along the Kalabagh fault is visible from space imagery (Figure 2.2). The Quaternary Kalabagh fault has displaced the Kalabagh Conglomerate, Indus River floodplain deposits, and lake beds near Khairabad (Figure 2.4), and has thrust Cambrian strata over alluvial fan gravels along the Ghundi lobe. Tectonic control of the linear Chisal Algad in the northern Kalabagh fault zone is remarkable. Uplifted stream terraces, faulted cobbles in late Quaternary conglomerate, tectonic blocks of evaporite and limestone, and truncated alluvial fans mark the northern segment of the Kalabagh fault. Regional uplift and neotectonic tilting because of right-lateral transpression in the Kalabagh fault zone suggests active faulting and folding.

The paleo-Indus River deposited far-derived channel conglomerates in the Chisal Algad drainage that was later separated from the source of these deposits and the modern Indus River. Uplift of the northern Kalabagh fault zone by transpression and thrust faulting may have diverted the Indus River to the east from a former course in the Chisal Algad (McDougall, 1988). Uplift in the area south of Nandrakki has exposed a section over 1500 m thick of these far-derived channel conglomerates (Figures 2.3 and 2.7).

Despite geomorphic and geological expression of Quaternary Kalabagh faulting, there are no known fault scarps on modern aggrading alluvial fans. Continual rejuvenation of topography with large alluvial fans emanating from the Salt Range, high erosion rates, and a large compressional component of strike-slip faulting contribute to poor preservation of earthquake-generated fault scarps.

Right-lateral displacement averaging 7-10 mm/year for the last 2 Ma classifies as a high activity rate, with abundant and discontinuous evidence of activity (Slemmons and DePolo, 1986). The recurrence interval for major earthquakes may be quite long, measured in thousands of years (Yeats and others, 1984). The Kalabagh fault is not known to have produced major historic earthquakes, however, conversations with local inhabitants suggest repeated moderate earthquakes in the northern Kalabagh fault zone. The Salt Range-Potwar Plateau decollement thrust has been described as relatively aseismic when compared with other frontal faults of the Himalayan Range. Microseismic activity recorded in the broad zone including the Kalabagh fault zone (Seeber and Armbruster, 1979; Seeber and others, 1981) indicates some release of accumulated strain, however much of this seismicity was south of the Salt Range.

Conclusions

Strike-slip offset in the Kalabagh fault zone conserves slip between frontal thrust ramps in the Salt Range and eastern Surghar Range. Cumulative displacement of piercing points along the Kalabagh and Surghar right-slip faults of 16-19 km gives an average displacement rate of 7-10 mm/year for the last 2 Ma. The Kalabagh fault system developed in the following sequence: (1) folding of the Nandrakki deformed zone of the southern Kohat Plateau, (2) inception of the eastern Surghar Range frontal thrust ramp and Salt Range frontal thrust ramp, (2) inception of the Surghar right-slip fault, truncating the eastern Surghar Range thrust, (3) inception of the Kalabagh right-slip fault, (4) formation of splay faults, including the Ainwan and Dinghot faults, east of the Kalabagh fault. The Surghar Range and Salt Range fold-thrust front emerged as thrust faulting propagated southward from the Kohat Plateau, beginning at 1.9-2.1 Ma. Uplift of the basement ridge beneath the lateral ramp of the western Salt Range must have preceded inception of the right-lateral Kalabagh tear fault zone. The N30W- to N-S-oriented Surghar fault underwent 4-5 km of right-lateral displacement during the time of early Salt Range frontal thrusting. Right-slip offset of 12-14 km along the N15W-trending Kalabagh fault followed

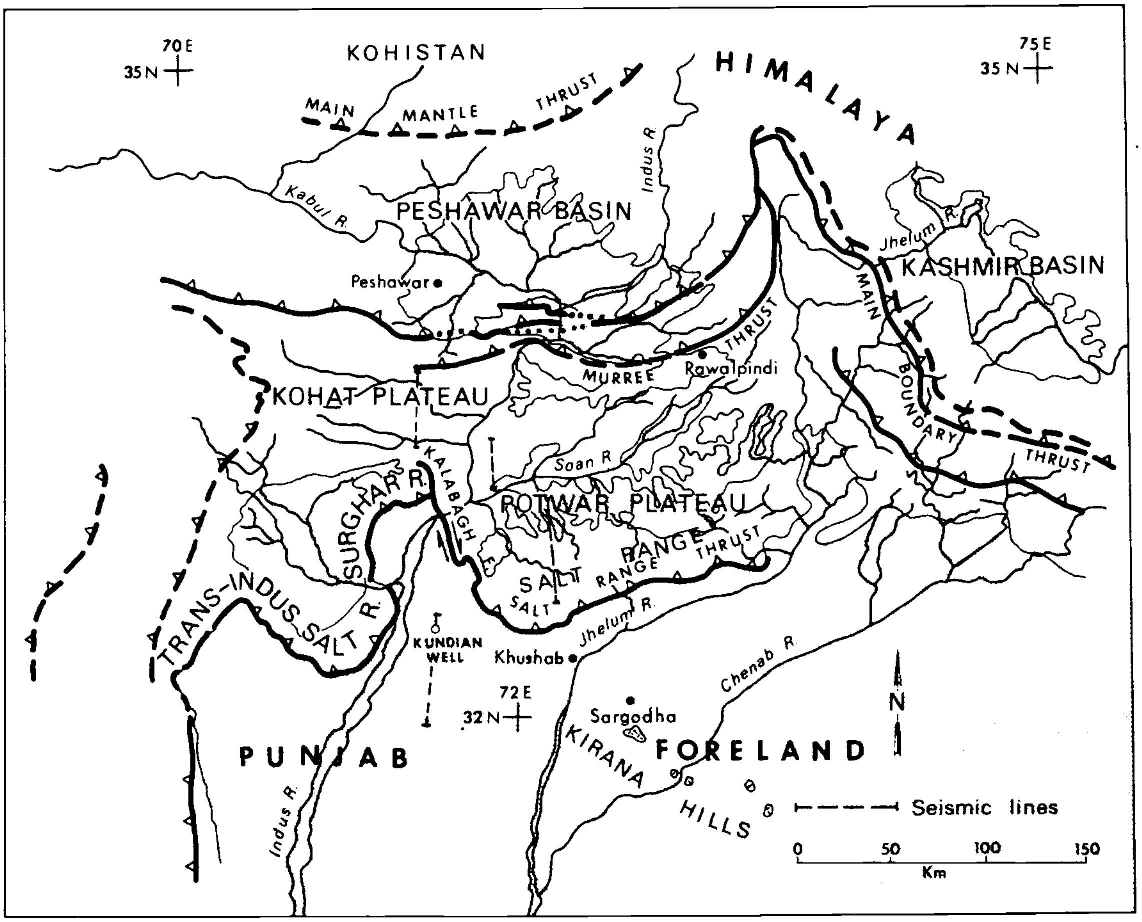
Kalabagh Conglomerate deposition and was contemporaneous with continued Salt Range decollement thrusting.

The configuration of basement rather than evaporite thickness was the fundamental structural control on the lateral ramp of the Kalabagh fault zone. The decoupled Salt Range allochthon was deflected upsection along a linear basement ridge below the western Potwar Plateau, interpreted from Bouguer gravity anomalies. Two major +30 mgal residual gravity anomalies trend SSE along the western Salt Range. The anomalies trend beneath the Indus and Jhelum River floodplains toward the Sargodha basement high.

NNW-trending folds and reverse faults in the northern Kalabagh fault zone and in the Ghundi lobe indicate compressional right-slip motion by tectonic transport in an approximately N-S direction. The Kalabagh fault zone is emergent topographically in a zone at least 5 km in width. Tectonic tilting along the Kalabagh fault system probably diverted the Quaternary Indus River away from the Chisal Algad segment of the fault.

The Kalabagh fault was active during the late Quaternary and is a seismic hazard. Earthquake hypocenters in the shallow tear fault zone (0-6 km), may result from release of significant amounts of strain energy. Although the Salt Range-Potwar Plateau allochthon is decoupled from basement, a basement earthquake of significant magnitude would produce shaking at the surface. Seismic events up to magnitude 5 were clustered along possible southward extensions of the Kalabagh fault zone in basement, as observed by Seeber and others (1981).

Figure 2.1: Index map showing Kalabagh fault zone (center left), Potwar Plateau (center), Kohat Plateau (center left), and surrounding regions of northern Pakistan. Thrust faults are bold lines, dashed where approximate, and teeth point toward upper plate. Shaded areas are Quaternary deposits, primarily in structural basins or depressions in the foreland fold-thrust belt and the Indus River floodplain. Patterned outcrops in Kirana Hills near Sargodha (lower right) are exposures of Precambrian basement.



70E
35N
KOHISTAN
MAIN MANTLE THRUST
HIMALAYA
75E
35N
Indus R.
Kabul R.
PESHAWAR BASIN
Jhelum R.
KASHMIR BASIN
Peshawar
MAIN BOUNDARY THRUST
THRUST
MURREE
Rawalpindi
KOHAT PLATEAU
Soan R
KALABAGH F.
SURGHAR R.
POTWAR PLATEAU
SALT RANGE
SALT RANGE THRUST
TRANS-INDUS SALT R.
KUNDIAN WELL
Khushab
Jhelum R.
Chenab R.
72E
32N
Sargodha
N
PUNJAB
FORELAND
KIRANA HILLS
Indus R.
Seismic lines
0 50 100 150
Km

Figure 2.1

Figure 2.2: Tectonic map of Kalabagh fault zone with accompanying Landsat scene (Bands 4,5, and 7, E-2691-04550, 1976). Outlines of modern alluvial fans shown as dotted lines along the western Salt Range and Surghar Range escarpments. Maps are based on geological mapping by author and by E.R. Gee.

Figure 2.2

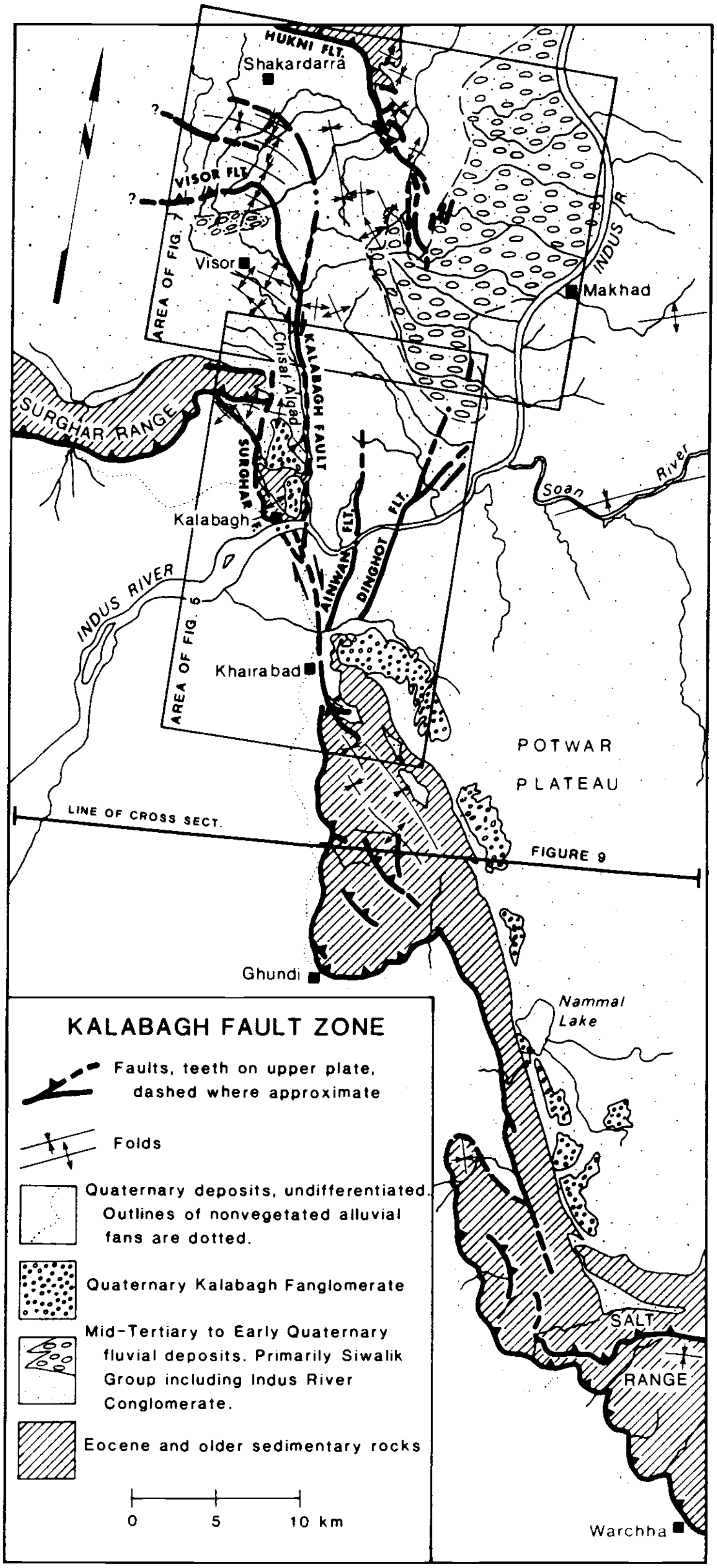

HUKNI FLT.
Shakardarra
VISOR FLT.
AREA OF FIG. 7
Visor
Makhad
INDUS R.
SURGHAR RANGE
Chisal Algad
KALABAGH FAULT
SURGHAR
Kalabagh
INDUS RIVER
AINWAN FLT.
DINGHOT FLT.
Soan River
AREA OF FIG. 5
Khairabad
POTWAR
PLATEAU
LINE OF CROSS SECT.
FIGURE 9
Ghundi
Nammal
Lake
SALT
RANGE
Warchha
KALABAGH FAULT ZONE
Faults, teeth on upper plate, dashed where approximate
Folds
Quaternary deposits, undifferentiated. Outlines of nonvegetated alluvial fans are dotted.
Quaternary Kalabagh Fanglomerate
Mid-Tertiary to Early Quaternary fluvial deposits. Primarily Siwalik Group including Indus River Conglomerate.
Eocene and older sedimentary rocks
0
5
10 km

Figure 2.2

Figure 2.3: Lithostratigraphic sections of post-collisional molasse deposits including the Murree and Kamlial Formations (Rawalpindi Group), the Chinji, Nagri, and Dhok Pathan Formations of the Siwalik Group, informally defined, and the Indus River conglomerate. Numbered sections are located on index map. Paleomagnetic age control is represented by bold solid bar in representative sections. Time lines are projected to sections 2, 4, and 5 without age control, assuming similar sedimentary accumulation rates and similar stratigraphic position for adjacent sections. Kundian well correlations are from the Geological Survey of Pakistan.

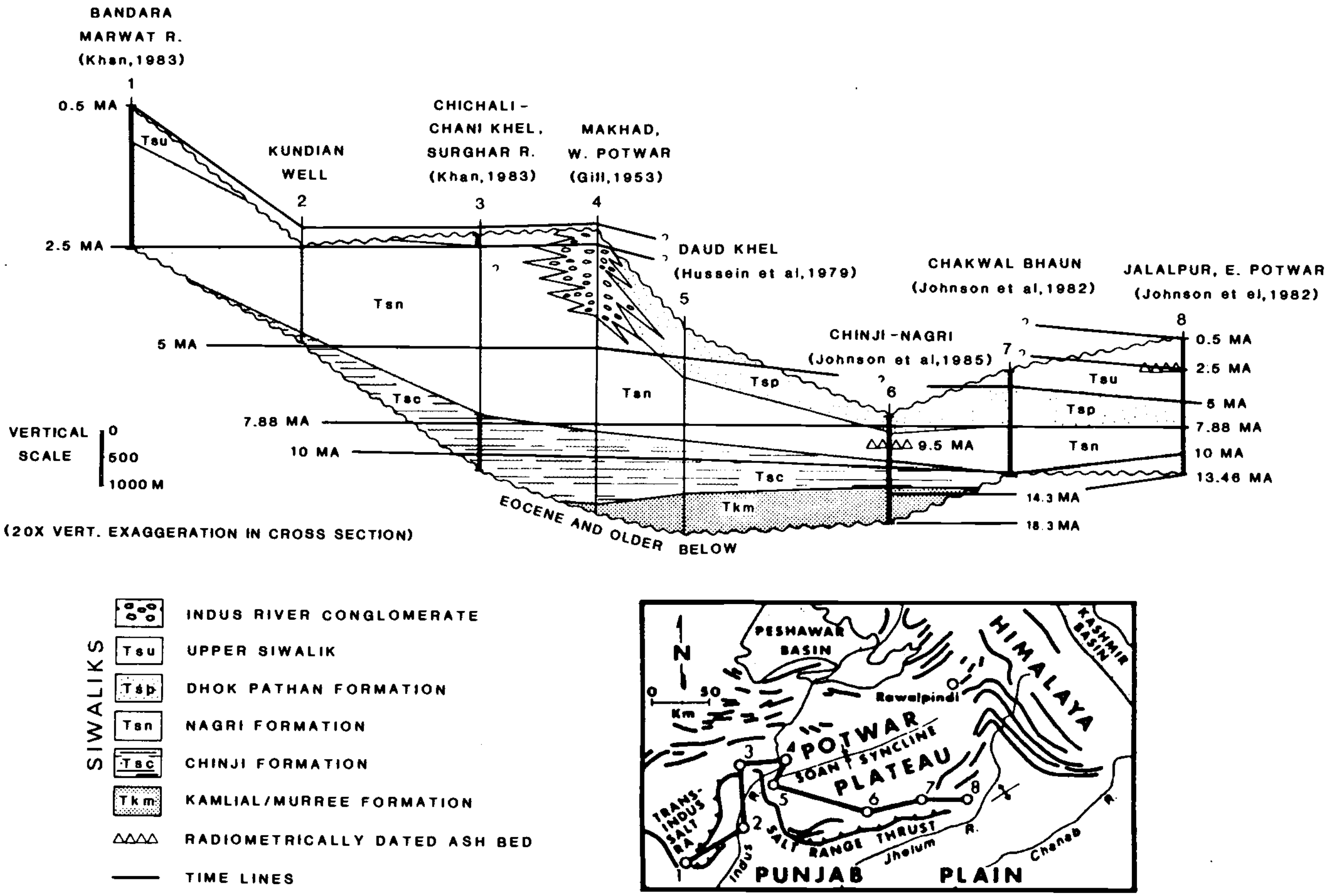

BANDARA
MARWAT R.
(Khan,1983)
1
0.5 MA
Tsu
KUNDIAN
WELL
2
CHICHALI -
CHANI KHEL,
SURGHAR R.
(Khan,1983)
3
MAKHAD,
W. POTWAR
(Gill,1953)
4
DAUD KHEL
(Hussein et al,1979)
5
2.5 MA
Tsn
5 MA
Tsc
7.88 MA
10 MA
VERTICAL SCALE
0
500
1000 M
(20X VERT. EXAGGERATION IN CROSS SECTION)
CHINJI -NAGRI
(Johnson et al,1985)
6
9.5 MA
Tsp
Tsn
Tsc
Tkm
EOCENE AND OLDER BELOW
CHAKWAL BHAUN
(Johnson et al,1982)
7
JALALPUR, E. POTWAR
(Johnson et al,1982)
8
Tsu
Tsp
Tsn
0.5 MA
2.5 MA
5 MA
7.88 MA
10 MA
13.46 MA
14.3 MA
18.3 MA
SIWALIKS
INDUS RIVER CONGLOMERATE
Tsu UPPER SIWALIK
Tsp DHOK PATHAN FORMATION
Tsn NAGRI FORMATION
Tsc CHINJI FORMATION
Tkm KAMLIAL/MURREE FORMATION
RADIOMETRICALLY DATED ASH BED
TIME LINES
N
0 50
Km
PESHAWAR BASIN
Rawalpindi
HIMALAYA
KASHMIR BASIN
POTWAR PLATEAU
SOAN SYNCLINE
TRANS-INDUS SALT RA.
SALT RANGE THRUST
Indus R.
Jhelum R.
Chenab R.
PUNJAB PLAIN
1
2
3
4
5
6
7
8

Figure 2.3

Figure 2.4: Faulted lake beds (L) in vertical cliff near Khairabad, in view facing south with person for scale. The fault dips 40°E with the upthrown block to the left. Lake beds are overlain by Quaternary gravels (Q) that indicate dip separation (S) along the fault. Photo by R.S. Yeats.

Figure 2.4

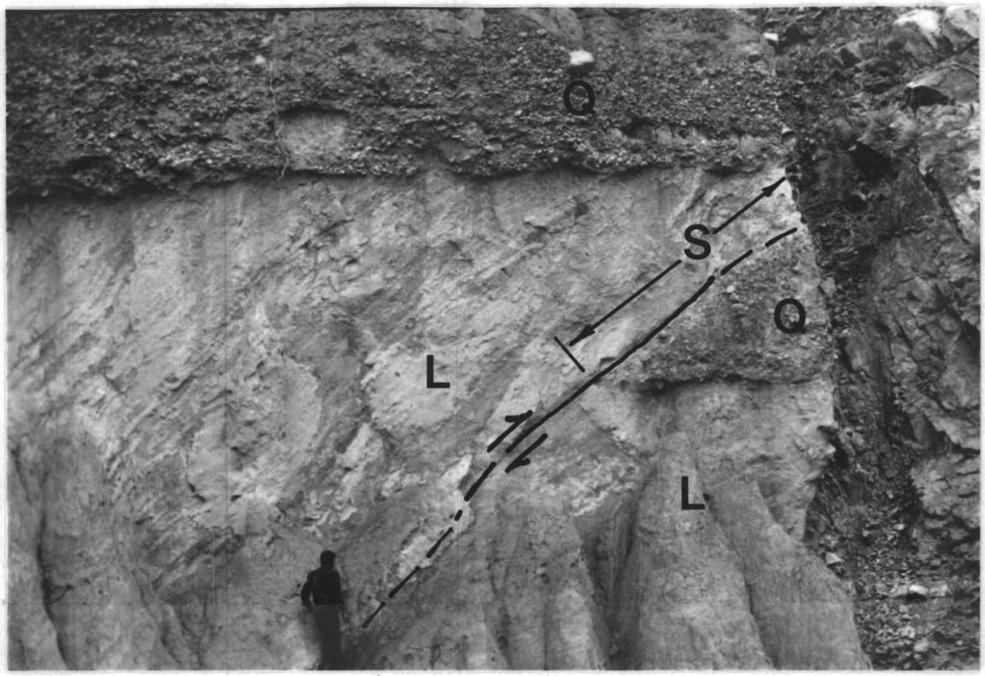


Figure 2.5: Map of the Kalabagh area with displacement of piercing points along Kalabagh fault (p-p'), and along Surghar fault (s-s'). The Kalabagh Conglomerate is not offset by the Surghar fault, but is offset 12-14 km by the Kalabagh fault. Lower right portion of map is from Gee (1980).

Figure 2.5

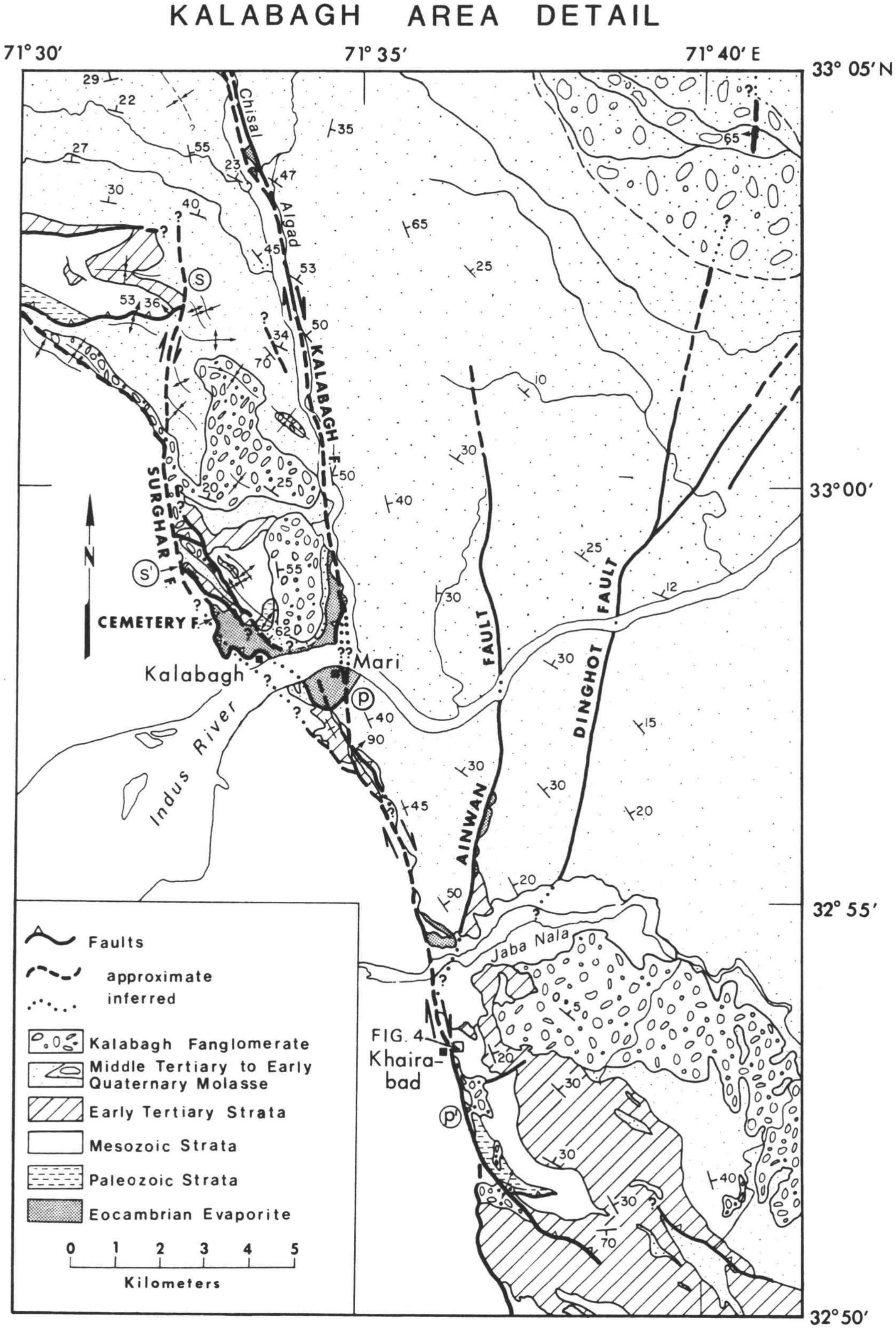

KALABAGH AREA DETAIL
71° 30′
71° 35′
71° 40′ E
33° 05′N
33° 00′
32° 55′
32° 50′
Chisal
Algad
KALABAGH F.
SURGHAR F.
CEMETERY F.
AINWAN FAULT
DINGHOT FAULT
Kalabagh
Mari
Indus River
Jaba Nala
FIG. 4
Khaira-bad
N
Faults
approximate
inferred
Kalabagh Fanglomerate
Middle Tertiary to Early Quaternary Molasse
Early Tertiary Strata
Mesozoic Strata
Paleozoic Strata
Eocambrian Evaporite
0 1 2 3 4 5
Kilometers

Figure 2.6: Map restoration of folds and faults of the Kalabagh area prior to Kalabagh fault zone offset of figure 2.5. This fold pattern in figure 2.5 is masked, in part, by Siwalik and younger deposits at the surface.

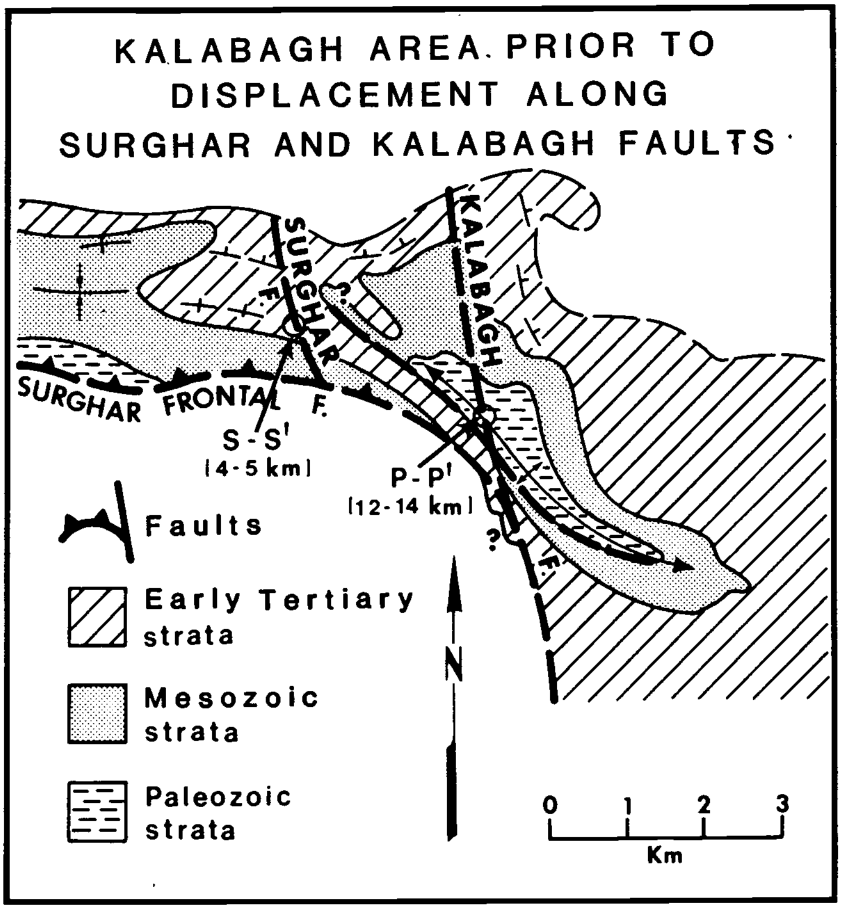

KALABAGH AREA PRIOR TO
DISPLACEMENT ALONG
SURGHAR AND KALABAGH FAULTS
SURGHAR F.
KALABAGH F.
SURGHAR FRONTAL F.
S-S'
(4-5 km)
P-P'
(12-14 km)
?
Faults
Early Tertiary strata
Mesozoic strata
Paleozoic strata
N
0
1
2
3
Km

Figure 2.6

Figure 2.7: Map of the Shakardarra-Nandrakki area and northern Chisal Algad with thrust faults including the Visor fault branching to the west from the northern part of the Kalabagh fault. Salt Range evaporite crops out in the northern Chisal Algad.

Figure 2.7

SHAKARDARRA AREA

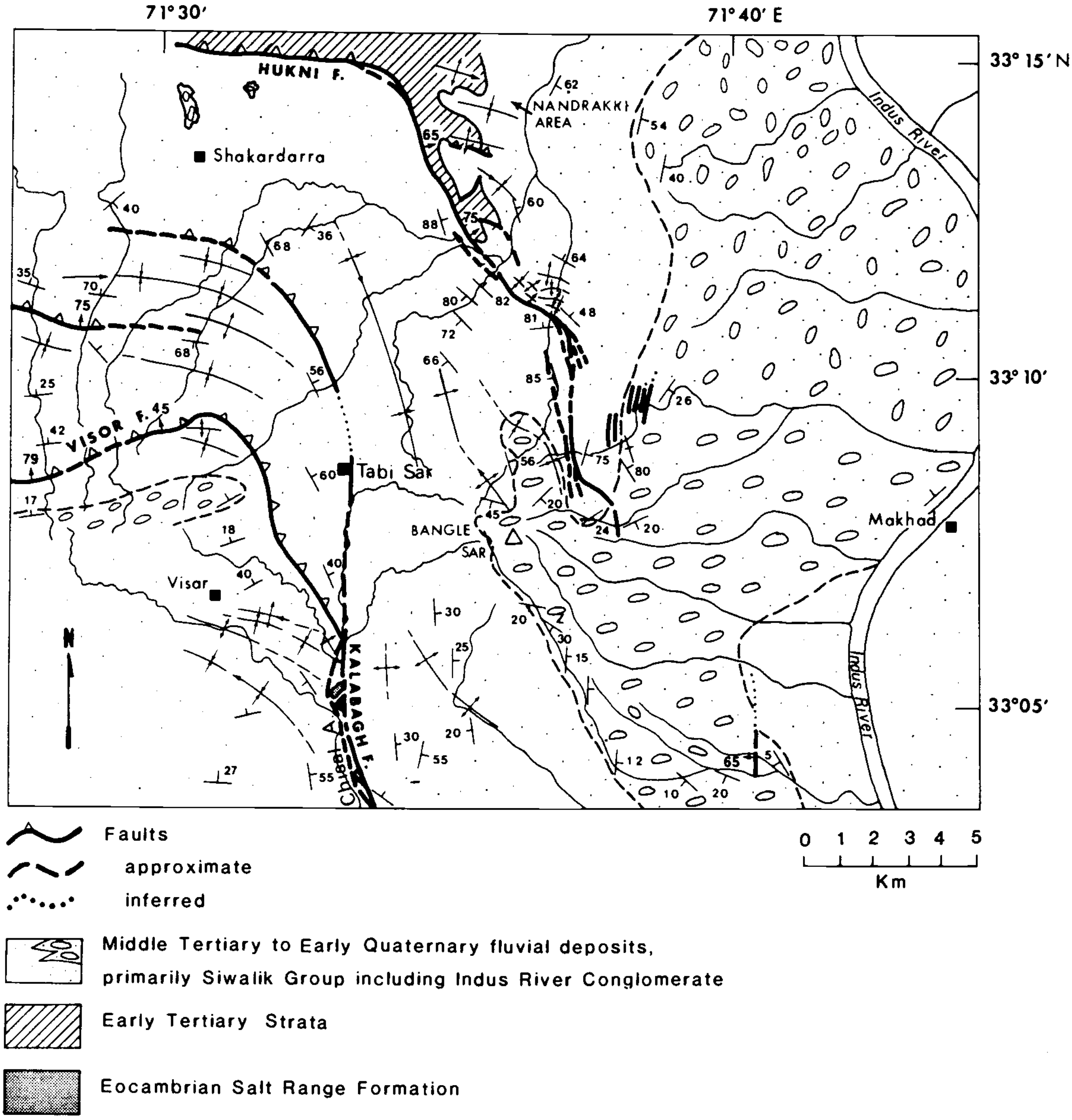


Figure 2.8-A: A portion of a Bouguer gravity composite map, in mgal, recorded by Oil and Gas Development Corp. of Pakistan and published in Farah et al, 1977. Shaded lines are the gradient from which the residual map was constructed, projected westward from the central Potwar Plateau and eastward across the Kalabagh re-entrant.

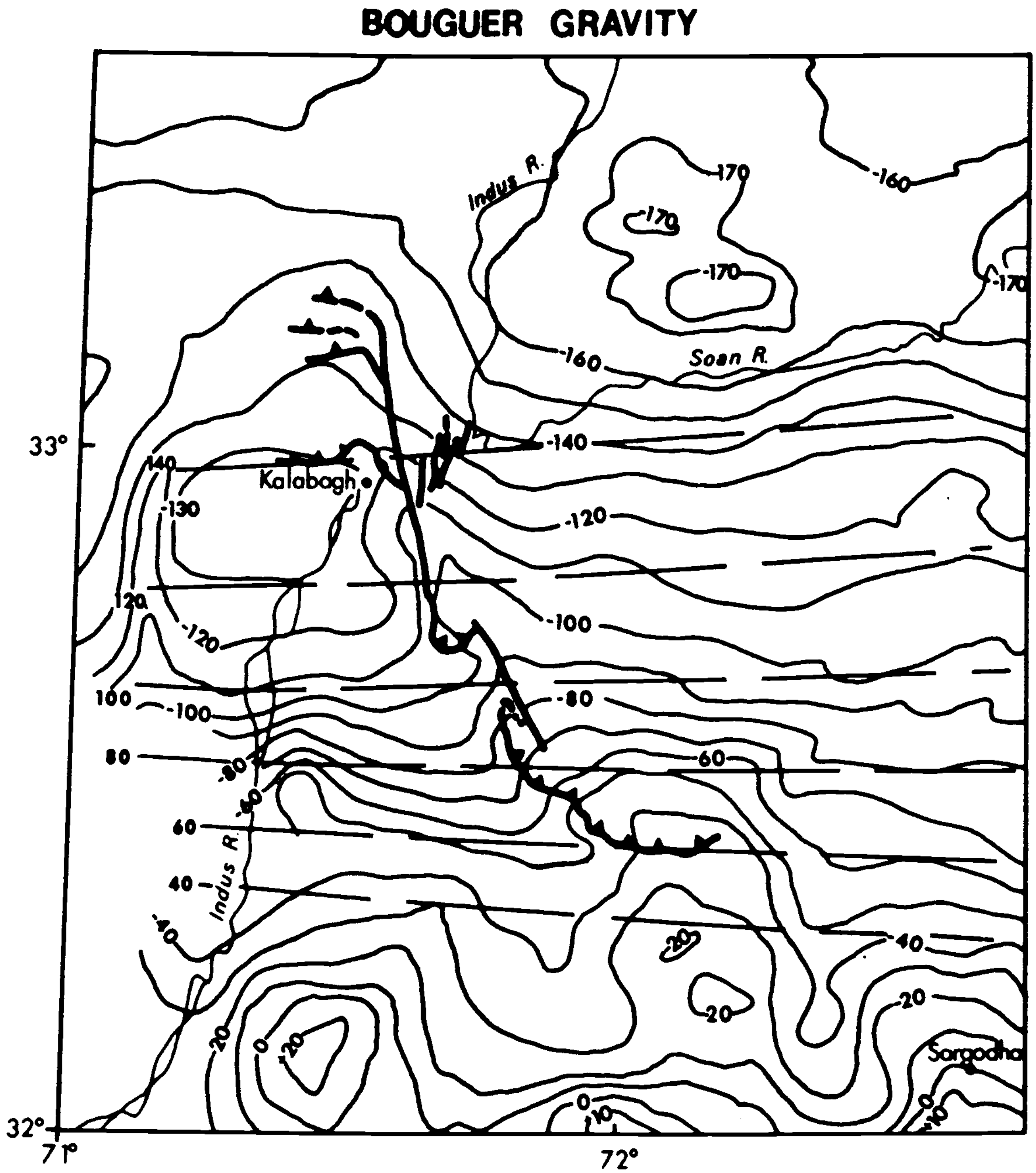

BOUGUER GRAVITY
Indus R.
-170
-170
-170
-160
-170
-160
Soan R.
33°
-140
140
Kalabagh
-130
-120
120
-120
-100
100
-100
-80
80
-80
-60
-60
60
Indus R.
40
-40
-40
-20
-20
-20
-20
0
-20
Sargodha
0
-10
0
-10
32°
71°
72°

Figure 2.8-A

Figure 2.8-B: Bouguer gravity residual anomalies, in mgal., where gravity values were contoured from the regional gradient of negative Bouguer gravity values increasing northward in 2.8-A to show the higher frequency component. Bold lines superimpose the Kalabagh fault zone and Surghar Range front fault.

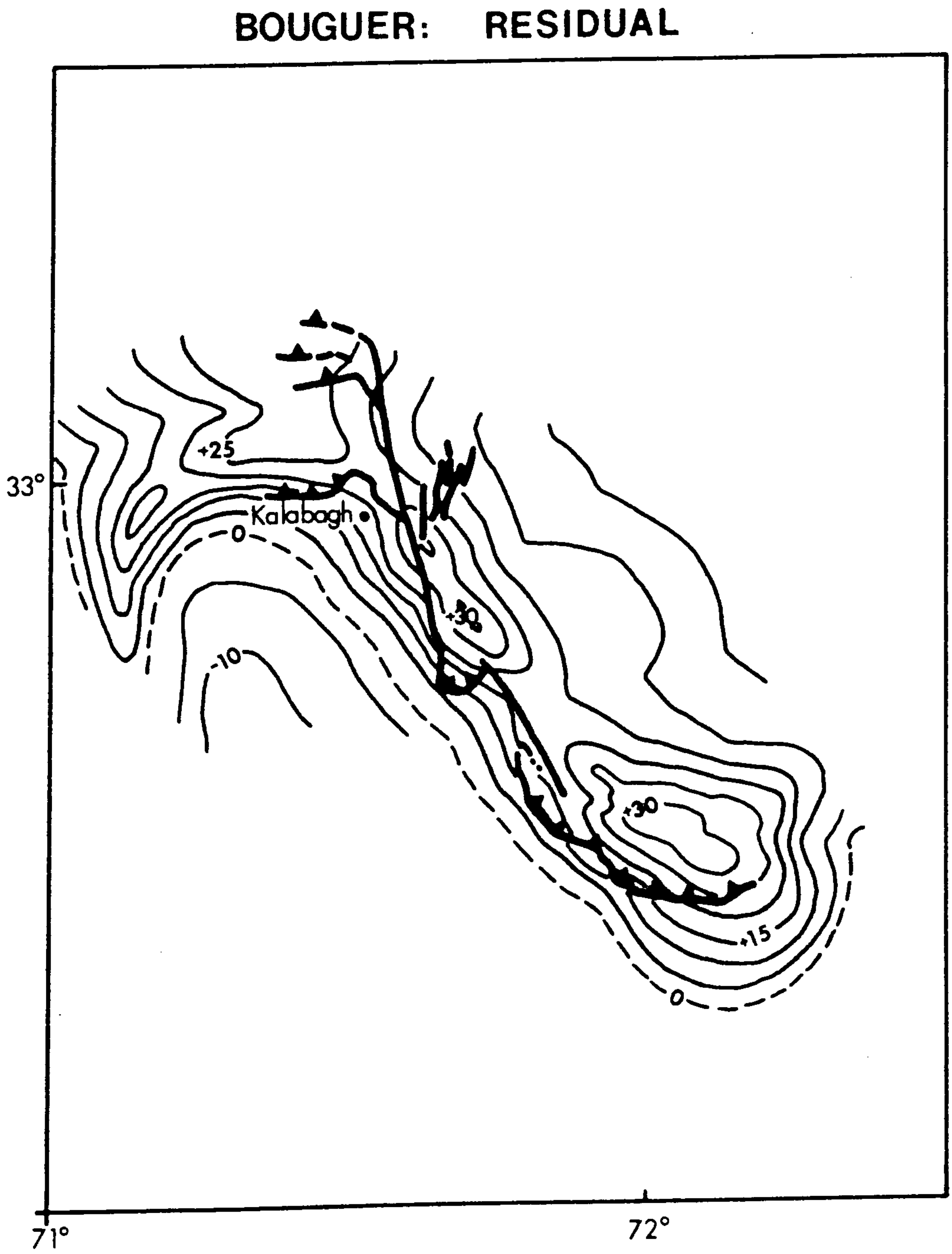


Figure 2.8-B

Figure 2.9: Schematic drawing of the Kalabagh fault lateral ramp with cutaway E-W cross section of the southern Ghundi lobe, located in figure 2.2. The basement ridge extends north to the Kalabagh area where it dies out, as suggested by reduction of the residual gravity anomaly of figure 2.8-B. Depths to basement and approximate thicknesses of section are projected from reflection seismic and well data east of area of diagram (Leathers, 1987).

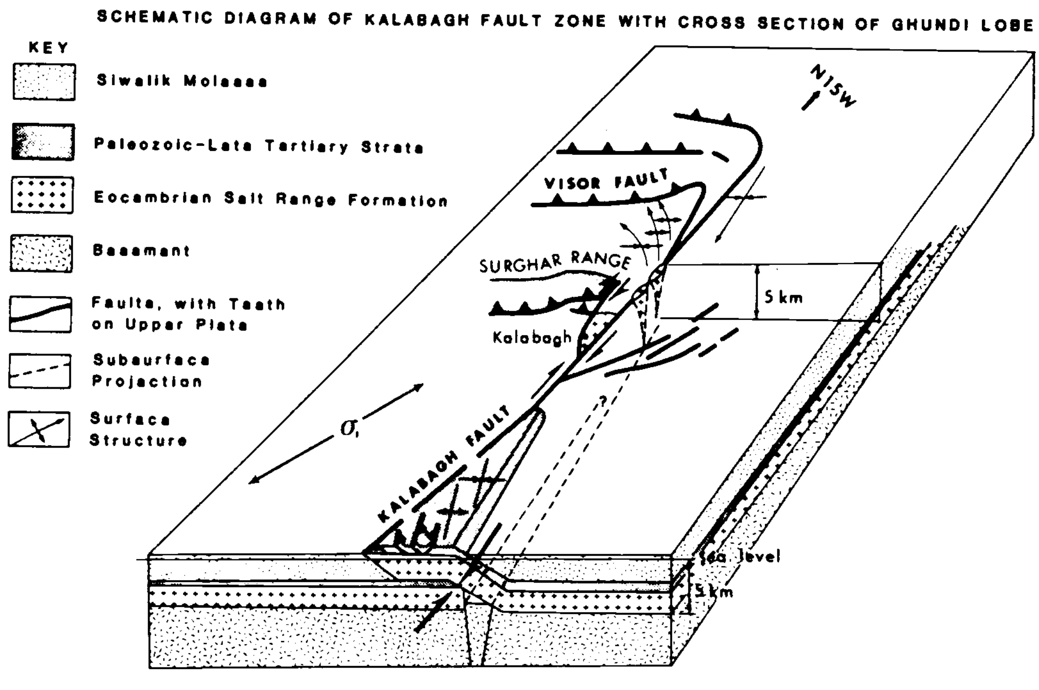

SCHEMATIC DIAGRAM OF KALABAGH FAULT ZONE WITH CROSS SECTION OF GHUNDI LOBE
KEY
Siwalik Molasse
Paleozoic-Late Tertiary Strata
Eocambrian Salt Range Formation
Basement
Faults, with Teeth on Upper Plate
Subsurface Projection
Surface Structure
N15W
VISOR FAULT
SURGHAR RANGE
Kalabagh
5 km
KALABAGH FAULT
Sea level
5 km

Figure 2.9

Figure 2.10: Comparison between the left-slip Jacksboro tear fault zone at southwest corner of the Pine Mountain thrust plate, southern Appalachians, and the Kalabagh right-lateral tear fault zone, northern Pakistan. Only major structures and geological units are shown. Figures are oriented to compare thrust fault to strike-slip fault transition zones and are at the same scale. The Jacksboro fault zone map is after Harris (1970, 1977).

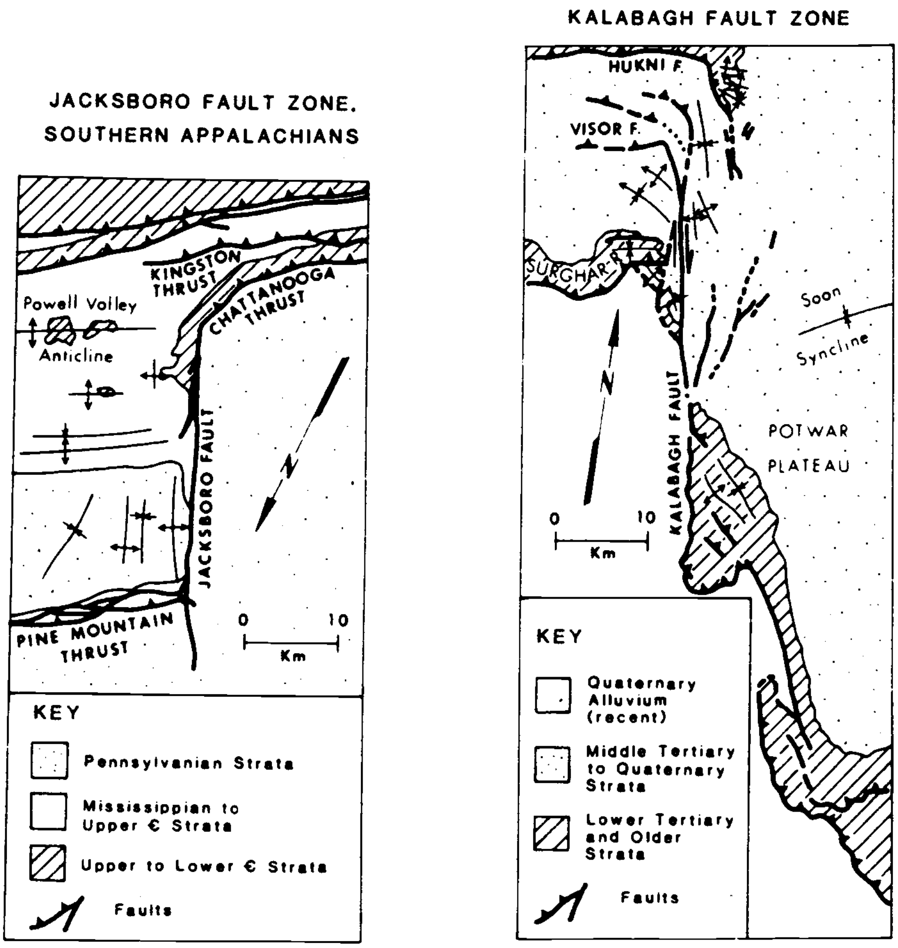

JACKSBORO FAULT ZONE, SOUTHERN APPALACHIANS
KINGSTON THRUST
CHATTANOOGA THRUST
Powell Valley Anticline
JACKSBORO FAULT
PINE MOUNTAIN THRUST
0 10 Km
KEY
Pennsylvanian Strata
Mississippian to Upper € Strata
Upper to Lower € Strata
Faults
KALABAGH FAULT ZONE
HUKNI F.
VISOR F.
SURGHAR R.
Soon Syncline
POTWAR PLATEAU
KALABAGH FAULT
0 10 Km
KEY
Quaternary Alluvium (recent)
Middle Tertiary to Quaternary Strata
Lower Tertiary and Older Strata
Faults

Figure 2.10

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III. TECTONICALLY-INDUCED DIVERSION OF THE INDUS RIVER WEST OF THE SALT RANGE, PAKISTAN

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Abstract

Neogene and Quaternary molasse deposition at the west end of the Salt Range in the foreland fold-thrust belt of northern Pakistan produced an unusually thick upper Siwalik section near the Indus River. Here, Siwalik sedimentary rocks coarsen upsection to 1500-m-thick, stacked channel-conglomerate deposits with a distant provenance, similar to gravels forming the bedload of the modern Indus River. The Chisal Algad, an underfit stream separated from the Indus River by a tectonically-induced drainage divide, contains a bedload clast assemblage resembling that of the Indus River. The Indus channel migrated eastward, abandoning the Chisal Algad and leaving high terrace remnants of Indus gravels unconformably overlying tilted Siwalik sedimentary rocks north of Shakardarra. Thrust faulting and transpression in the right-slip Kalabagh fault zone tilted and uplifted a block measuring 15 km east-west by 30 km north-south.

The block has been incised by juvenile consequent drainage toward the Indus River. The Indus River was diverted eastward since 0.5 Ma and now occupies the lower part of the Soan River valley.

Introduction

Neogene and Quaternary molasse sedimentation and deformation characterize the foreland fold-and-thrust belt in the western Potwar Plateau and southeastern Kohat Plateau of Pakistan. The region received fluvial sediments from mountainous areas as far as 600 km to the north and northeast that were uplifted as a result of continental collision. A broad clastic wedge stretching across the frontal Himalaya is involved in Pliocene and Quaternary deformation. The Salt Range thrust that bounds the Potwar Plateau on the south is still active (Yeats and others, 1984; Baker and others, 1988).

The Murree and Siwalik molasse sequence in the eastern Potwar Plateau ranges in age from mid-late Miocene to late Pleistocene (Gill, 1952). Gill recognized lateral changes and the time-transgressive nature of stratigraphic units within the Siwaliks, previously named by Pilgrim (1913) and others. Paleomagnetic stratigraphy and radiometric ages of volcanic ashes within the Siwalik sequence define an

18.3-5.1 Ma age range in the south-central Potwar Plateau (Johnson and others, 1982, 1985). In the Trans-Indus Salt Range and Surghar Range, west of the Indus River, Siwaliks are assigned paleomagnetic ages of 11.8-0.5 Ma (Khan, 1983). Raynolds and Johnson (1985) described southward migration of a synorogenic depression across the the eastern Potwar Plateau since 2.1 Ma as the foreland depocenter advanced ahead of the deformation front.

Depositional-deformational relationships in the vicinity of the Indus River

Faults cutting the pre-molasse section north of the Himalayan frontal fault typically die out as blind thrusts within the Siwalik molasse section, producing uplift of their hanging walls. Faults associated with the right-lateral Kalabagh fault system cut the entire section and reach the surface. Siwalik strata were deformed as the deformational front of the fold-thrust belt migrated from the Kohat Plateau southward. A regional angular unconformity, dated near Rawalpindi, indicates cessation of deformation and uplift of the Soan syncline at 1.9-2.1 Ma (Johnson and others, 1986), but a comparable unconformity has not been recognized near the Indus River. Nearly continuous syntectonic fluvial deposition appears to have occurred near the channel axis of the Indus River during Neogene and Quaternary time.

The upper 1500 meters of the Siwalik section near the Indus River north of Kalabagh is dominated by channel conglomerate. This conglomerate averages 80% metamorphic and igneous rock clasts and 20% sedimentary rock clasts; dominantly limestone. The provenance for this clast assemblage is as far as 600 km to the north in the upper Indus drainage and includes the Karakoram and Kohistan regions of northern Pakistan. Rock exposures of polymictic upper Siwalik conglomerate are indistinguishable in clast content from modern Indus River channel deposits. Paleo-channels align approximately N-S, as do the modern channels. These conglomerates fill the depocenter of the Plio-Pleistocene Indus River in the Indus River and Chichali sections (Figure 3.1).

The Indus River conglomerate compares with true polymictic conglomerates described previously by Anderson (1927) and others, and implied to be far-derived. Gill (1952) showed a conglomerate-dominant section in the western Potwar Plateau in the upper Nagri, Dhok Pathan, and younger stages of Siwalik deposition. Gill (1952) also recognized an unconformity between the upper Siwaliks and flat-lying Lei Conglomerate in the central Potwar Plateau that corresponds to the unconformity dated at 1.9-2.1 Ma in the Soan syncline by Johnson and others

(1986). An absolute age for the Indus River conglomerate has not been determined, and time correlations from magnetostratigraphic sections 60 km to the southeast (Johnson and others, 1982, 1985) and 20 km to the west (Khan, 1983) are tenuous. Figure 3.1 shows the lithology and relative age of the Indus River section based on current Siwalik age determinations from fossils and correlation with sections elsewhere that have been dated by tephrochronology and magnetic stratigraphy. In contrast to the Indus River conglomerate, fanglomerates such as the Kalabagh Conglomerate of Gee (1945, 1947, 1980) are dominated by clasts of locally-derived lower Tertiary limestone.

Indus River conglomerate deposits dominate the upper Siwalik succession throughout the region between the south-draining Chisal Algad and north-draining Lagorai Algad (algad = small stream) on the west and the modern Indus River on the east (Figure 3.2). Indus River terrace remnants also cap flat-topped hills immediately north of Shakardarra. Recycled far-derived conglomerate cobbles occur throughout the drainage systems of the Chisal Algad and Lagorai Algad, including tributaries draining eastward. Fluvial terraces containing far-derived cobbles occur more than 50 meters above present base level in tributaries of the Chisal Algad. The Chisal Algad and Lagorai Algad are now characterized by intermittent sediment discharge typical of an arid region and are underfit. For example, at its confluence with the Indus River near Kalabagh, the Chisal Algad braidplain is nearly 500-m-wide. I conclude that the Indus River formerly occupied the drainage area now occupied the Chisal Algad and formed the channel of the Chisal Algad. The Lagorai Algad may also have been part of the paleo-Indus channel.

Neotectonics

Eastward diversion of the Indus River channel away from the Chisal Algad indicates uplift due to oblique compression in the active right-lateral Kalabagh fault zone. Gentle eastward dips in erosionally-resistant conglomerate beds west of the Indus River, opposite the Soan-Indus confluence, indicate eastward tilting of an elongate crustal block measuring approximately 15 km east-west by 30 km north-south, between the modern Indus channel and the proposed abandoned channel (Figure 3.2).

Topographic profiles across the block indicate uplift as well as incision by the Chisal Algad and Lagorai Algad (Figure 3.3). The undissected N-S profile of high topography of the block is a broad convex upward curve with a maximum elevation of 659 meters above the modern Indus River, indicating minimum vertical uplift. Longitudinal profiles of the Chisal Algad and Lagorai

Algad are upwardly concave toward the north and south, respectively, to a divide near Tabi Sar that is 470 meters above the present Indus River profile (Figure 3.3). The modern Indus River channel occupies a hinge zone bounding the block on the east (figure 3.2). The Indus river gradient is reduced by 50% below Kalabagh, where the river flows onto the Indus River floodplain.

Juvenile subsequent drainage incises the eastward-sloping tilted block, and the Indus River cuts a gorge through erosionally resistant Nagri sandstone upstream from the town of Kalabagh. Elsewhere in the region, Indus and Soan River tributaries have dendritic or trellis drainage patterns. Although some eastward migration of the Indus River may continue, the tectonic hinge zone (Figure 3.2) may confine the channel and restrict further migration. The eastern boundary of the block may be the location of continued fault displacement. Overall sense of displacement in the zone of faults near the Indus-Soan confluence is enigmatic, i.e., several of these faults have dip separation whereas the overall sense of motion may be right-slip.

The present path of the Indus River for the 50 km between the Lagorai-Indus confluence and the Kalabagh area may also be a former tributary and trunk stream segment of the Soan River. Because of the tectonically-induced channel diversion, the Soan River did not capture the much larger Indus River by headward erosion of its tributary.

Uplift rates for the block may be related to late Quaternary right-lateral displacement rates of 7-10 mm/year or more along the Kalabagh fault, with uplift related to oblique compression (McDougall, 1987, 1988). Uplift is not confined to the block itself. Uplifted terrace deposits north of Shakardarra and in east-draining tributaries of the Chisal Algad indicate uplift along thrust faults branching west from the main Kalabagh fault that bounds the block on the west.

Although the time of channel migration has not been determined, displacement of the Kalabagh fault is post-2.1 Ma in age and may be dominantly post-0.5 Ma in age (McDougall, 1988). The Indus River diversion occurred during a period of rapid uplift in the Kalabagh fault zone, probably in the last 500,000-100,000 years. Active faulting affecting the course of the Indus River continues to the present day.

Conclusions

Conglomerate deposits associated with the paleo-Indus River occur in an area over 20 km wide (E-W), west of the Indus River, that has been tectonically separated from the source region of these deposits. These far-derived polymictic conglomerates occur as a thick bedded sequence that was later exposed by uplift, as high terrace remnants north of Shakardarra, and in the bed load of the Chisal Algad and Lagorai Algad. Block tilting because of transpression and thrust faulting in the Kalabagh fault zone restructured the drainage system since 2.1 Ma. Rapid uplift probably diverted the Indus River eastward since 0.5 Ma., causing it to occupy part of the paleo-Soan River system.

Figure 3.1: Stratigraphic position and thicknesses of lithostratigraphic units of the Indus River section (2) of this paper relative to the Chichali-Chani Khel composite paleomagnetic section (1) of Khan (1983) in the Surghar-Shinghar Ranges, the Daud Khel section (3) of Hussein and others (1979), and the Chinji-Nagri paleomagnetic section (4) of Johnson and others (1985) in the south-central Potwar Plateau. Thicknesses of units in the Indus River section compare with those near Makhad in the western part of the lithostratigraphic section of Gill (1952, p. 389). Siwalik divisions are based on Pilgrim's (1913) Chinji, Nagri, and Dhok Pathan Formations and fossil ages summarized by Pilbeam and others (1977). Location of sections (1-4) are shown on index map.

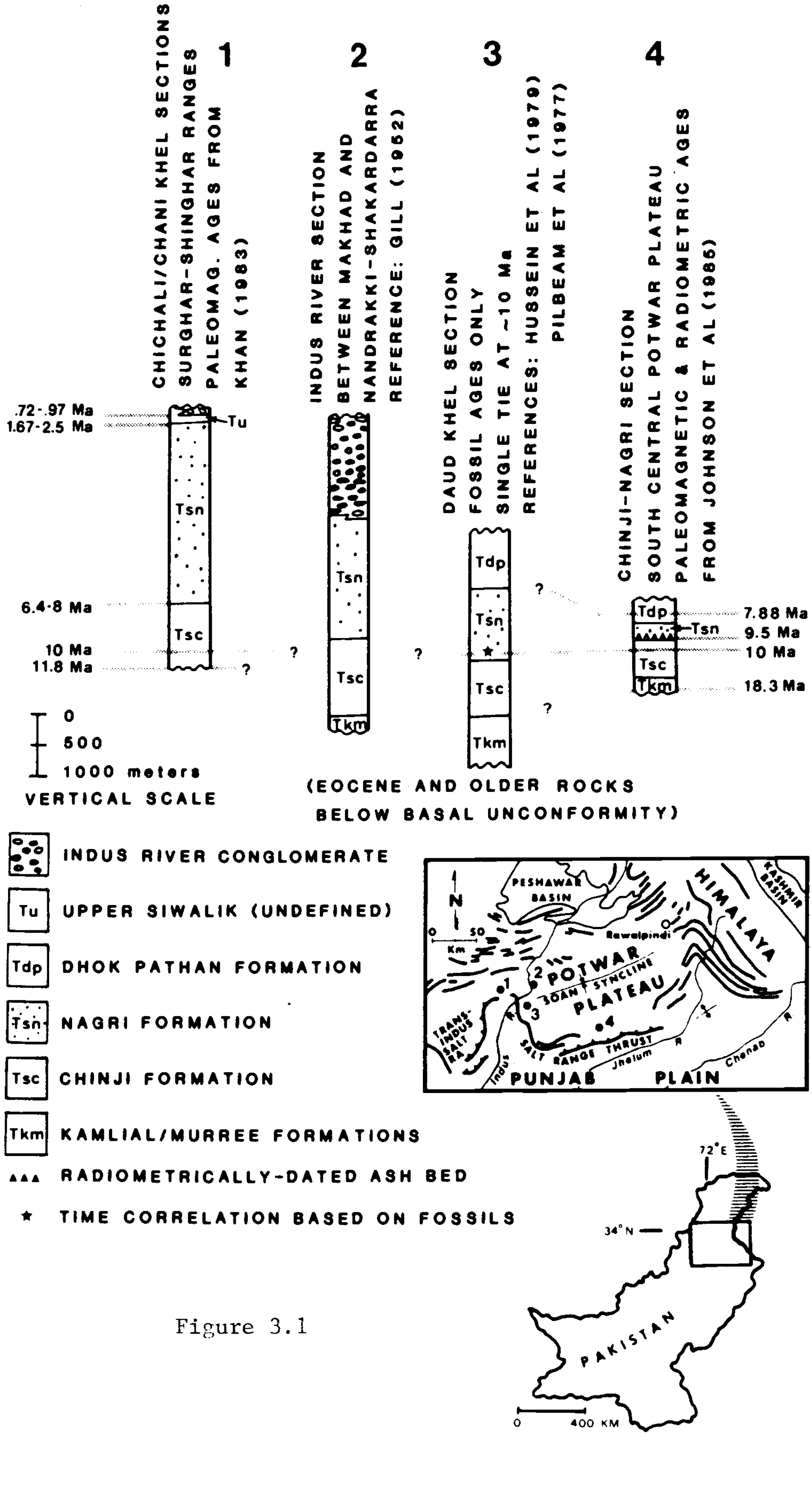

1
CHICHALI/CHANI KHEL SECTIONS
SURGHAR-SHINGHAR RANGES
PALEOMAG. AGES FROM
KHAN (1983)
2
INDUS RIVER SECTION
BETWEEN MAKHAD AND
NANDRAKKI-SHAKARDARRA
REFERENCE: GILL (1952)
3
DAUD KHEL SECTION
FOSSIL AGES ONLY
SINGLE TIE AT ~10 Ma
REFERENCES: HUSSEIN ET AL (1979)
PILBEAM ET AL (1977)
4
CHINJI-NAGRI SECTION
SOUTH CENTRAL POTWAR PLATEAU
PALEOMAGNETIC & RADIOMETRIC AGES
FROM JOHNSON ET AL (1985)
.72-.97 Ma
1.67-2.5 Ma
Tu
Tsn
6.4-8 Ma
Tsc
10 Ma
11.8 Ma
Tdp
Tkm
7.88 Ma
9.5 Ma
10 Ma
18.3 Ma
?
0
500
1000 meters
VERTICAL SCALE
(EOCENE AND OLDER ROCKS
BELOW BASAL UNCONFORMITY)
INDUS RIVER CONGLOMERATE
Tu UPPER SIWALIK (UNDEFINED)
Tdp DHOK PATHAN FORMATION
Tsn NAGRI FORMATION
Tsc CHINJI FORMATION
Tkm KAMLIAL/MURREE FORMATIONS
RADIOMETRICALLY-DATED ASH BED
TIME CORRELATION BASED ON FOSSILS
PESHAWAR BASIN
KASHMIR BASIN
HIMALAYA
N
0 50 Km
Rawalpindi
POTWAR PLATEAU
SOAN SYNCLINE
TRANS-INDUS SALT RA.
SALT RANGE THRUST
Indus
Jhelum
Chenab
R
PUNJAB PLAIN
72°E
34°N
PAKISTAN
0 400 KM

Figure 3.1

Figure 3.2-A: Area of Quaternary diversion of the Indus River along the Kalabagh fault with major structural, tectonic, and geomorphic elements at the surface. The ridge line is on the high side of the tilted block. Large arrows indicate general sense of shear in the Kalabagh fault zone, and the hinge line is shaded at the center right.

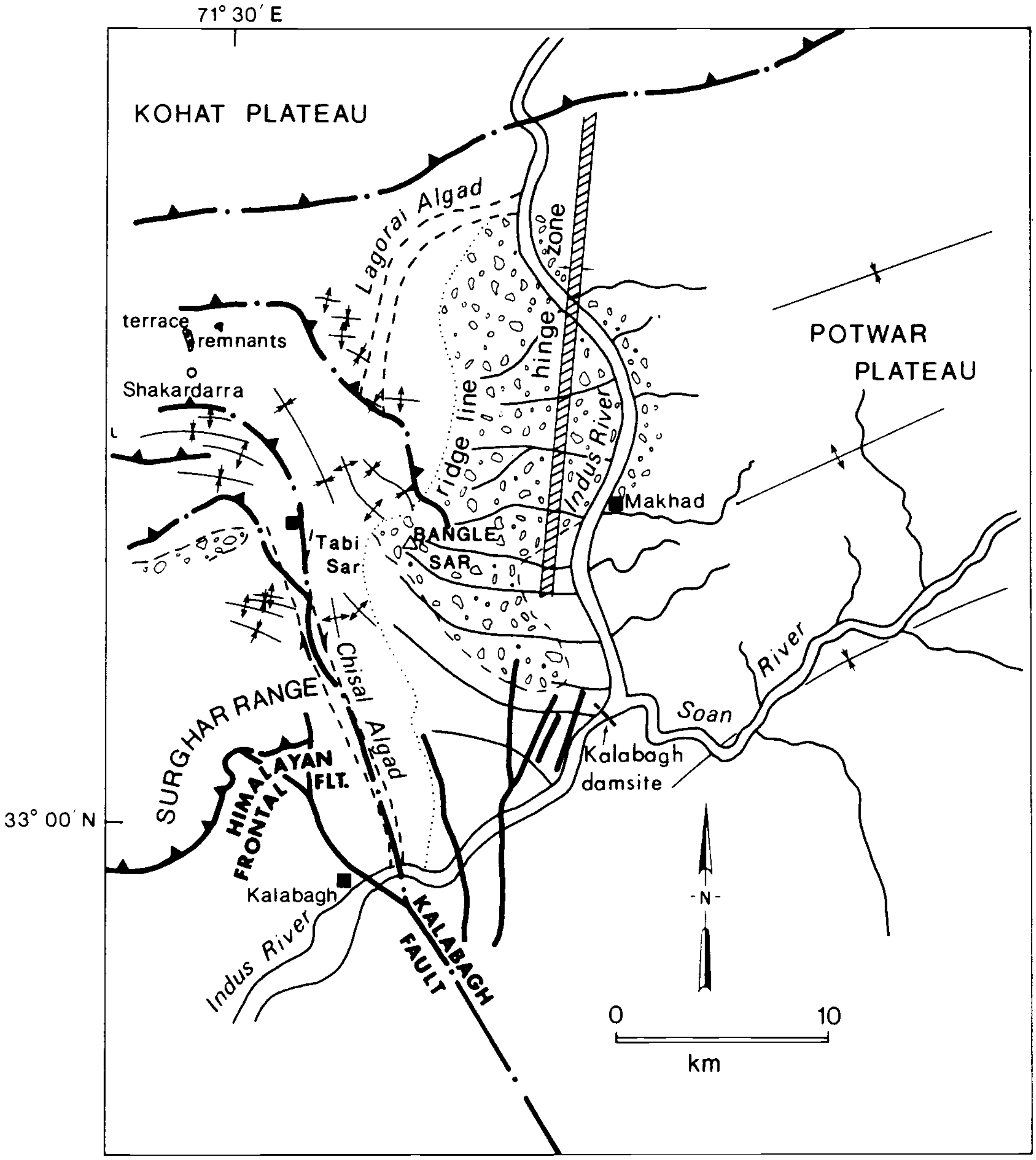

71° 30′ E
KOHAT PLATEAU
Lagorai Algad
terrace remnants
Shakardarra
POTWAR PLATEAU
ridge line
hinge zone
Indus River
Makhad
Tabi Sar
BANGLE SAR
Chisal Algad
SURGHAR RANGE
HIMALAYAN FRONTAL FLT.
Soan River
Kalabagh damsite
33° 00′ N
Kalabagh
Indus River
KALABAGH FAULT
N
0
10
km

Figure 3.2-A

Figure 3.2: (Bottom) Three-dimensional sketch of tilted block with cutaway along ENE line of cross section. Indus River conglomerate is shown as upper Siwalik bedded unit and terrace deposits in upper left (near Shakardarra). Indus gravels indicated with cobble pattern are polymictic conglomerates with similar distant provenance.

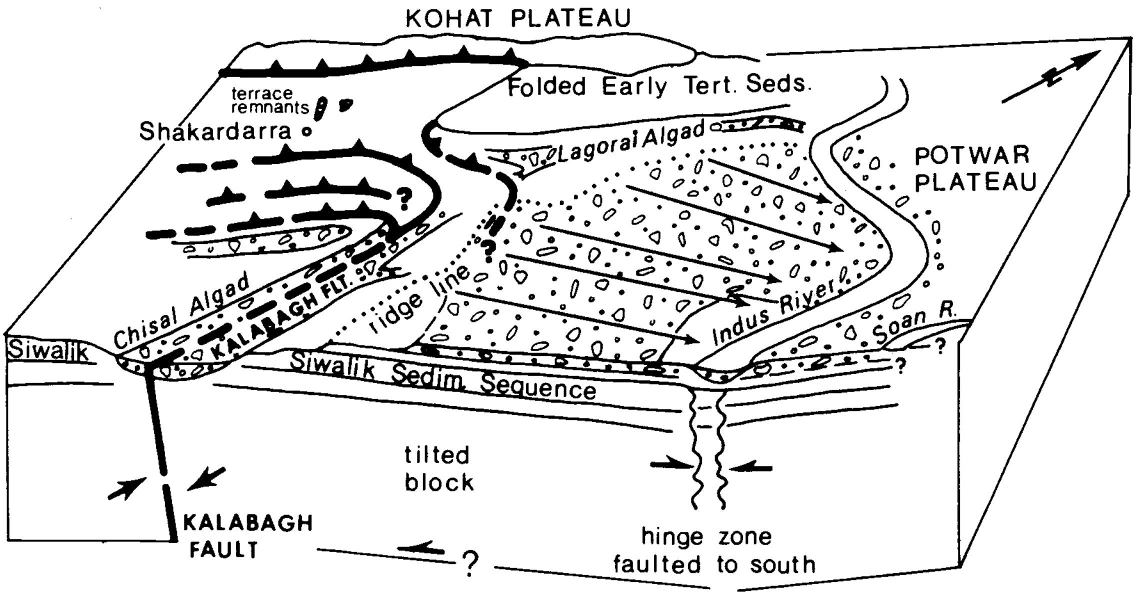

KOHAT PLATEAU
Folded Early Tert. Seds.
terrace remnants
Shakardarra
Lagorai Algad
POTWAR PLATEAU
Chisal Algad
KALABAGH FLT.
ridge line
Indus River
Soan R.
Siwalik
Siwalik Sedim. Sequence
tilted block
KALABAGH FAULT
hinge zone faulted to south

Figure 3.2-B

Figure 3.3: Longitudinal profiles of the Chisal Algad and Lagorai Algad (A-A'), the divide of the uplifted block (B-B'), and the modern Indus River (C-C'), with vertical exaggeration where indicated. Line with shorter dashes in B-B' indicates an idealized profile of the tectonically-induced high topography of the divide prior to erosion. Gradient changes were not detected in the modern Indus River except downstream from the confluence with the Chisal Algad, where the gradient is reduced 50% from that indicated on the figure.

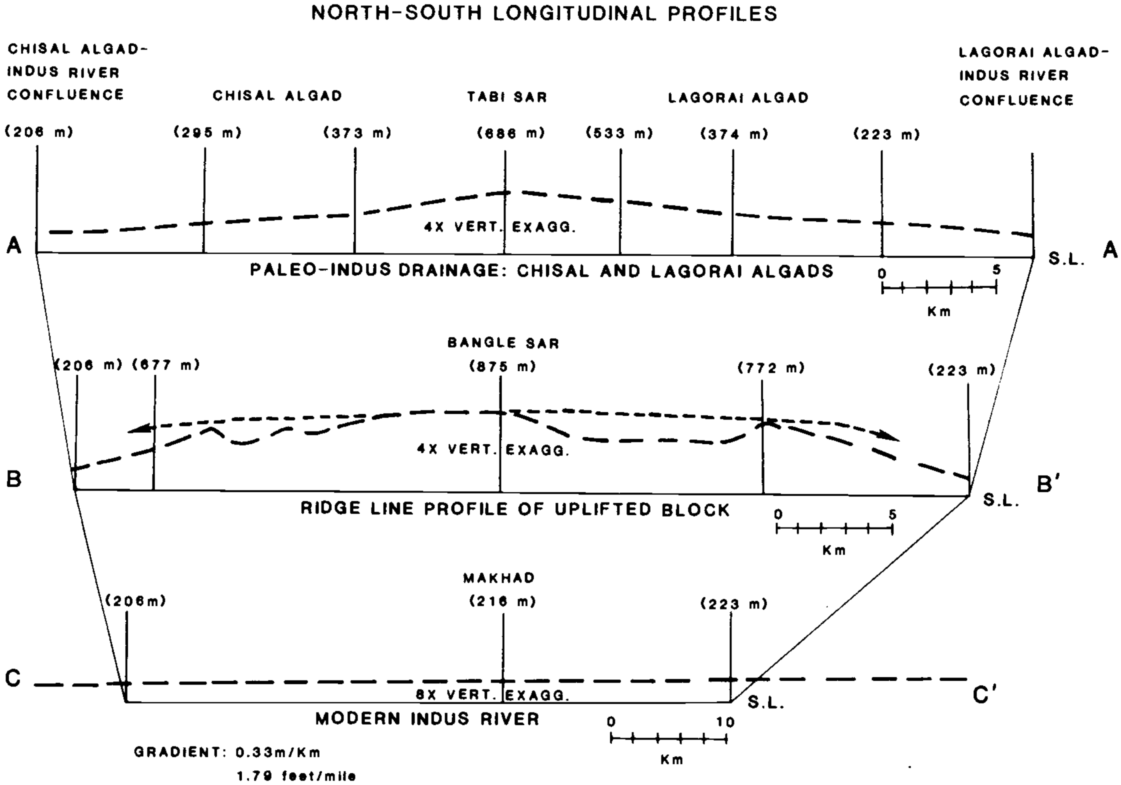
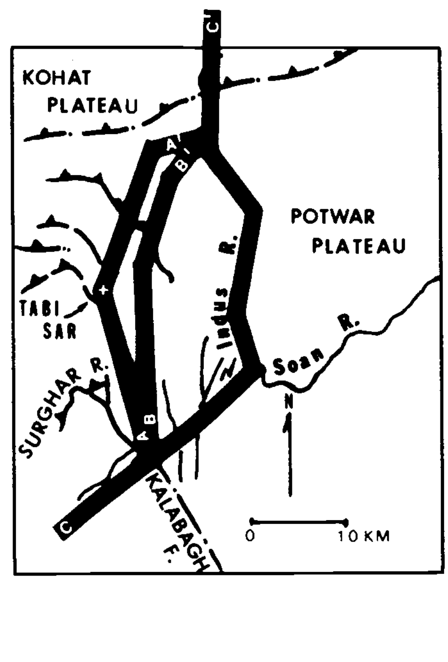

NORTH-SOUTH LONGITUDINAL PROFILES
CHISAL ALGAD-
INDUS RIVER
CONFLUENCE
CHISAL ALGAD
TABI SAR
LAGORAI ALGAD
LAGORAI ALGAD-
INDUS RIVER
CONFLUENCE
(206 m)
(295 m)
(373 m)
(686 m)
(533 m)
(374 m)
(223 m)
4X VERT. EXAGG.
A
A'
S.L.
PALEO-INDUS DRAINAGE: CHISAL AND LAGORAI ALGADS
0
5
Km
BANGLE SAR
(206 m) (677 m)
(875 m)
(772 m)
(223 m)
4X VERT. EXAGG.
B
B'
S.L.
RIDGE LINE PROFILE OF UPLIFTED BLOCK
0
5
Km
MAKHAD
(206m)
(216 m)
(223 m)
C
C'
8X VERT. EXAGG.
S.L.
MODERN INDUS RIVER
0
10
Km
GRADIENT: 0.33m/Km
1.79 feet/mile

Figure 3.3


KOHAT
PLATEAU
POTWAR
PLATEAU
TABI
SAR
SURGHAR R.
Indus R.
Soan R.
KALABAGH F.
N
0
10 KM
C'
A'
B'
A
B
C

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IV. FOLD-AND-THRUST PROPAGATION IN THE WESTERN HIMALAYA, BASED ON A BALANCED CROSS SECTION OF THE SURGHAR RANGE AND KOHAT PLATEAU, PAKISTAN

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Abstract

Layer-parallel slip dominated a wedge tapering approximately 2° across the 70-km-wide Kohat foreland fold-thrust belt, between the Main Boundary thrust (MBT) and the Surghar Range of northern Pakistan. Decollement thrust sheets with individual displacement as much as 32 km were deformed by fault-bend folds. Balanced cross sections show over 50% line-length shortening by blind thrusting of which less than half is documented in faults and folds at the surface. This discrepancy may be explained by buried tip lines and decoupling at the base of the overlying Siwalik clastic wedge, a surface across which fold harmonics also vary. Folds, thrust faults, and backthrusts in the Kohat Plateau commonly die out in the overlying molasse that probably pre-dates the structures.

Decollement thrusting advanced across the Kohat Plateau toward the southernmost frontal thrust ramp at the Surghar Range that emerged at about 2 Ma. The Surghar Range thrust appears to pre-date thrust faults 12-20 km to the north in the Kalabagh fault zone. This out-of sequence thrusting is interpreted as a taper-building response to increased decollement dip. Surface geology, seismic reflection data, and a Bouguer gravity anomaly were used to interpret a north-facing fault scarp in the basement below the Surghar Range.

Low basal shear traction ($\tau_0 \leq 1$ MPa) along Eocene and Eocambrian evaporite layers predicts the low critical taper of the Kohat-Surghar wedge. The wedge is presently subcritical and undergoing taper-preserving deformation internally over a nearly flat basement.

Introduction

The active Himalayan fold-thrust belt south of the Main Boundary thrust (MBT) in northern Pakistan (Figure 4.1) is an allochthonous wedge of deformed sedimentary rocks with a low ($\leq 4°$) cross-sectional taper that propagated rapidly southward during the Quaternary. The lower boundary for decollement thrusting is the top of the north-dipping Indian shield basement, mapped with seismic reflection profiles (Lillie and others, 1987) and modeled regionally with gravity data (Farah and others, 1977; Duroy and others, 1988). Mechanical models of deformation in the foreland fold-thrust belt north of the Salt Range thrust (Jaume and Lillie, 1988) indicate decoupling along a stratigraphic horizon dominated by evaporites, following Davis and Engelder (1985). Earthquakes concentrated at depths 10 km in the Hazara and Indus-Kohistan seismic zones north of the MBT (Seeber and Armbruster, 1979; Seeber and others, 1981) locate a probable backstop for the active wedge. Slip extends beneath the wedge south of the MBT, with low seismicity, to active frontal thrust faults at the Salt Range (Yeats and others, 1984; Baker and others, 1988), and the Kalabagh fault zone (McDougall and Khan, 1988).

Commercial seismic reflection profiles were used in determining the low north slope of the top of basement in the Kalabagh re-entrant (McDougall, 1988) and beneath the western Potwar Plateau (Leathers, 1987). A cross section of the central Salt Range thrust from seismic reflection profiles was used to estimate lateral shortening of about 20 km at the frontal ramp (Baker and others, 1988).

Surface geology, seismic reflection data, drill hole data, and a Bouguer gravity map were used to constrain a balanced cross section of the foreland fold-thrust belt of the Kohat Plateau and western Potwar Plateau. Geological mapping of Yeats and Hussain (1987), A. Hussain (unpublished data), Meissner and others (1974), E.R. Gee (1980, unpublished data), McDougall (1988), and McDougall and Khan (1988) was used with seismic reflection profiles to locate thrust ramps and major folds and the depth to basement in the Kohat foreland fold-thrust belt. Construction of balanced (retrodeformable) cross sections incorporates ideas of Rich (1934), Dahlstrom (1969), Boyer and Elliott (1982), Suppe (1983), Woodward and others (1985), and many others.

The 75 km long cross section extends from the Main Boundary thrust (MBT) to the Surghar Range frontal thrust fault and the edge of the Indus River floodplain (Figures 4.1, 4.2). Data from the northeastern Kohat Plateau, northern Potwar Plateau, southern Kala Chitta Range, and western Salt Range are used in the cross section. These data represent the fold-thrust belt between the MBT on the north, the Kalabagh re-entrant on the south, the

Indus River on the east, and the western Kohat Plateau (~71°15') on the west.

Horizontal shortening along major decollement thrust faults in the foreland fold-thrust belt is calculated from balanced cross sections. The style of deformation is shown in the direction of tectonic transport. The stability of the wedge, implications for surface faulting, and the sequence of thrust propagation are addressed.

Data and observations

Surface geology:

The Main Boundary thrust (MBT), as defined by Yeats and Hussain (1987) along the south flank of the Kala Chitta Range, truncates subparallel folds of the foreland fold-thrust belt in the northern Kohat Plateau (Figure 4.2). A window in the MBT at Mazari Tang, exposing the Eocene Kuldana Formation 2 km north of the thrust front, indicates the shallow north dip of the MBT.

At least two groups of folds characterize the Kohat Plateau south of the MBT, where folded lower Tertiary rocks underlie strata of the Murree amd Kamlial formations, and the Siwalik Group. E-W to ENE-trending folds (F_1), with wavelengths of 1 km or less, were deformed into broader, elongated domes and basins of similar trend (F_2) with wavelengths of 3-5 km. Folds are either cogenetic or F_1 preceded F_2. The broader folds include the Panoba dome in the northeastern Kohat Plateau and the Nandrakki dome near Shakardarra (Figure 4.2). The F_2 folds commonly have overturned limbs by passive amplification, e.g., limbs of the ENE-trending Panoba dome dip steeply toward the core of Paleocene-Eocene Patala Formation. Parasitic ENE-trending F_1 folds on the Panoba dome include a tight syncline at the crest of the dome. A steeply north-dipping thrust fault bounds the Panoba dome to the south. At the Nandrakki dome (F_2) in the southern Kohat Plateau, tight (F_1) box folds of Eocene Jatta Gypsum, Mami Khel Clay, and Kohat Limestone plunge east below the ~3-km-thick Siwalik molasse. The Hukni fault bounds the southern Kohat Plateau and the E- to SSE-trending Nandrakki dome to the south and west.

South of the Hukni fault (Figure 4.2), the northern Kalabagh fault zone is characterized by thrust faults and W- to NW-trending folds of less than 1 km wavelength in Siwalik strata. Cumulative shortening in the northern Kalabagh fault is estimated to be 2.5-4 km at the surface (McDougall and Khan, 1988). The Siwalik sequence thickens southward to more than 4 km on the northern flank of the Surghar Range.

Emergent Paleozoic to early Tertiary rocks of the Surghar Range are flanked on the north by Siwalik strata that dip 30°N. The Surghar Range is bounded on the south by a thrust fault bringing the foreland fold-thrust belt over Indus floodplain sediments of the Kalabagh re-entrant. A nearly vertical fault displaces the north limb of a tight uplifted syncline in the eastern Surghar Range. Evaporite deposits of the Eocambrian Salt Range Formation do not crop out in the Surghar Range, but are exposed at Kalabagh, 5-6 km SSE of the Surghar Range, and farther to the SSE along the western Salt Range.

Wells and stratigraphic data:

Deep wells, including the Dhermund and Dhurnal wells in the western Potwar Plateau, and the Kundian well in the Kalabagh re-entrant (Figure 4.1) provide regional stratigraphic control (Figure 4.3). The Kundian well penetrates an 1478 m-thick molasse section and a 685 m-thick Paleozoic section. The Dhermund well, in the west-central Potwar Plateau near the Soan River, penetrates a 3059 m-thick Siwalik-Kamlial-Murree molasse section, 401 m of lower Tertiary strata, a 230 m-thick Mesozoic section, 660 m of Paleozoic section, and the upper 42 m of the Salt Range Formation. The Dhurnal well, near the Kala Chitta Range, penetrates a 3742 m-thick molasse section generally older than that of the Dhermund well, a comparable 427 m-thick lower Tertiary section, no Mesozoic section, a 571 m-thick Paleozoic section, and the upper 27 m of the Salt Range Formation.

Stratigraphic sections include the Surghar Range section of Meissner and others (1974), with a lower Tertiary section about 1 km thick, and a Mesozoic section over 1 km thick that is not completely exposed. The Chichali section (Figure 4.3) combines the thickness of pre-Miocene rocks of the Surghar Range section with a Siwalik molasse section over 4 km thick (E.R. Gee, unpublished mapping).

The northern Kohat Plateau section (Figure 4.3), used in the cross section of the foreland fold-thrust belt, is projected from regional deep wells and stratigraphic sections. The Siwalik Group, Kamlial, and Murree formations in general thicken southward. The lower Tertiary section (including Eocene evaporite deposits) and Mesozoic section thicken to the west from the Potwar Plateau toward the Surghar Range and do not reach the Kundian well in the Kalabagh re-entrant. The northern Kohat Plateau section incorporates a thickness of the lower Tertiary and Mesozoic section similar to the Surghar Range to the south (Meissner and others, 1974). The northern Kohat Paleozoic section is extrapolated from the Dhurnal and Dhermund wells. A total thickness of about 2300 m for lower Tertiary (pre-molasse), Mesozoic, and Paleozoic strata is predicted for the northern Kohat Plateau section.

The Eocambrian Salt Range Formation is predicted at the base of the northern Kohat section from deep drill hole data of the Potwar Plateau (Dhurnal, Dhermund, and other wells) and the style of deformation in the Kohat foreland fold-thrust belt south of the MBT. The pre-Miocene (pre-molasse) section thickness in the fold-thrust belt south of the MBT compares (±1000 m) with thicknesses of strata of equivalent age north of the MBT. Uncertainty in stratigraphic thickness estimation increases to the north because of deformation and poor resolution by seismic reflection data.

Seismic reflection profiles:

Seismic reflection lines are from a data set with the highest density of coverage in the southernmost Kohat Plateau. Seismic data quality is generally low and lines are not tied to wells with velocity surveys, therefore representative interval velocities, based in part on stacking velocities, were applied to lines. Regional seismic reflection data from the Potwar Plateau and the Kalabagh re-entrant were also used to model the N-S cross section between the MBT and the Surghar Range frontal thrust.

Seismic line AW-15-AM (Figure 4.4), extending from near Kohat city across the Kohat Plateau (Figure 4.2), shows reflections at 4.0 sec. (2-way time), interpreted as the top of basement, that may dip north at the very northern end of the line, near the MBT. Along strike to the east, comparable basement reflections at 4.0-4.2 sec. on northern Potwar Plateau lines indicate a similar thickness of the allochthon (e.g., Lillie and others, 1987). The flat crest of a major fault-bend fold was interpreted in the center of line AW-15-AM, at 1.8 to 3.0 sec., 2-way time. The southern part of the line shows highly diffracted seismic energy from a zone of north-dipping thrust faults.

In the northeastern Kohat Plateau, N-S seismic line AW-15-AL near the Indus River (Figure 4.5) shows a major thrust ramp to basement. This ramp, below the projection of the Panoba dome, is probably on strike with the basement ramp near the center of line AW-15-AM (Figure 4.4).

The southern margin of the Kohat Plateau and northern Kalabagh fault zone are crossed by N-S seismic line NK-1 (Figure 4.6), that intersects the Hukni fault near Shakardarra. A fault-bend fold is interpreted on the southern half of line NK-1 at 1.7 to 2.5 sec. The crest of the fault-bend fold is 900-1200 m lower on a N-S seismic line 5 km to the east, along strike, indicating that the fold plunges east. A thrust ramp projects from the surface through the center of line NK-1. A weak basement reflection crosses line NK-1 at 3.8-4.0 sec. (2-way time).

In the Kalabagh re-entrant, 60 km to the south of the Surghar Range, seismic line AW-15-N shows basement dipping north about 0.8° and flattening northward toward the Surghar Range (Figure 4.7). Reflections terminating southward against the basement reflection on line AW-15-N indicate onlap of strata toward the WNW extension of the Sargodha high (Kirana Hills of figure 4.1).

Structural detail: balanced cross sections A-A', B-B', and C-C'

On northern cross section line C-C' (Figure 4.8), the window in the MBT at Mazari Tang overlies a 45° kink bend in the underlying plate. Weakening of the allochthon as it passed through this bend and compression probably produced tight folds (F_1) in the "M" thrust sheet (lines C-C', B-B'). Late-stage thrusting along the MBT, which lies to the north, may also have deformed the already mobile thrust sheet "M".

The large (5-6 km wavelength) F_2 fold culminating in the Panoba dome, strikes ENE across section B-B' in thrust sheet "M". The 50°N-dipping thrust fault on the south flank of the Panoba dome and shortening producing it and other F_2 folds may result from backlimb thrusting along the "N" thrust ramp to the south.

In northern cross section line A-A' (Figure 4.8), the major thrust sheet "M" was displaced at least 32 km and deformed by a fault-bend fold and imbricate thrust faults to the south. The "M" thrust sheet extends eastward to lines B-B' and C-C' where southward displacement is estimated as about 29 km. The crest of the fault-bend fold underlying the northern Kohat Plateau (center: line AW-15-AM; km marks 45-60 on line A-A') is overlain by emergent F_1 folds at the surface. The upper thrust plate propagated downsection and delaminated the crest of the fault-bend fold to the south, at km marks 30-45 on line A-A'. The Eocene Bahadur Khel Salt of the southern Kohat Plateau probably controlled delamination and shallow compressional deformation north of the Hukni fault.

Imbricate thrust faults in the southern Kohat Plateau overlie a major fault-bend fold beneath the northern Kalabagh fault zone. This fault-bend fold (on line NK-1, figure 4.6; km marks 23-33 on line A-A') dies out eastward beneath more tightly folded Siwalik strata. These strata repeat along the Visor fault and other thrust faults branching from the Kalabagh fault (Figure 4.8).

South of seismic line NK-1, surface dips project to the basal decollement thrust between axes of kink bends, following techniques of Suppe (1983, 1985). A keystone block in the emergent Surghar ramp (Figure 4.8: km marks 4-6 on line A-A') is bounded on the north by a down-to-the-north fault. This fault is shown to continue in basement from the cutoff line where it was truncated and rotated counterclockwise about 20° during displacement of 3-4 km along the thrust ramp. A normal fault in basement below the Surghar Range is interpreted from surface geology, projected seismic lines including AW-15-N (from the Kundian well to the Sargodha high, figure 4.7), AW-15-AM (Figure 4.4), NK-1 (Figure 4.6), and seismic lines and deep drill holes in the western Potwar Plateau. An

E-W-trending +25-30 mgal residual Bouguer gravity anomaly also follows the Surghar Range.

Discussion

Sequence of thrust faulting and associated deformation:

Decollement thrusting and folding in the Kohat foreland fold-thrust belt west of the Indus River developed from an undeformed foreland in the following sequence, determined from sequential palinspastic restoration of the balanced cross section (Figure 4.9):

(A) Succeeding 2.8-0.6 Ma displacement along the MBT, as discussed by Yeats and Hussein (1987), the blind "M" thrust sheet ramped in front of the MBT and began uplifting the Kohat Plateau (Figure 4.9-A). Displacement along this major decollement thrust eventually reached ~32 km along A-A′ and 29 km along B-B′ and C-C′. Wedging beneath overlying Tertiary strata probably concealed the tip line of thrust sheet "M", although associated compressional deformation probably reached the surface. Deformation within this thrust sheet included tight F_1 folds (less than 1 km wavelength), broader F_2 folds such as the Panoba dome, and associated thrust faults and backthrusts that were later exposed in the Kohat Plateau by erosion of the molasse cover. Between this thrust sheet and the MBT is a thrust sheet with unknown relative timing that was later involved in backlimb thrusting near the frontal MBT (Figure 4.9-A).

(A to B) As the major blind thrust sheet of (A) was transported southward, a fault-bend fold "O" developed below and in front of it (Figure 4.9-B), so that total slip was distributed between the two faults. A thrust system also developed along a ramp "N" to the south as the local taper of the wedge was increased. The earlier-formed major thrust sheet "M" of (A) converged on the "N" ramp, probably rotating the thrust fault south of the Panoba dome to a higher north dip (Figure 4.9-B).

(B to C) Movement on thrusts "M" and "O" continued and this northern thrust stack impinged on the "N" ramp to the south. Uplift and possible emergence of the toe of the "M" thrust sheet is shown.

(C to D) Continued convergence along the major thrust sheet "M" toward the simple step thrust ramp "N" to the south produced decoupling downsection to the lower Tertiary section of the flat fold hinge. Tight folds and thrust faults of the southern Kohat Plateau "P" were formed, that sole out along the Eocene Bahadur Khel Salt. These include tight F_1 folds exposed at the Nandrakki dome. No movement in thrust sheet "O" occurs at this stage. Backlimb thrusting at "Q" uplifted the northern Kohat Plateau.

(D to E) As deformation beneath the Kohat Plateau continued, the decollement thrust system stepped ~50 km to the south. Decollement thrusting over the top of basement, and probably along bedding planes of the Salt

Range Formation, produced the emergent frontal ramp that uplifted the Surghar Range. The basal thrust fault was probably deflected to the surface at a previously existing step in the basement (Figure 4.9-D). The step may have formed in association with loading of the lithosphere by thrust sheets farther to the north, as discussed by Lillie and others (1987) and Duroy and others (in press) for a similar feature north of the Salt Range. A fault propagation fold "R" also developed at this time 14 km to the north of the Surghar Range ramp.

(E to F) A fault-bend fold "S" developed between the Surghar Range and southern Kohat Plateau (Figure 4.9-F) beneath the Shakardarra area and northern Kalabagh fault (on line NK-1, figure 4.6). The tip line of this thrust fault reaches the surface as the Visor fault.

(F to G) Thrusting on ramp "T" along the backlimb of ramp anticline "S" produced deformation in the overlying molasse that includes E-W to ENE-trending branch faults "U" of the northern Kalabagh fault zone. This thrust emplacement along "T" also uplifted the southern Kohat Plateau.

Fault-bend folding

Fault-bend folds associated with blind thrust faults may be characterized by the following:

(1) Flat fold hinges that conform to a flat thrust below.

(2) Flat thrusted toe ends, i.e., a low-dipping panel at the toe of the thrust, with the angle of dip the same as the cutoff angle of the decollement thrust.

(3) Cutoff angles at incipient ramps from 14° to 32° for fault-bend folds in the Kohat Plateau-Surghar Range fold-thrust belt. Cutoff angles for a simple step fault-bend fold generally range from 8° to 24° and the maximum cutoff angle for a simple step fault-bend fold is 30° (Suppe, 1983). Beneath the Kohat Plateau, cutoff angles of ramps determined from seismic reflection profiles are associated with broad, low relief structures. Higher cutoff angles up to 32° are normally associated with younger out-of-sequence faults that may have been influenced by earlier ramp systems in front of the faults. A northward increase in the north dip of basement may produce the high cutoff angle of the lower thrust plate of cross section C-C'.

(4) A ramp spacing of 12-22 km beneath the Kohat Plateau that generally exceeds the thrust fault spacing of a simple imbricate stack.

Sedimentary layers deformed by F_1 and F_2 folds and associated thrust faults that crop out in the Kohat Plateau area are shown decoupled from the underlying broader wavelength fault-bend folds. In the southern Kohat Plateau, annihilation of a flat fold crest produced tight (less than 1 km wavelength) folding over a shallow decollement thrust that projects down the north flank of the fault-bend fold. This blind decollement thrust fault became emergent as the Hukni fault.

Backlimb thrusting along fault-bend folds in the Kohat Plateau area occurred where the original ramp provided a geometrically favorable condition to produce an overlapping thrust ramp. Backlimb roof thrusting characterizes ramps "M" and "N" on line A-A' (km marks 57-70, 30-45), ramp "N" below the Panoba dome on line B-B', and the imbricate stack forming the northern Kalabagh fault zone that is thrust over the fault-bend fold "S" south of the Kohat Plateau on line A-A' (km marks 27-42).

Implications: thrust fault propagation and associated erosion and deposition of molasse

The Kohat foreland fold-thrust belt propagated along blind thrusts including fault-bend folds beneath a roof thrust (figure 4.9-B,C), of which several are shown to be contemporaneous. Decollement thrusting generally propagated southward with increasing displacement, however the Surghar Range frontal thrust preceded deformation in the Kalabagh fault zone to the north. Backlimb thrusting also propagated downsection along the Bahadur Khel Salt and flat crest of a fault-bend fold in the southern Kohat Plateau (figure 4.9-D). The Kohat wedge has a very low topographic slope of 0.1° southward and seismic reflection profiles indicate a low decollement dip above a nearly flat basement.

Lithospheric flexure during stacking of thrust sheets may step the basement along faults below the MBT and the Surghar Range with intervening flat basement. Low instrumental seismicity in the Kohat foreland fold-thrust belt may support moderate vertical loading of the lithosphere and low strength of the wedge formed by decollement thrusting.

The critical taper for stable sliding of the wedge (Coulomb behavior) is based on the critical sum of topographic slope and decollement dip. "The addition of extra mass in front of an already critical wedge results in a taper-preserving series of deformations, which enlarge the wedge by propagating toward the back" (Davis and others, 1983). Frontal growth of a thrust system indicates adjustment to a supercritical state (Roeder, 1988).

Basal shear traction may vary over time, causing a previously critical wedge to become supercritical (Davis and others, 1983). This probably occurred during late Pliocene to early Quaternary time when the thrust system was extended southward ~50 km to the Surghar Range ramp (Figure 4.9-D,E). The Surghar Range frontal thrust formed at 1.9-2.1 Ma and was then displaced by the right-slip Surghar fault of the Kalabagh fault zone (McDougall and Khan, 1988). Rapid thrust propagation southward over the foreland exceeded the present-day instantaneous plate convergence rate of about 40 mm/year of Minster and

Jordan (1978) to form the Salt Range thrust (Yeats, 1986). The critical taper of the Kohat fold-thrust belt effectively decreased during this southward advance of the decollement thrust system.

Properties within the Kohat wedge are not well known, however, the taper of 1.9°-2.0° indicates basal decollement thrusting along a layer of low-strength evaporite (Figure 4.10). The plasticity of evaporite in a thin low-temperature wedge will produce exceptionally low basal shear traction (≤1 MPa, e.g., Davis and Engelder, 1985) and thus violate Coulomb behavior (Davis and others, 1983). The taper of the Kohat wedge is greater than that of the eastern Potwar Plateau (0.8°), and compares with that of the western and central Potwar Plateau (≤4°) (Jaume and Lillie, 1988). Drill hole data show the Potwar Plateau wedge to be underlain by evaporites of the Eocambrian Salt Range Formation. Taper of the Kohat wedge is significantly less than critical taper of 8.0° -9.5° of the wedge of decollement thrusts in the arc-continent collision zone of western Taiwan (Davis and others, 1983)

The increase in decollement dip of the Surghar Range ramp thickens the critical wedge. Out-of-sequence thrusting in the active northern Kalabagh fault zone, north of the Surghar Range, was probably a taper-preserving response to a basement-induced ramp at the Surghar Range. A fault propagation fold (Suppe, 1985), 14 km north of the Surghar Range thrust ramp, may also indicate failure of the thrust sheet because of resistance to sliding at the Surghar Range ramp.

Siwalik strata were uplifted and tilted at the Surghar Range ramp, but are up to 4 km thick near the toe of the Kohat wedge, 0-20 km to the north of the Surghar Range (Chichali section, figure 4.3). Out-of-sequence thrusting and moderate uplift, with good preservation of the molasse section north of the Surghar ramp, suggest that the wedge is presently subcritical.

An emergent thrust (Morley, 1986) may divide molasse depocenters in an area of relatively low topography, such as the Salt Range thrust (Burbank and Raynolds, 1988). As blind thrusting builds topographic slope and wedge taper, increased sediment bypassing is likely to occur, and this was probably the case for the Kohat Plateau. Large Quaternary intermontane basins such as the Peshawar Basin (Figure 4.1) are not developed along the Kohat cross section. The depocenter for clastic sediments was diverted south of the Kohat wedge during the Quaternary period.

Cumulative line-length shortening along the major thrust ramps south of the MBT is 84 km, with a restored length of 154 km along cross section A-A', giving 54.4% strain ($-\Delta L/L_0 \cdot 100$, from Suppe, 1985). A composite cross section along lines C-C', B-B', and the southern part of line A-A' gives a restored length of 220 km and ΔL = 105-

110 km, indicating 50% shortening. Along line A-A' (Figure 4.8), emergent thrust faults have cumulative offset of approximately 14 km, accounting for only 7.5-10% strain (15-20% of ΔL). Intra-Siwalik sinuous bed shortening of 14-16% (26-30% of ΔL) in folds at or near the surface is documented on line A-A' (Figure 4.8), between the Hukni fault of the southern Kohat Plateau and the Surghar Range thrust. North of the Hukni fault to the MBT on line A-A', sinuous bed restoration at the top of the lower Tertiary section gives 13-14% shortening. Surface fault displacement and fold shortening are 50% of ΔL for the foreland fold-thrust belt along line A-A'. Dermal sinuous bed shortening was about half the calculated shortening in a cross section of the Valley and Ridge province of the central Appalachians in Pennsylvania, described by Gwinn (1970).

Decoupling at the base of the Siwalik-Kamlial-Murree molasse sequence allows emplacement of underlying blind thrust sheets relatively southward in the Kohat wedge. Tight folds (F_1) and faults in lower Tertiary strata that die out upsection, such as those at the Nandrakki dome, may characterize the zone of decoupling. Fold harmonics also vary upsection from thrust sheets with large horizontal displacement at depth to overlying F_1 and F_2 folds (e.g. Panoba dome) near the surface. Wedging of thrust sheets below passive roof backthrusts is reported in thrust systems that include the Kirthar and Sulaiman thrust belts of Pakistan (Banks and Warburton, 1986). A similar process in the Tertiary cover of the Kohat wedge, integrated during emplacement, may compose over 50% of the 84-110 km horizontal line-length shortening of the Kohat wedge (Figure 4.11). Backthrusts with this magnitude of displacement are not mapped. Tip lines (Boyer and Elliott, 1982) of blind thrusts of large displacement (up to 32 km) remain concealed.

Conclusions

Balanced cross sections of the Kohat foreland fold-thrust belt of northern Pakistan, from the MBT to the Surghar Range, resolve thrust propagation dominated by layer-parallel slip. Emplacement of blind thrust sheets over a nearly flat basement produced collapse of footwall ramps to form fault-bend folds and southward wedging beneath the Tertiary Siwalik clastic wedge. F_1 and F_2 folds, decollement thrusts, and backthrusts in exposed Tertiary strata overlie concealed blind thrust sheets having about 50% more cumulative horizontal shortening than documented at the surface. Emergent thrusting uplifted the Surghar Range before out-of-sequence thrust faults formed in the Kalabagh fault zone, 12-20 km north of the Surghar Range. The subcritical wedge tapers ~2° overall and is undergoing taper-preserving deformations that increase its thickness. The wedge was probably supercritical when propagating into an area of low basal friction at about 2 Ma. These mechanical considerations may be applied to decollement thrust systems with low strength bedding planes, low topographic slope and decollement dip, and high rates of underthrusting.

Figure 4.1: Index map of the western Himalayan fold-and-thrust belt, northern Pakistan. Thrust faults are bold lines, dashed where approximate, with teeth toward the upper plate. Quaternary deposits are shaded. Patterned outcrops in the Kirana Hills, lower right, are Precambrian basement. The Kohat Plateau is center left, with lines of cross section A-A', B-B', and C-C'. The Kundian well and intersecting seismic line AW-15-N, Dhurnal well, and Dhermund well are discussed in text. India-Eurasia convergence vectors are from Minster and Jordan (1978).

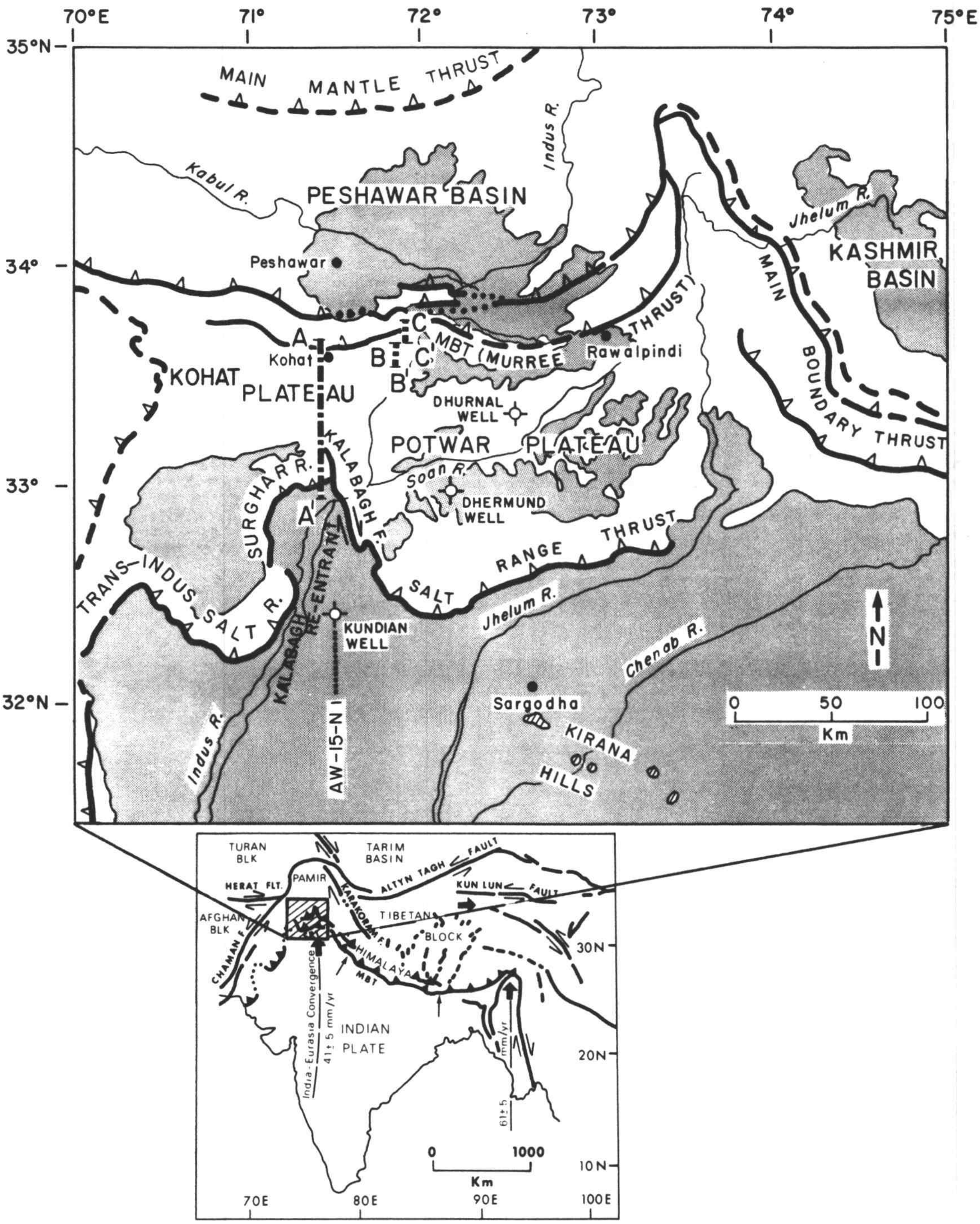
70°E
71°
72°
73°
74°
75°E
35°N
34°
33°
32°N
MAIN MANTLE THRUST
Indus R.
Kabul R.
PESHAWAR BASIN
Peshawar
Jhelum R.
KASHMIR BASIN
MAIN BOUNDARY THRUST
THRUST
MBT (MURREE
Rawalpindi
Kohat
KOHAT PLATEAU
DHURNAL WELL
POTWAR PLATEAU
KALABAGH F.
Soan R.
DHERMUND WELL
SURGHAR R.
SALT RANGE THRUST
TRANS-INDUS SALT R.
KALABAGH RE-ENTRANT
KUNDIAN WELL
Jhelum R.
Chenab R.
Sargodha
KIRANA HILLS
AW-15-N
Indus R.
N
0
50
100
Km
TURAN BLK
TARIM BASIN
PAMIR
HERAT FLT.
ALTYN TAGH FAULT
KUN LUN FAULT
AFGHAN BLK
TIBETAN BLOCK
CHAMAN F.
KARAKORAM F.
HIMALAYA
MBT
India-Eurasia Convergence
41 ± 5 mm/yr
INDIAN PLATE
mm/yr
61 ± 5
30N
20N
10N
0
1000
Km
70E
80E
90E
100E

Figure 4.1

Figure 4.2: Tectonic map of the Kohat Plateau, northern Kalabagh fault zone and eastern Surghar Range, including lines of balanced cross sections and seismic profiles illustrated in other figures. Rock units are simplified as (1) mid-Tertiary and younger: including molasse strata of the Rawalpindi and Siwalik Groups and more recent deposits and (2) Lower Tertiary and older: including all pre-molasse sedimentary strata above the basement.

Figure 4.2

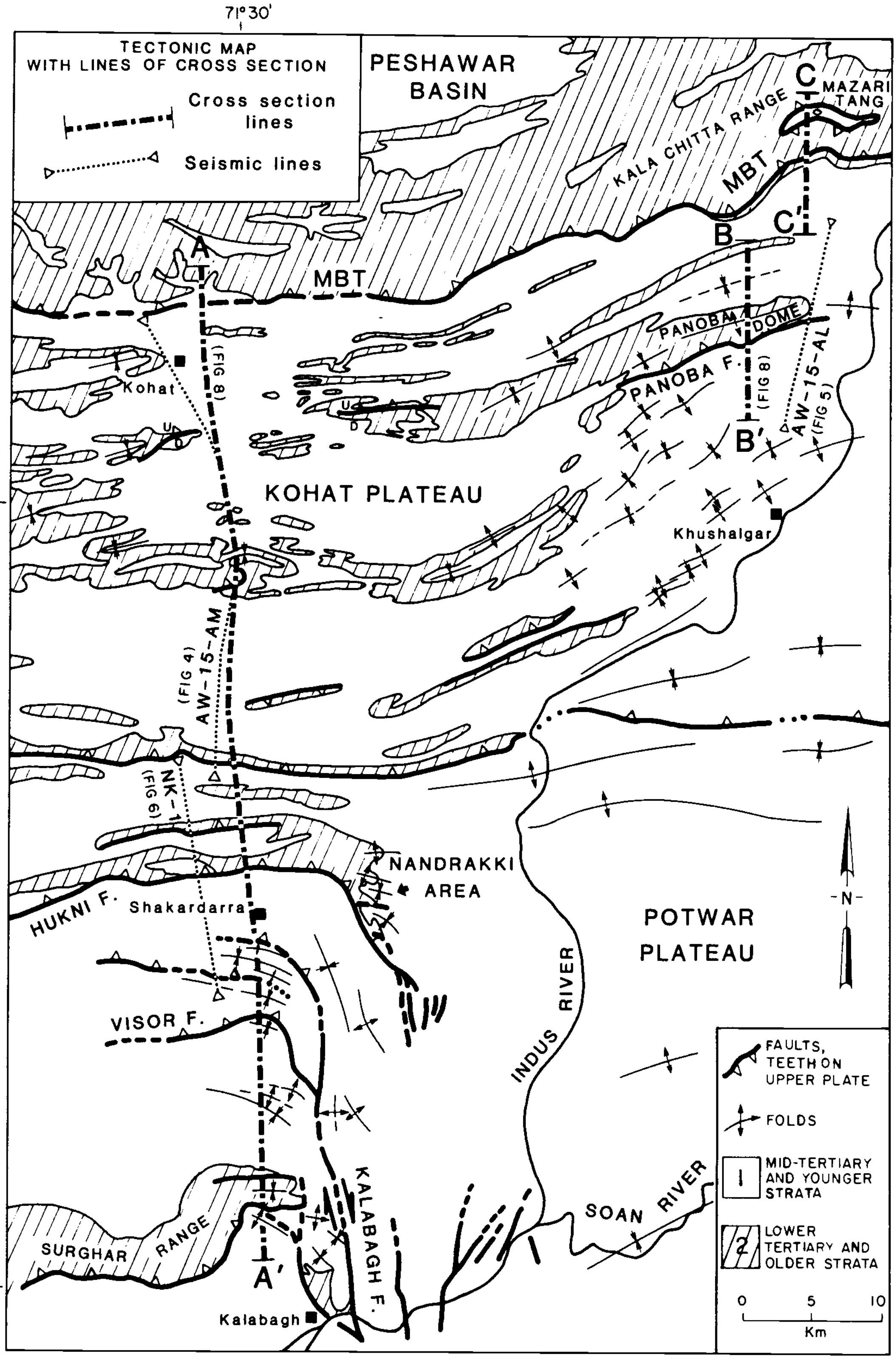
71°30'
TECTONIC MAP
WITH LINES OF CROSS SECTION
Cross section lines
Seismic lines
PESHAWAR BASIN
KALA CHITTA RANGE
MAZARI TANG
MBT
C
C'
B
B'
A
A'
PANOBA DOME
PANOBA F.
(FIG 8)
AW-15-AL
(FIG 5)
Kohat
KOHAT PLATEAU
33°30'
Khushalgar
AW-15-AM
(FIG 4)
NK-1
(FIG 6)
NANDRAKKI AREA
HUKNI F.
Shakardarra
POTWAR PLATEAU
VISOR F.
INDUS RIVER
KALABAGH F.
SOAN RIVER
SURGHAR RANGE
33°
Kalabagh
-N-
FAULTS, TEETH ON UPPER PLATE
FOLDS
MID-TERTIARY AND YOUNGER STRATA
LOWER TERTIARY AND OLDER STRATA
0 5 10
Km

Figure 4.3: Schematic diagram of stratigraphic columns from the Kundian, Dhermund, and Dhurnal wells with tops from the Geological Survey of Pakistan and the Oil and Gas Development Corp. of Pakistan (see figure 4.1 for location). The eastern Surghar Range stratigraphic section (Meissner and others, 1974), and the Chichali Gorge section, both in the Surghar Range, are based on surface data. The predicted northern Kohat section is based on extrapolation from these and other regional stratigraphic data. Correlations of Siwalik formations are lithologic and do not imply time equivalence.

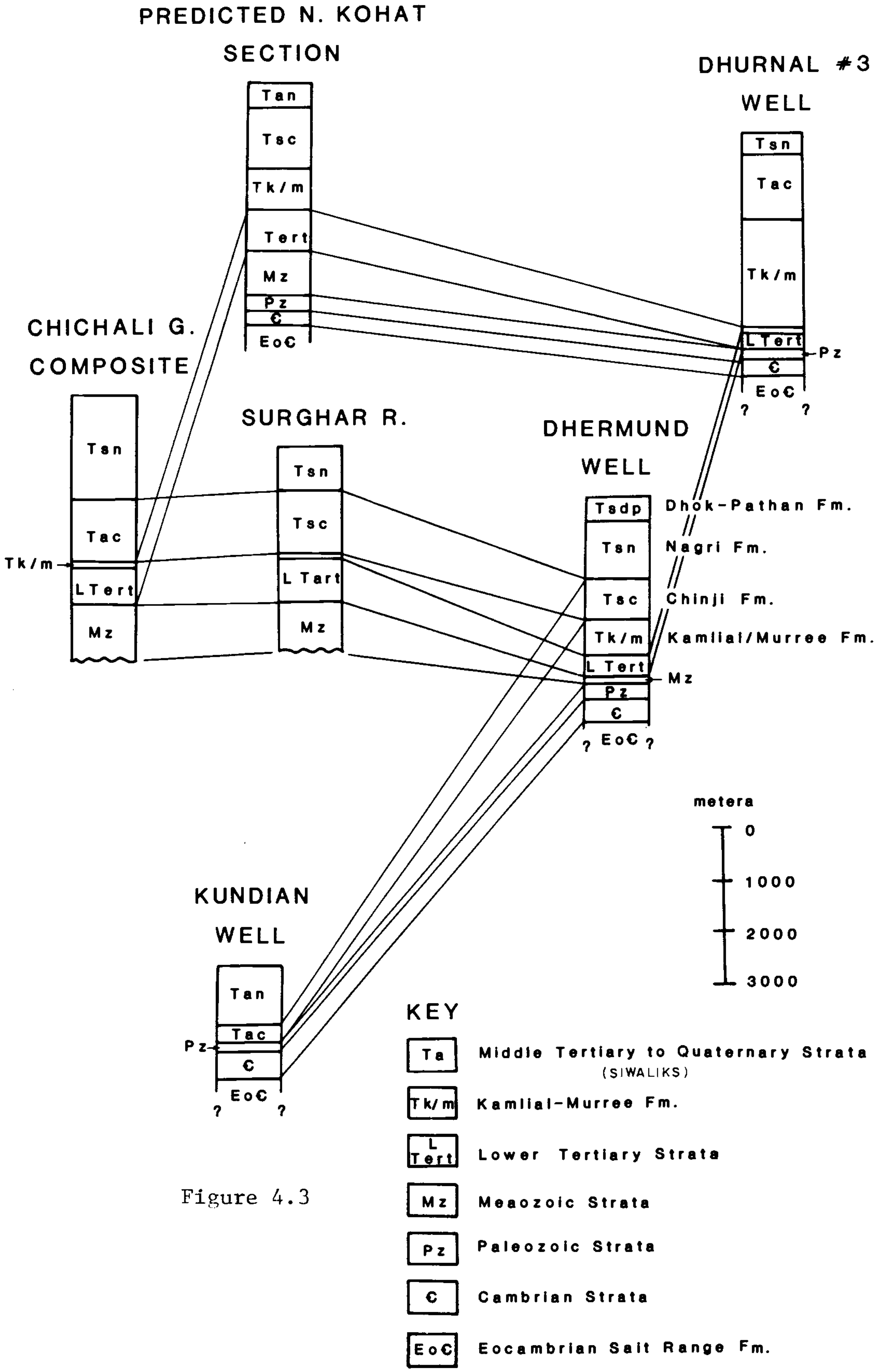
PREDICTED N. KOHAT SECTION
Tan
Tsc
Tk/m
Tert
Mz
Pz
Є
EoЄ
DHURNAL #3 WELL
Tsn
Tac
Tk/m
L Tert
Pz
Є
EoЄ
? ?
CHICHALI G. COMPOSITE
Tsn
Tac
Tk/m
LTert
Mz
SURGHAR R.
Tsn
Tsc
L Tert
Mz
DHERMUND WELL
Tsdp
Tsn
Tsc
Tk/m
L Tert
Pz
Є
? EoЄ ?
Dhok-Pathan Fm.
Nagri Fm.
Chinji Fm.
Kamlial/Murree Fm.
Mz
meters
0
1000
2000
3000
KUNDIAN WELL
Tan
Tac
Pz
Є
EoЄ
? ?
KEY
Ta Middle Tertiary to Quaternary Strata (SIWALIKS)
Tk/m Kamlial-Murree Fm.
L Tert Lower Tertiary Strata
Mz Mesozoic Strata
Pz Paleozoic Strata
Є Cambrian Strata
EoЄ Eocambrian Salt Range Fm.

Figure 4.3

Figure 4.4: Seismic reflection line AW-15-AM (not migrated), across the northern Kohat Plateau, intersecting Kohat city on the northern end, located on figure 4.2. A major roof thrust (thrust sheet "M") overlies a fault-bend fold in a footwall duplex (e.g., Boyer and Elliott, 1982) across the center of the line.

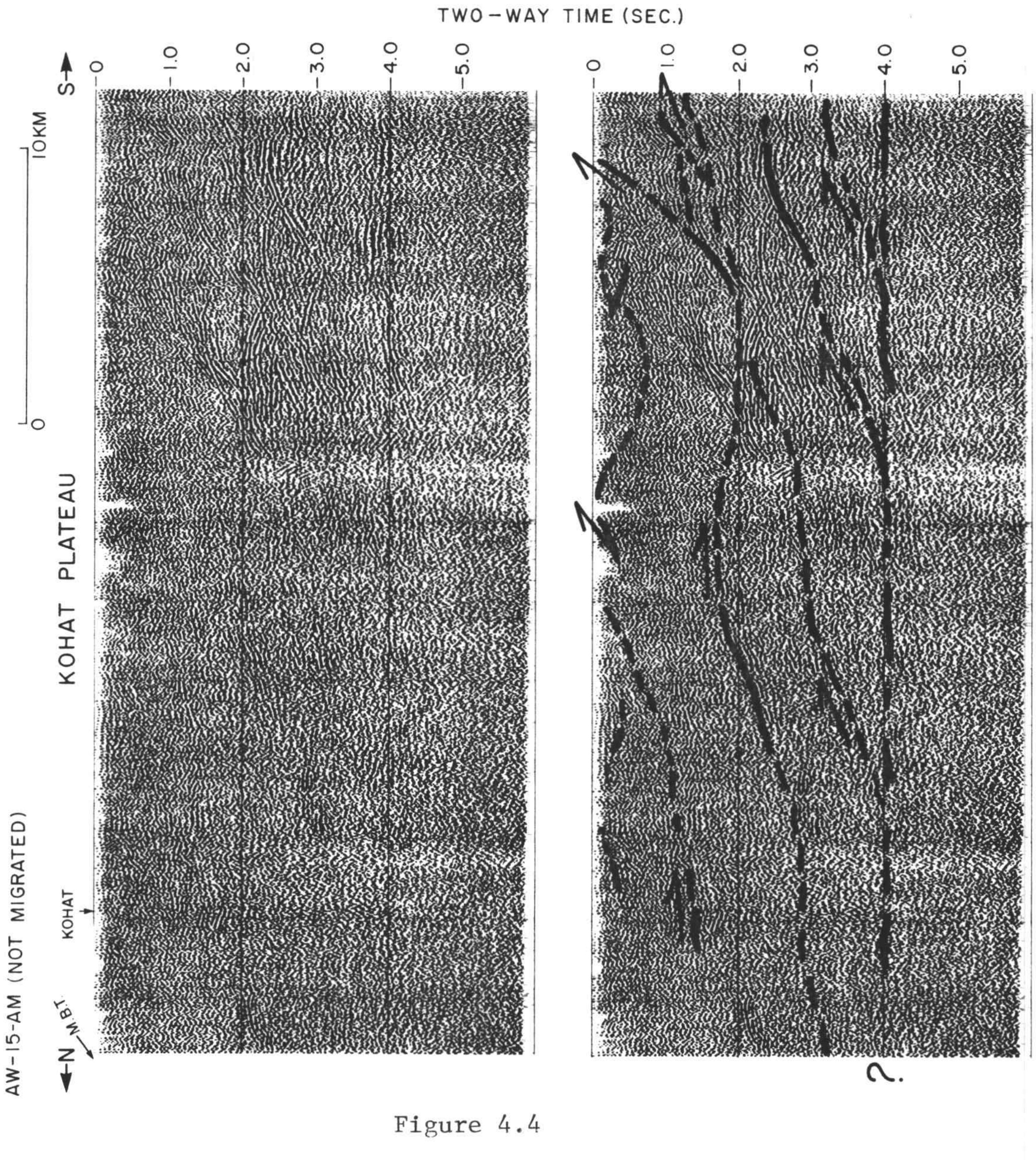
TWO-WAY TIME (SEC.)
0
1.0
2.0
3.0
4.0
5.0
S
N
10KM
0
KOHAT PLATEAU
KOHAT
M.B.T.
AW-15-AM (NOT MIGRATED)

Figure 4.4

Figure 4.5: Seismic reflection line AW-15-AL (migrated), in the northeastern Kohat Plateau, west of the Indus River, located on figure 4.2. The interpretation is limited by data quality, however, the thrust ramp "N", from the top of basement appears as dipping reflections at 3.0-4.0 sec in the northern half of the line.

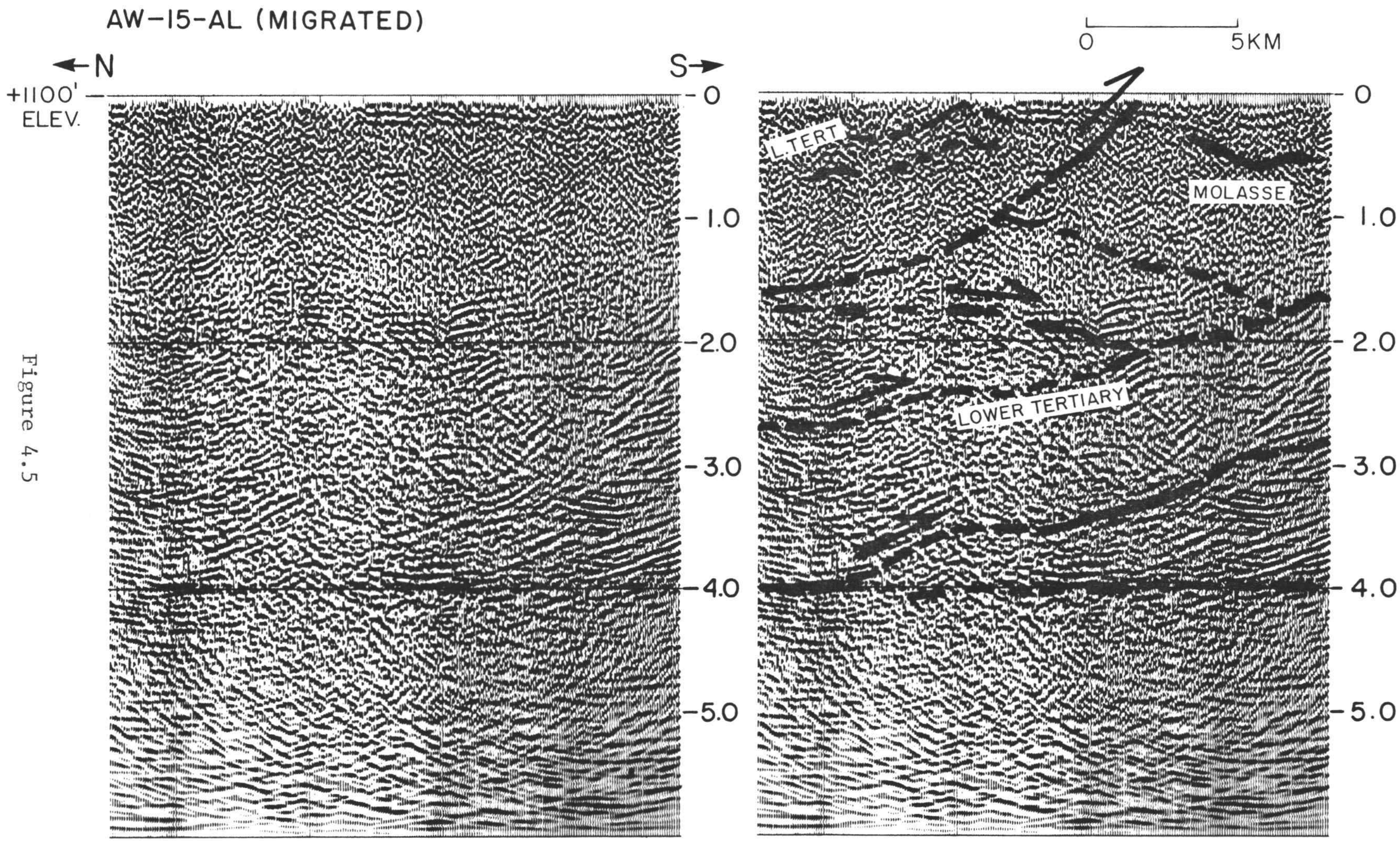
AW-15-AL (MIGRATED)
N
S
+1100'
ELEV.
0
1.0
2.0
3.0
4.0
5.0
0
5KM
L.TERT
MOLASSE
LOWER TERTIARY
0
1.0
2.0
3.0
4.0
5.0

Figure 4.5

Figure 4.6: Seismic reflection line NK-1 (not migrated), in the Shakardarra area, intersecting the Hukni fault, located on figure 4.2. A large fault-bend fold is interpreted below the Kalabagh fault zone, that is best defined at its crest. South dipping reflections, e.g, at 3.0-4.0 sec below the Hukni fault, may be diffractions from kink bends in strata climbing the ramp.

NK-I (NOT MIGRATED)

Figure 4.6

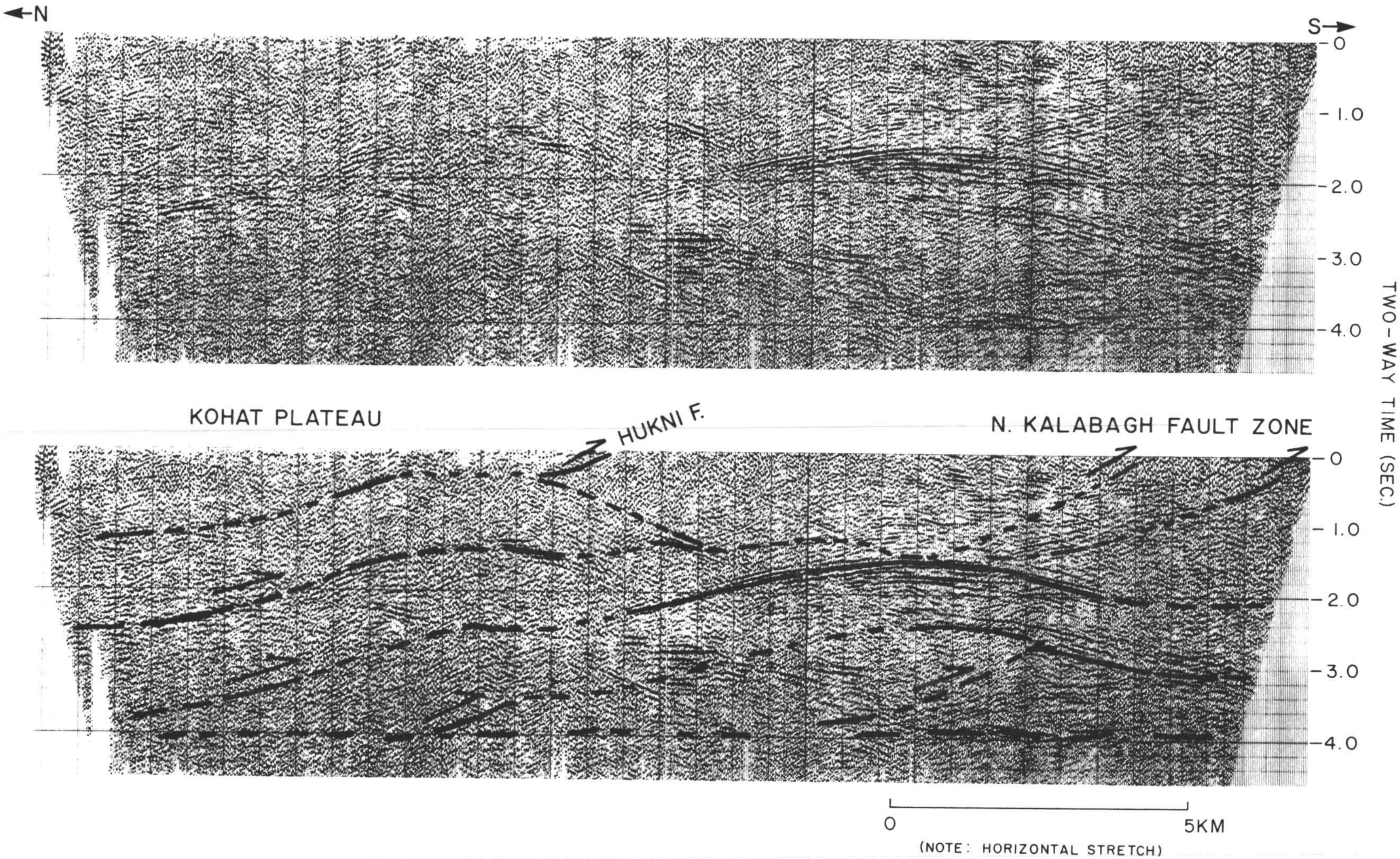

Figure 4.7: Seismic reflection line AW-15-N (not migrated), in the Kalabagh re-entrant, that extends from the Kundian well to the south, located on figure 4.1. The Kundian well (section in figure 4.3) penetrates the Eocambrian Salt Range Formation but does not reach the basement. The high area in basement to the south on line AW-15-N is the westward subsurface projection of the Sargodha high (forebulge): where basement crops out at the surface in the Kirana Hills (Figure 4.1).

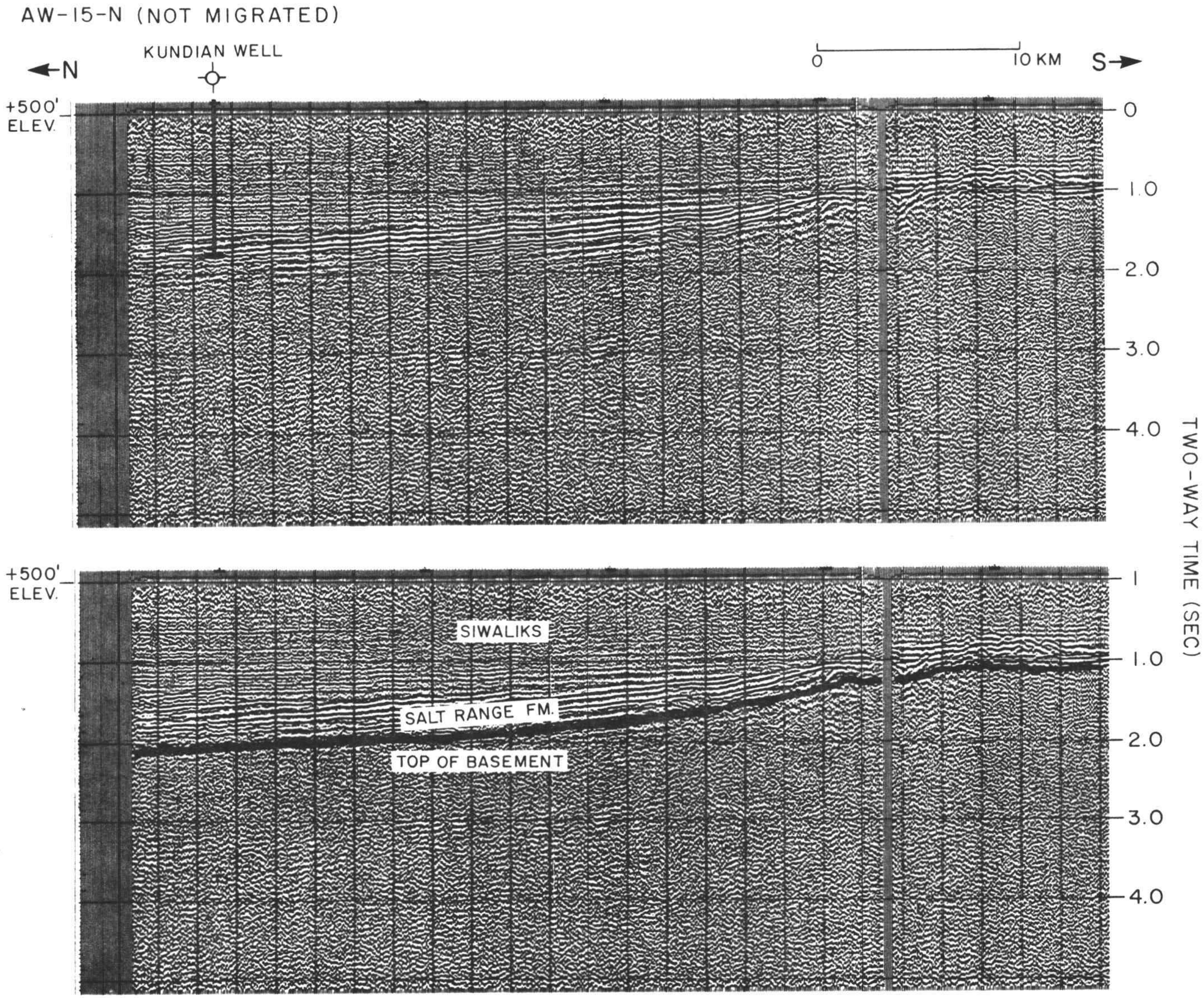
AW-15-N (NOT MIGRATED)
KUNDIAN WELL
◄N
0
10 KM
S►
+500'
ELEV.
0
1.0
2.0
3.0
4.0
TWO-WAY TIME (SEC)
+500'
ELEV.
1
1.0
2.0
3.0
4.0
SIWALIKS
SALT RANGE FM.
TOP OF BASEMENT

Figure 4.7

Figure 4.8: Balanced cross sections of Himalayan fold-and-thrust belt south of the Main Boundary thrust in northwestern Pakistan, located on figures 4.1 and 4.2. Cross section A-A' extends from the MBT, near Kohat city, to the eastern Surghar Range, near Kalabagh. Section B-B' crosses the Panoba dome north of Khushalgar. Section C-C' crosses the MBT and the Mazari Tang window and extends B-B' to the north, with a 4 km offset. B-B' and C-C' incorporate geological mapping of Ahmad Hussein and A-A' incorporates geological mapping of Meissner and others (1974), E.R. Gee (unpublished data), and McDougall (1988).

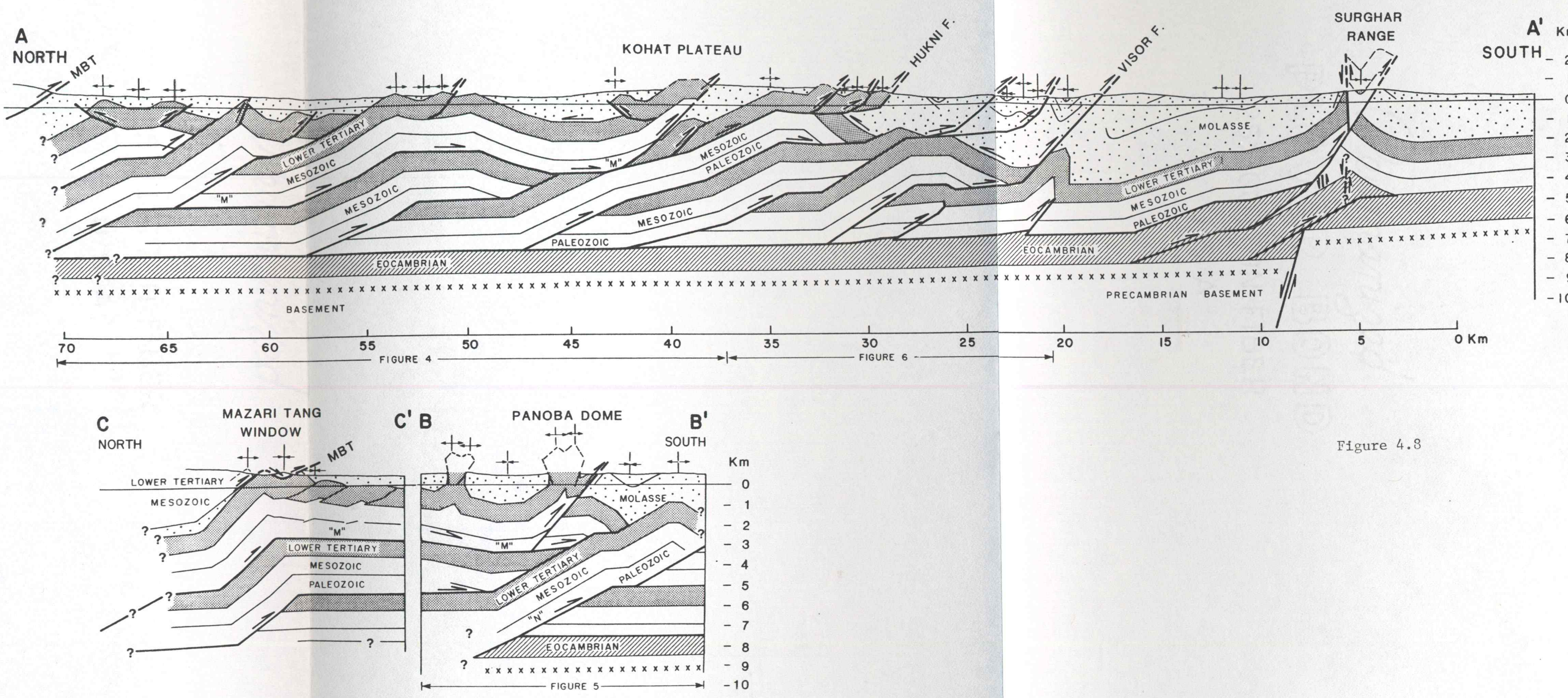
A
NORTH
MBT
KOHAT PLATEAU
HUKNI F.
VISOR F.
SURGHAR
RANGE
A'
SOUTH
Km
LOWER TERTIARY
MESOZOIC
"M"
PALEOZOIC
MOLASSE
EOCAMBRIAN
BASEMENT
PRECAMBRIAN BASEMENT
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0 Km
FIGURE 4
FIGURE 6
C
NORTH
MAZARI TANG
WINDOW
C' B
PANOBA DOME
B'
SOUTH
"N"
FIGURE 5

Figure 4.8

Figure 4.9: Palinspastic restoration of the decollement thrust propagation sequence in western Himalayan fold-and-thrust belt along the line of cross section A-A' (Figure 4.8). The asterisk indicates a supplemental pin line to conserve space.

(A) Thrust sheet "M" developed in front of the Main Boundary thrust and driven under clastic wedge.

(B) Development of fault-bend folds ("N","O") beneath and in front of the thrust sheet "M" during southward advance of thrusting and continued motion on "M".

(C) Backlimb thrusting, increasing the thickness of the wedge and decoupling at "Q" and along the flat hinge of "N".

(D) Annihilation of the flat hinge of the fault-bend fold by thrust propagation downsection beneath the southern Kohat Plateau "P" with development of a small backthrust.

(E) Frontal ramp development by ~50 km horizontal toe addition to the future Surghar Range. Footwall horses (Boyer and Elliott, 1982) in the Salt Range Formation develop above the normal fault in basement.

(F) Fault-bend folding at "S" and inception of backlimb thrusting "T" to begin general uplift of southern Kohat Plateau.

(G) Modern configuration, showing development of thrust faults "S" and "T" that reach the surface in the northern Kalabagh fault zone "U".

Figure 4.9

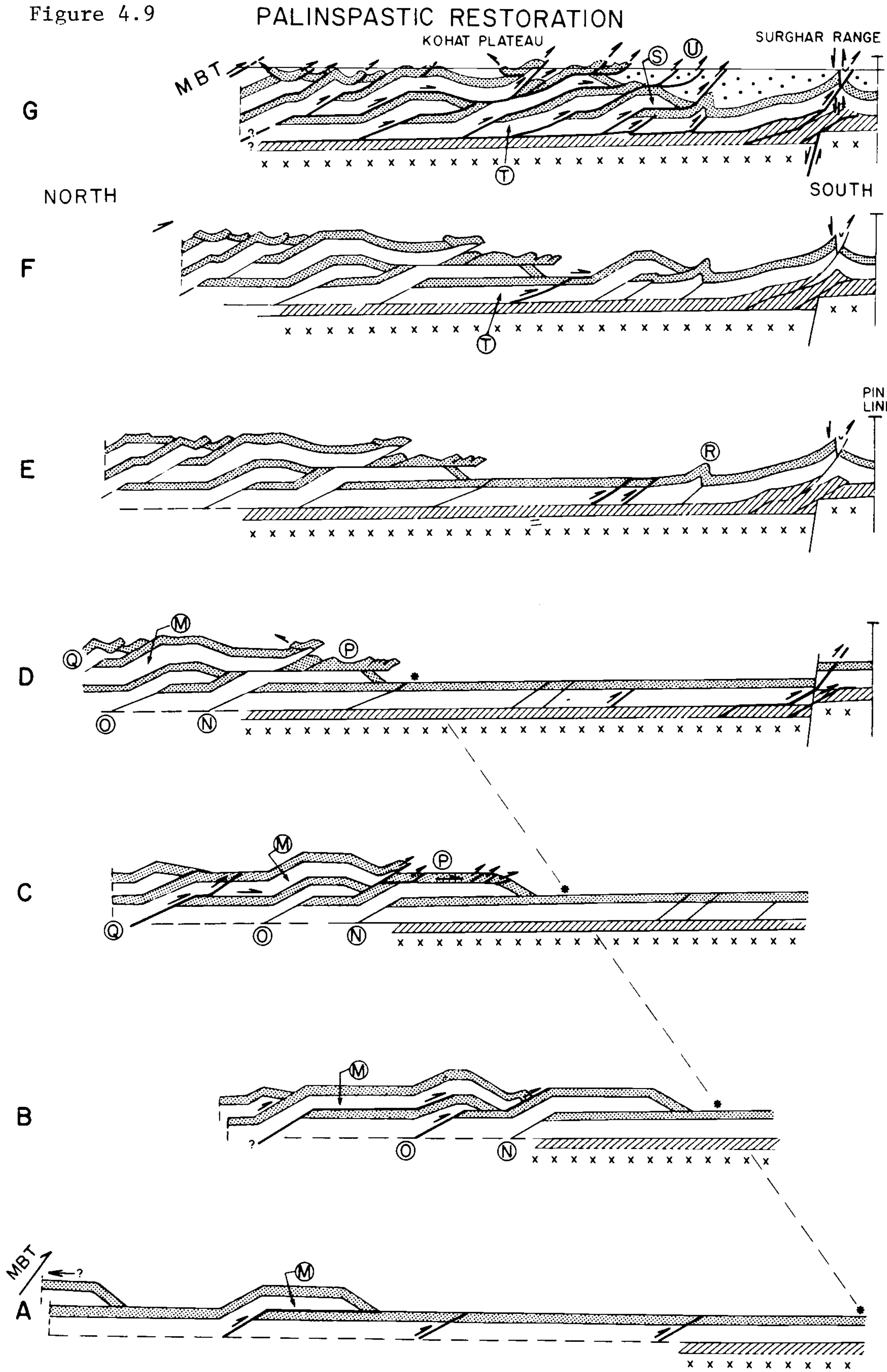
PALINSPASTIC RESTORATION
KOHAT PLATEAU
SURGHAR RANGE
MBT
G
S
U
T
?
NORTH
SOUTH
F
E
R
PIN LINE
D
M
Q
P
O
N
C
B
A
MBT

Figure 4.10: Taper of Kohat wedge of cross section A-A' (Figure 4.8) compared with cross sectional taper of the Potwar Plateau wedge (Jaume and Lillie, 1988) and average critical taper of the wedge of decollement thrusts in western Taiwan (Davis and others, 1983). Angle alpha refers to topographic slope and angle beta refers to decollement dip.

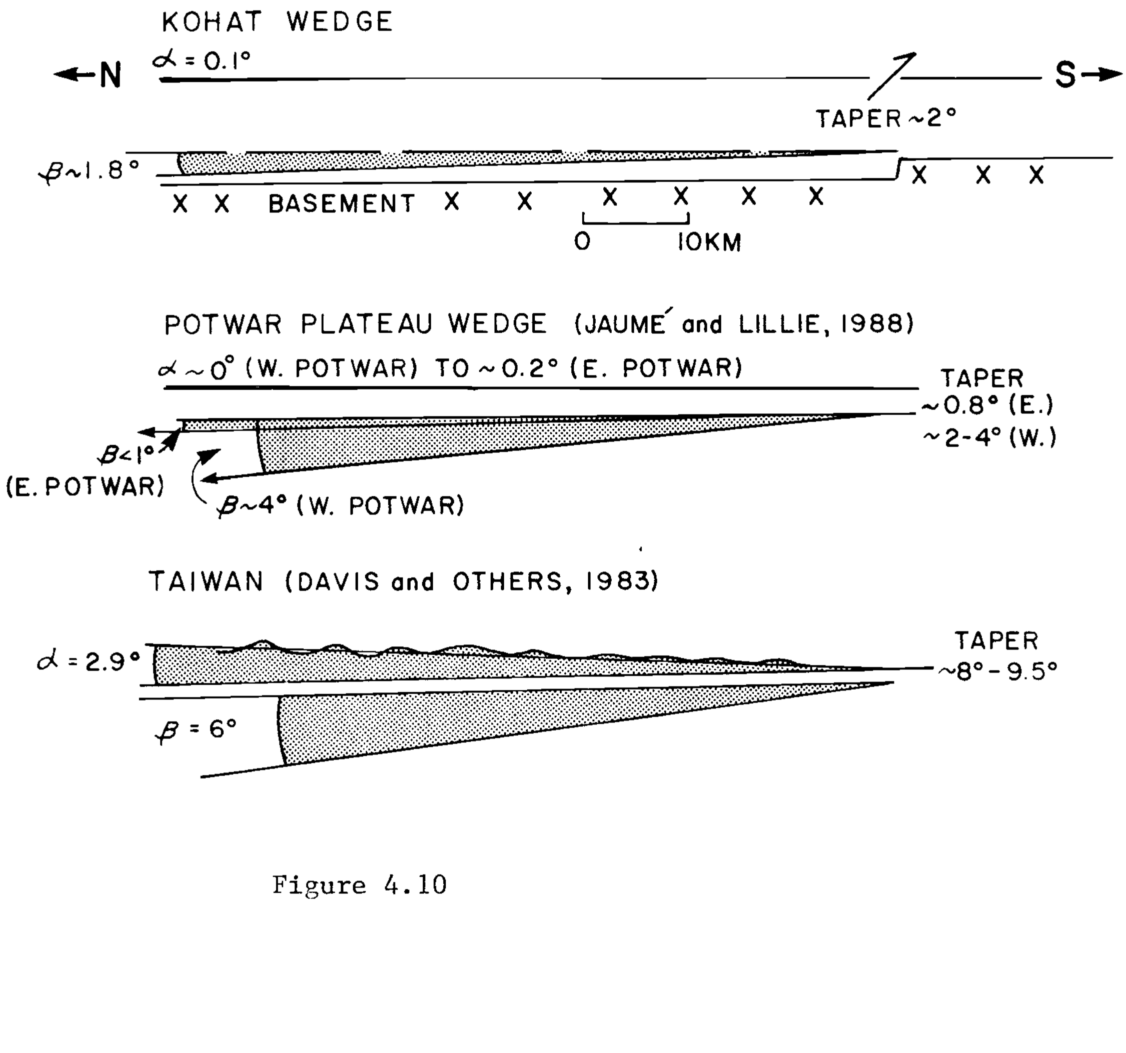
KOHAT WEDGE
N
S
α = 0.1°
TAPER ~2°
β~1.8°
X X BASEMENT X X X X X X
X X X
0 10KM
POTWAR PLATEAU WEDGE (JAUMÉ and LILLIE, 1988)
α ~ 0° (W. POTWAR) TO ~ 0.2° (E. POTWAR)
TAPER
~0.8° (E.)
~2-4° (W.)
β<1°
(E. POTWAR)
β~4° (W. POTWAR)
TAIWAN (DAVIS and OTHERS, 1983)
α = 2.9°
TAPER
~8° - 9.5°
β = 6°

Figure 4.10

Figure 4.11: Wedging beneath Siwalik molasse during emplacement of blind thrust sheets produces passive roof backthrusts. Erosion of roof thrusts accompanies progressive emplacement of simple step fault-bend fold (above). Hypothetical configuration of eroded roof backthrusts (below) is shown for the Kohat Plateau during stage B (Figure 4.9).

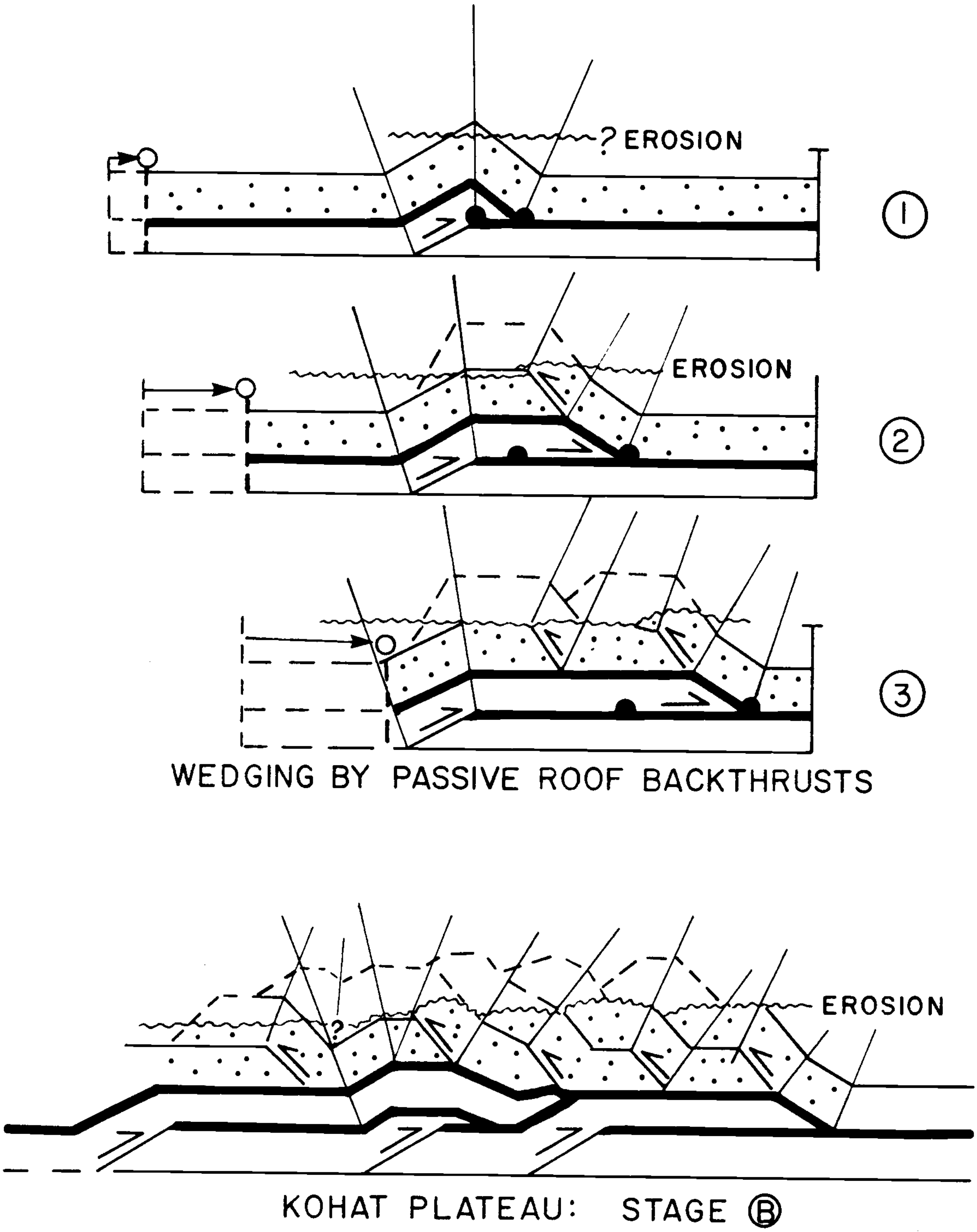
? EROSION
①
EROSION
②
③
WEDGING BY PASSIVE ROOF BACKTHRUSTS
?
?
EROSION
KOHAT PLATEAU: STAGE Ⓑ

Figure 4.11

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APPENDICES

APPENDIX 1: TECTONIC MAP AND DESCRIPTION OF THE NORTHERN KALABAGH FAULT ZONE AND VICINITY, NORTHERN PAKISTAN

James W. McDougall, E. Rowland Gee

Introduction

The tectonic map of the northern Kalabagh fault zone is the result of a field study and data compilation that includes nearly all of the Survey of Pakistan 15 minute quadrangle map 38/O/12 and adjacent areas to the south and west. The map overlaps and is a northern extension of the Salt Range map series of Gee (1980). Unpublished field data of Gee were also used extensively in geological mapping by McDougall in 1982-85. More field data are expected to be acquired within the area of the map and an enlarged area to be studied with future work.

Rock units are grouped according to tectonic importance, both structurally and stratigraphically. Divisions are based on interpretation of significant tectonic events or periods between events. Resolution of tectonic units is better in the more recent part of the geological record.

The area covered by the 1:50,000 scale map is important to work by McDougall on the Kalabagh fault system. Although the density of observations has been collectively quite good, the map is a regional tectonic map. Some units of Gee (1980) were retained, including the Kalabagh Conglomerate.

Description of tectonic units

Qal: QUATERNARY ALLUVIUM

These surficial deposits include modern alluvial fans and Indus River floodplain deposits. Deposits within this group also include lake bed deposits (Nammal Lake, Khairabad sag feature in Kalabagh strike-slip fault zone). Sedimentary rocks in this group from neighboring regions include those sediments (e.g., Potwar silt) that were ponded in intermontane basins such as the Soan River depression, Campbellpore basin, and Peshawar basin.

An age assignment of 0.5 Ma and younger for these deposits does not restrict some of them from being older Quaternary. Deposits from the underlying Siwalik sequence were given a magnetostratigraphic age as young as 0.5 Ma age by Khan (1983) in a stratigraphic section immediately west of the map.

Most of the sediment being deposited as Quaternary alluvium bypasses the western Salt Range and aggrades on the Indus River floodplain. These deposits reflect the modern tectonic regime.

Qkc: KALABAGH CONGLOMERATE

The Kalabagh Conglomerate of Gee (1945, 1947, 1980) is a fanglomerate deposit associated with emergent thrust faulting (Morley, 1986) in areas that probably include the Surghar Range, Kalabagh hill, and the western Salt Range. This unit was deposited prior to right-lateral offset along the main Kalabagh fault, but not before significant offset along the right-lateral Surghar fault (McDougall, 1988). The locally-derived Kalabagh Conglomerate is composed of dominantly Tertiary limestone clasts, with subordinate ferruginous sandstone clasts of the Siwalik Group.

The Kalabagh Conglomerate overlies tilted lower and middle Siwalik strata (Chinji and Nagri formations) with an unconformable relationship at Kalabagh hill that is probably toplap (terminology of Mitchum and others, 1977). The age relationship between the Kalabagh Conglomerate and the Siwalik strata given a 0.5 Ma age by Khan (1983) is uncertain. The Kalabagh conglomerate is younger than incipient propagation of the thrust front of the Himalaya to the Surghar Range, that occurred at approximately 2 Ma. This corresponded with the closely-timed emergence of the Salt Range frontal thrust at 1.9-2.1 Ma, based on a similar age of erosional truncation of the Soan syncline (Raynolds and Johnson, 1985).

Local folding and thrust faulting produced uplift of source areas for the Kalabagh Conglomerate. Peak deposition of fanglomerate probably corresponded with peak emergence of these source areas (that may include the Kala Chitta Range to the north). Rates of accumulation and associated uplift may have decreased to the present day.

Tcc: INDUS RIVER CHANNEL CONGLOMERATE

Channel conglomerates of the paleo-Indus River were deposited before local tectonic tilting and channel migration associated with Kalabagh faulting. These deposits contain distantly-derived clasts (80% metamorphic and igneous rock clasts and 20% sedimentary rock clasts, dominantly limestone), that are similar to deposits of the modern Indus River.

These deposits are dominantly Quaternary in age, occurring in the uppermost Siwalik section and are also recycled in terrace and fluvial deposits. The age of transition from net accumulation to net erosion of Indus River channel conglomerates in the map area is not determined.

Ts: SIWALIK AND RAWALPINDI GROUPS

Tertiary Siwalik and Rawalpindi group rocks are fluviatile molasse deposits derived from the main Himalayan mountain range. Deposition in the modern Kohat and Potwar Plateau areas of the foredeep included the area south of the modern frontal thrust on the Indus

River floodplain. Ts deposits are post-collisional and in general onlap a basal unconformity that is younger southward and westward in the area of the tectonic map. While the Murree Formation is a transitional marine deposit in the Hazara-Kashmir syntaxis, with a Paleocene age (Bossart and others, 1988), Ts strata in the map area are continental deposits. 7-10 km northwest of Chichali Pass (33°N, 71.25°E), the top of a paleomagnetic section by Khan (1983) is younger than the Bruhnes-Matuyama polarity reversal, indicating overlying Siwaliks as young as 0.5 Ma. The maximum age of Ts in the map area is probably comparable to an 18-20 Ma magnetostratigraphic age at the base of the Kamlial member of the Rawalpindi Group, from the Chinji village area in the south-central Potwar Plateau (Johnson and others, 1985).

Tcm: LOWER TERTIARY STRATA

Early Tertiary marine shelf and basin deposits include the Chharat Group (Nammal, Sakesar, Kohat, Mami Khel, Shekkan, and Jatta Formations) and Makarwal Group (Patala, Lockhart, and Hangu Formations). This stratigraphic succession ranges from a 38-40 Ma age at the top to a major unconformity at the base of the Tertiary. Limestone strata dominate the lower Tertiary section in the area of the tectonic map.

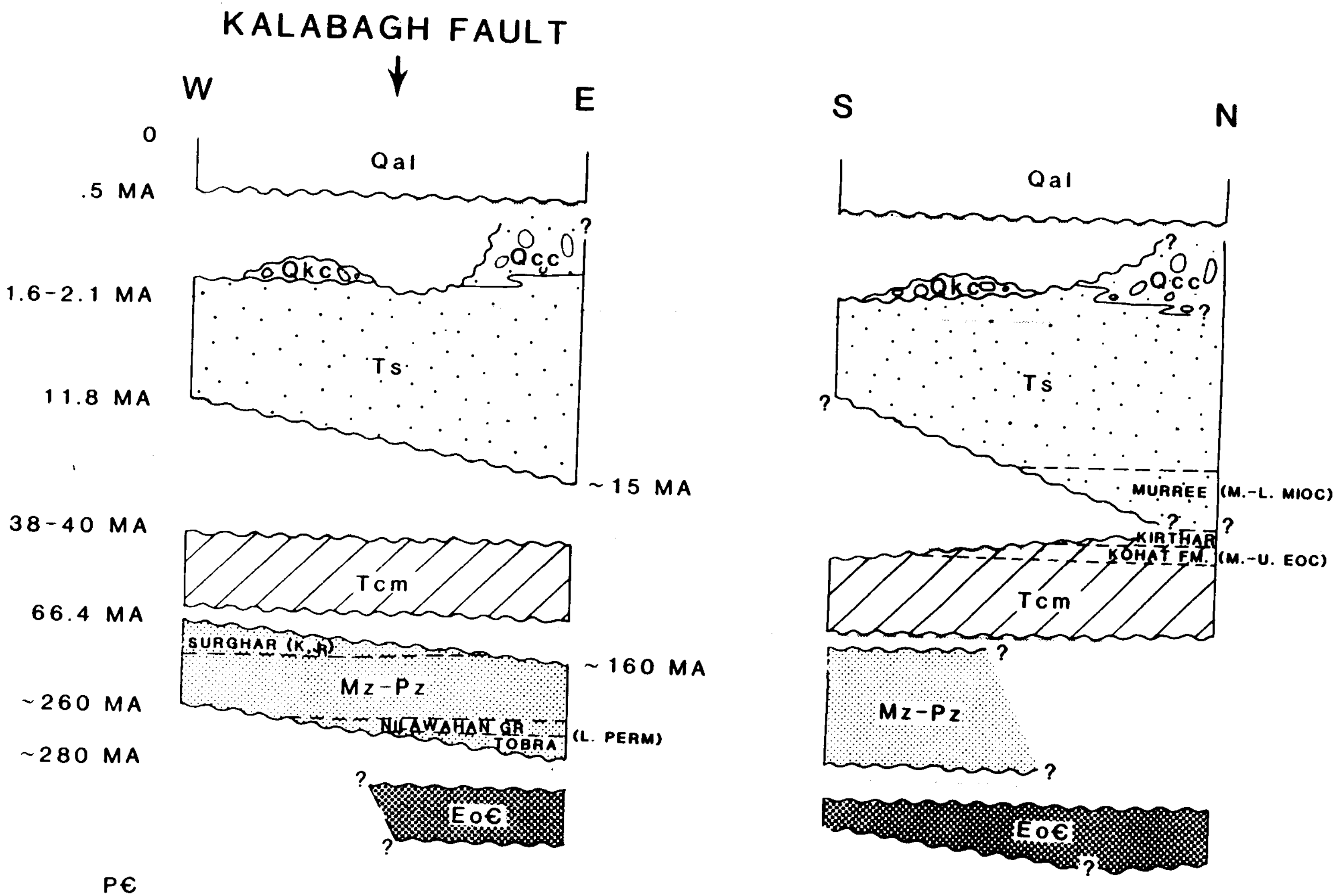
Mz-Pz: MESOZOIC AND PALEOZOIC STRATA

Mesozoic and Paleozoic sedimentary rocks were largely marine deposits on the pre-collisional stable shelf of the N-facing Indian plate margin. Older strata in this stratigraphic succession pre-date the breakup of the Gondwana supercontinent. Included in this tectonic unit are Permian glacial deposits of the Tobra Formation. Mesozoic rocks pinch out to the east against the overlying angular unconformity at the base of the Tertiary (Gee, 1980)

SRF: SALT RANGE FORMATION

Eocambrian evaporite deposits of the Salt Range Formation may have been deposited in a euxinic basin associated with rifting. Cambrian deposits that crop out to the west of the tectonic map area pinch out to the west along a major unconformity above the middle Cambrian.

KEY


KALABAGH FAULT
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Qal
Qkc
Qcc
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SURGHAR
Mz-Pz
NILAWAHAN GR
TOBRA
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KIRTHAR
KOHAT FM. (M.-U. EOC)

PLATE 1