Pakistan Journal of Hydrocarbon Research
Vol.5, No.1&2 (January & July 1993), P.15-36, 10 Figs.

Balanced Structural Cross-section of the Sulaiman Lobe, Pakistan: Evolution, Geometry, Shortening and Hydrocarbon Prospects of a Thrust System at the Western Terminus of the Indian Plate

Ishtiaq A. K. Jadoon[1], Robert J. Lillie[2], and Robert D. Lawrence[2]

ABSTRACT

Surface and subsurface data from the Sulaiman fold-and-thrust belt are integrated to evaluate geometry of a thrust system and tectonic shortening across the western margin of the Indian subcontinent. A balanced structural cross-section suggests 4 to 10 km uplift of Cretaceous and younger strata from foreland to hinterland of the Sulaiman lobe of Pakistan. This structural uplift is due to a thin-skinned, passive-roof duplex style of deformation. The duplex sequence is bounded between a decollement on the crystalline basement and a passive-roof thrust in the Cretaceous shales. The passive-roof sequence is preserved for about 150km in the Sulaiman thrust system. Structural cross-section shows ophiolites, a triangle zone, out-of-sequence structures (secondary faults and related pop-ups), fault-related, and concentric buckle folds from hinterland to foreland respectively.

A balanced structural cross-section 349 km long from the Sulaiman fold belt restores to an original length of 727 km, suggesting a maximum of 378 km of shortening in the cover strata of the Indian subcontinent. The shortening in the roof sequence is accommodated along emergent passive-roof thrust and backthrusts. Calculation of displacement rates over the Sulaiman lobe (18 mm/yr) added to the resolved rate of the Chaman fault vector for the component parallel to the plate convergence direction (15 mm/yr) are close to the current India-Asia plate convergence rate (37 mm/yr).

Total shortening of about 378 km and transitional crust underneath the Sulaiman lobe compared to full thickness crust in northern Pakistan suggests an early stage of collision along the western margin of the Indian plate.

INTRODUCTION

The Sulaiman lobe (Sarwar and DeJong, 1979) to the west of the Himalayas is a broad (>300 km) and gentle (<1°) fold-and-thrust belt that is tectonically active (Figures 1 and 2). It is developed by transpression as a result of left-lateral strike-slip motion along the Chaman fault and southward thrusting along the western terminus of the Indian subcontinent (Lawrence et al., 1981a; Farah et al., 1984; Quittmeyer et al., 1984). Its surface geology is dominated by continental platform and shallow marine rocks bordered by ophiolites and flysch in the rear and continental molasse strata in the foredeep (Figure 2). This broad fold belt is apparently in an early stage of continental convergence; nowhere are continental basement rocks exposed in the fold-and-thrust belt or interpreted to be involved in the thrusting at depth. The fold belt is interpreted to overlie transitional or oceanic crust of a previously extended continental margin (Lillie, 1991; Jadoon, 1992; Khurshid et al., 1992). In contrast, the main Himalayas have continental crust of nearly twice normal thickness, as interpreted using surface wave dispersion (Gupta and Narain, 1967; Chun and Yoshii, 1977; Chun, 1986) and Bouguer gravity data (Duroy et al., 1989). In addition, basement rocks are exposed at the surface above the Main Central thrust (LeFort, 1975).

Recent studies constrained by seismic reflection and borehole data in the North American Cordillera, Appalachians, Alps, Himalayas, and Taiwan have provided insight into the mechanism of deformation, geometry, and evolution of structures in the collision zones (Rich, 1934; Dahlstrom, 1969, 1970; Suppe, 1980, 1983; Laubscher, 1981; Acharyya and Ray, 1982; Bachman et al., 1982; Jones, 1982; Davis et al., 1983; Davis and Engelder, 1985; Banks and Warburton, 1986; Boyer, 1986; Mitra, 1986; Lillie et al., 1987; Jaume and Lillie, 1988; Izatt, 1990; McDougal and Hussain, 1991; Jadoon et al., 1992). Studies of active mountain belts (i.e. Himalaya and Taiwan) are important because they provide constraints on collisional

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[1] Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan
[2] Department of Geosciences, Oregon State University, Corvallis OR 97331, USA

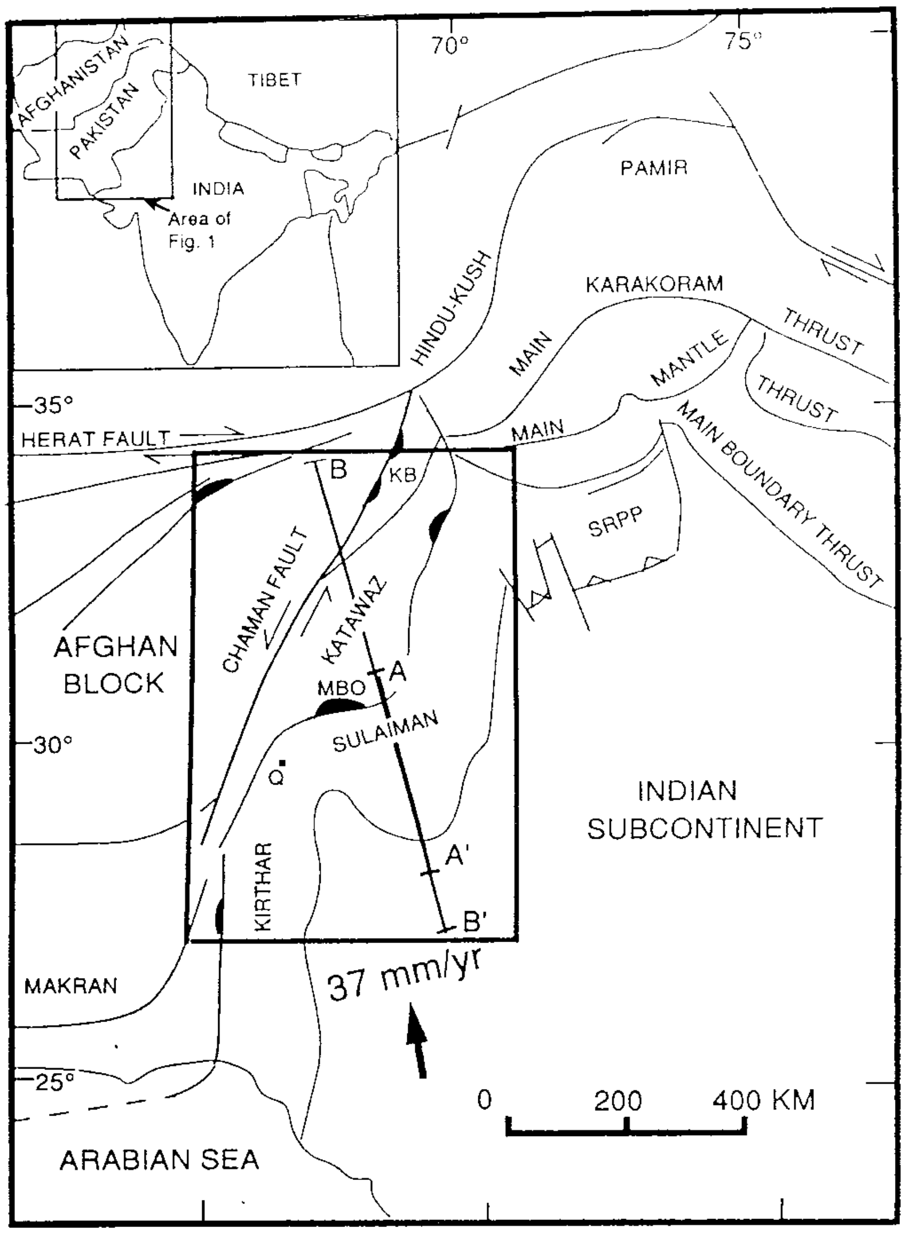


Figure 1– Simplified tectonic map of the Indian/Afghan collision zone. The arrow shows convergence vector of India relative to the Afghan block (Minster et al., 1974). Lines A-A′ and B-B′ show the locations of the balanced structural (Figure 9) and crustal (Jadoon, 1992) sections respectively. Box shows the location of the Figure 2. KB=Kabul Block, MBO=Muslimbagh Ophiolites, Q=Quetta, SR/PP=Salt Range/Potwar Plateau.

processes that are unavailable in ancient mountain belts. In this study seismic reflection and well data, available from the foreland of the active Sulaiman fold belt are integrated with surface geology and Landsat data to draw a balanced cross-section across the entire Sulaiman fold belt to: (1) recognize geometry, structural style, and evolution of surface and deep structures in the Sulaiman fold belt; and (2) evaluate shortening in the cover strata of the Indian subcontinent.

Our balanced structural cross-section favours the duplex style of deformation in the Sulaiman lobe. In these structures, floor and roof faults are the major flats and multiple ramp faults between them form duplexes (Dahlstrom, 1970; Boyer and Elliot, 1982). The rock units above the roof fault are known as the roof sequence. Recently, investigators have recognized roof faults in which the sense of motion is opposite to the vergence of the thrust system as a whole, called passive-backthrusts (Jones, 1982; Banks and Warburton, 1986; Wallace and Hanks, 1990; and Humayon et al., 1991). In some cases, these roof sequences are shown in balanced structural cross-sections as thin and continuous units of great length (Hobson, 1986). The balanced structural cross-section in this study along the central line of the Sulaiman lobe, Pakistan has one of the longest passive-roof structures yet described. This actively deforming foreland thrust lobe provides new data on the development of such systems.

TECTONIC FRAMEWORK AND STRATIGRAPHY

The Himalayan mountain belt changes trend from northwest-southeast in India to northeast-southwest in Pakistan (Figure 1). Typical of the foreland part of the northwestern Himalaya in Pakistan are two broad lobate features: Salt Range/Potwar Plateau and the Sulaiman fold belt. Their lobate geometry is interpreted to be the result of rapid southward translation along a weak decollement of the tear fault bounded thrust sheets (Sarwar and DeJong, 1979; Seeber et al., 1981). This is similar to the foreland translation of the Pine Mountain thrust block of the Central Appalachians (Rich, 1934; Harris and Milici, 1977) and the Jura Mountains of Europe (Laubscher, 1981). Deformation is progressively younger toward the foreland, as constrained by magnetic stratigraphy (Johnson et al., 1985; Raynolds and Johnson, 1985) and neotectonic activity in the Salt Range/Potwar Plateau (Yeats et al., 1984; Yeats and Lillie, 1991). In the Sulaiman fold belt progressive deformation is evidenced by structural style (Hunting Survey Corporation, 1961; Kazmi and Rana, 1982), a prominent topographic front, and seismicity over the frontal folds (Quittmeyer et al., 1979; 1984), and magnetostratigraphy (Ahmad and Khan, 1990).

Unlike the Salt Range/Potwar Plateau that is associated with the main zone of Himalayan convergence, the Sulaiman fold belt is located along a zone of transpression (Sarwar and DeJong, 1979; Lawrence et al., 1981a; Klootwijk et al., 1981, 1985; Farah et al., 1984) in the northwestern part of the Indian subcontinent (Figure 1). The broad Sulaiman fold belt is bounded to the west and north by the left-lateral strike-slip Chaman fault zone (Figure 2). The foredeep basin to the east and south of the active Sulaiman Lobe is formed mainly as a result of tectonic compression between the Indian plate and the Afghan block (Figure 2). The initial event of collision is manifested by the

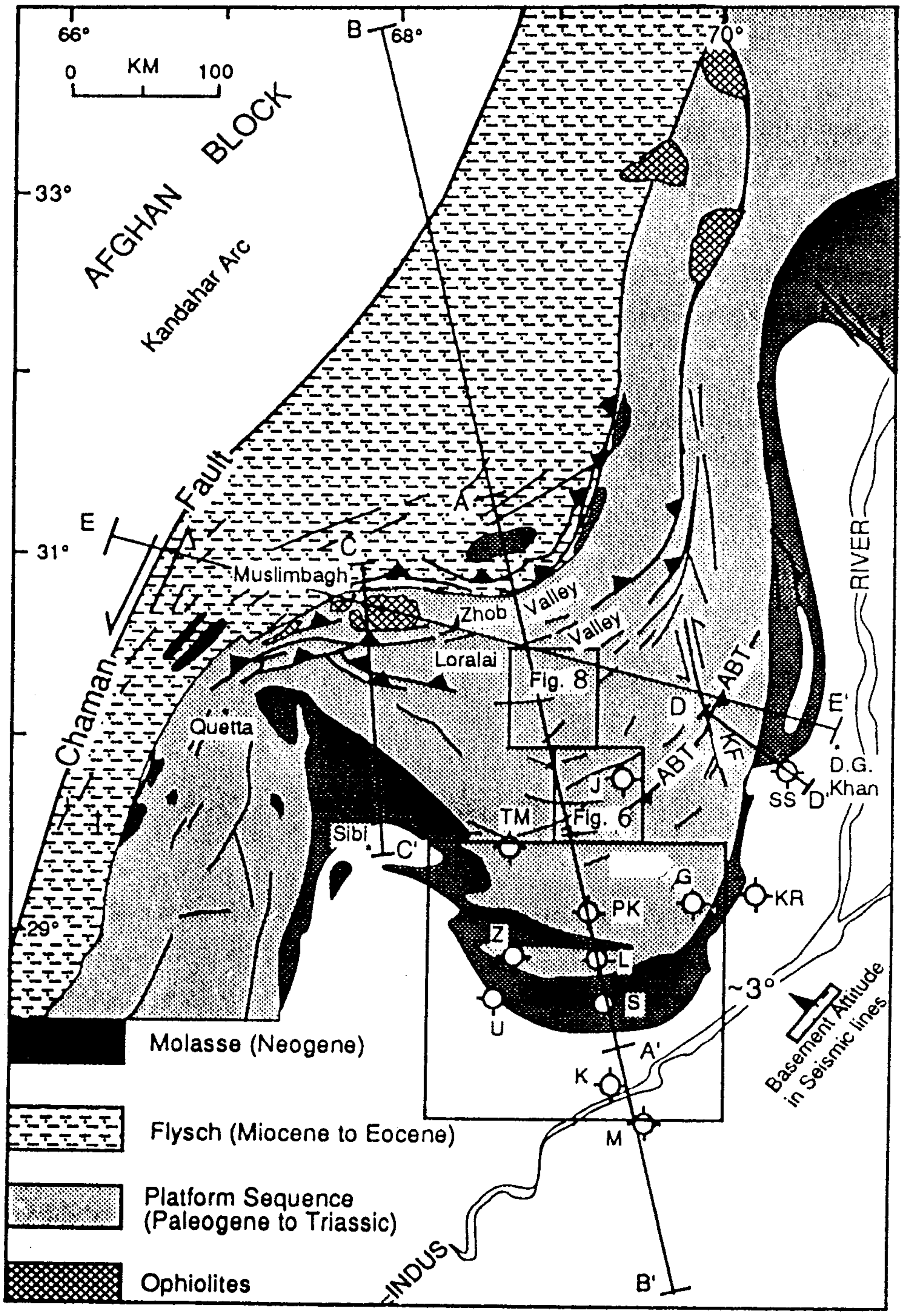


Figure 2– Generalized tectonic map of the Sulaiman lobe (modified from Kazmi and Rana, 1982). Areas of Figures 6 and 8 are shown by boxes. See Jadoon (1991a) for a detailed geological map of the southern box. Lines A-A′ and B-B′ show the locations of the balanced structural (Figure 9) and crustal (Jadoon, 1992) sections respectively. C-C′ and D-D′ show the location of balanced cross-sections by Banks and Warburton (1986) and Humayon et al. (1991), respectively. E-E′ shows gravity profile by Khurshid et al. (1992). Well abbreviations: G = Giandari-1, J = Jandran, K = Kandkot-2, KR = Kotrum, L = Loti-2, M = Mari-2, PK = Pirkoh-2, S = Sui-1, SS = Sakhi Sarwar, TM = Tadri Main, U = Uch, Z = Zin.

emplacement of the Muslimbagh ophiolite between Late Cretaceous and Early Eocene times (Allemann, 1979). An unconformity between Cretaceous and Paleocene rocks in the Attock Cherat Ranges north of the Potwar Plateau (Yeats and Hussain, 1987) extends all the way to the Loralai valley of the Sulaiman Range (Hunting Survey Corporation, 1961). Renewed southward thrusting since late Oligocene-early Miocene constantly reworked the molasse strata migrating the Indus basin farther east and south (Banks and Warburton, 1986; Waheed and Wells, 1990). This is similar to the southward migration of the active foredeep basins of the Ganges plain in India and the Jhelum plain in Pakistan (Acharyya and Ray, 1982; Raiverman et al., 1983; Johnson et al., 1985; Raynolds and Johnson, 1985).

The main structural elements in the Sulaiman fold belt are east-west trending arcuate folds and faults which rotate rapidly to a north-south direction along the margin of the active fold belt (Figure 2). Imbricate faults are visible at the surface only in the north (Hunting Survey Corporation, 1961; Kazmi and Rana, 1982). They gradually disappear toward the frontal part of the fold belt in the subsurface.

Rocks from the Sulaiman fold belt can be divided into three main groups to emphasize their tectonic significance. From south to north these units are: (1) late Oligocene to Recent molasse deposits; (2) Eocene to Permian, shallow-marine shelf to deep marine rocks (Kazmi and Rana, 1982)); and (3) late Eocene to early Oligocene Khojak Flysch (Lawrence and Khan, 1991). The Muslimbagh ophiolites in the Zhob valley represent pieces of oceanic crust thrust over Maestrichtian shelf strata (Abbas and Ahmad, 1979). See Jadoon (1991a) and Jadoon et al. (1992) for a stratigraphic column of the Sulaiman fold belt at the deformation front based on surface geology, well data, and seismic reflection profiles. The exposed Eocene to Permian rocks from the Sulaiman fold belt are similar to those of the Salt Range, except that the 7 km thick carbonate dominated sequence is much thicker than that of the Salt Range. The Sulaiman fold belt with such a thick sedimentary section yet with relatively high Bouguer gravity anomalies is interpreted to overlay an extended crust (Jadoon et al., 1989; Lillie, 1991; Jadoon, 1992; Khurshid et al., 1992). Absence of the involvement of the crystalline basement and the presence of a transitional crust about 20 km thick suggest an early stage of convergence in the Sulaiman lobe. This implies that active collision structures may be observed through a younger stage of evolution in the Sulaiman than main Himalayas.

The hydrocarbon prone Sulaiman fold belt has not been mapped or structurally investigated in detail. Recent structural studies suggest different models for its evolution. Banks and Warburton (1986) proposed duplex style of deformation for the western Sulaiman/Kirthar Ranges. This is favoured by the Humayon et al. (1991) and Jadoon et al. (1992). The duplex style of deformation is in contrast of the Sulaiman lobe consisting of a series of imbricate, forward verging thrust sheet (Bannert et al., 1989) or the basement involvement in the thrusting (Ahmed and Ali, 1991). Discussion to follow based on surface and subsurface data presents a balanced cross-section in order to comprehend the evolution and shortening of the Sulaiman thrust system.

GENERAL OBSERVATIONS FROM INTEGRATION OF SURFACE AND SUBSURFACE DATA

Seismic reflection profiles from the frontal part of the Sulaiman fold belt and the adjacent foredeep in Pakistan have been interpreted in conjunction with drill hole, surface geology, and Landsat data (Figures 3-9). The main conclusions are:

(1) The thickness of the Phanerozoic sedimentary wedge at the deformation front is exceptionally high, about 10 km. The structurally duplicated sedimentary section in the hinterland is about 20 km thick. This thickness includes more than 7 km of carbonate-dominated Paleozoic to Eocene strata (compared to about 1 km for the same age strata in the Salt Range).

(2) Basement dip is about 2.5° to the north. Basement is not involved in the deformation at least as far back as the Bugti syncline. This is based on the critical observation of the seismic data from southern Sulaiman foreland (Figure 3). However, farther north involvement of the basement is not precluded as the nature of the crust is inferred to be transitional below the Sulaiman fold belt (Jadoon, 1992; Khurshid et al., 1992).

(3) Seismic reflection profiles show that basal decollement is located at the interface between crystalline basement and sedimentary wedge (i.e. 81-LO-2 in Figure 3) in the Sulaiman lobe. Evidence suggests that the Eocambrian evaporite sequence that provides an effective zone of decoupling at the base of the section in the Salt Range and Potwar Plateau (Lillie et al., 1987; Jaume and Lillie, 1988) may not be present along decollement in the Sulaiman lobe. However, a weak decollement in the Sulaiman fold-and-thrust belt may be in pelitic rocks or fine carbonates above the crystalline basement at a depth of more than 10 to 15 km. This is supported by average geothermal gradient of about 30°C in the foreland of the Sulaiman fold belt (Jadoon, 1991a).

(4) The southern Sulaiman lobe reflects a coherent stratigraphy in which older rocks are progressively exposed in the cores of more northerly, tighter anticlines

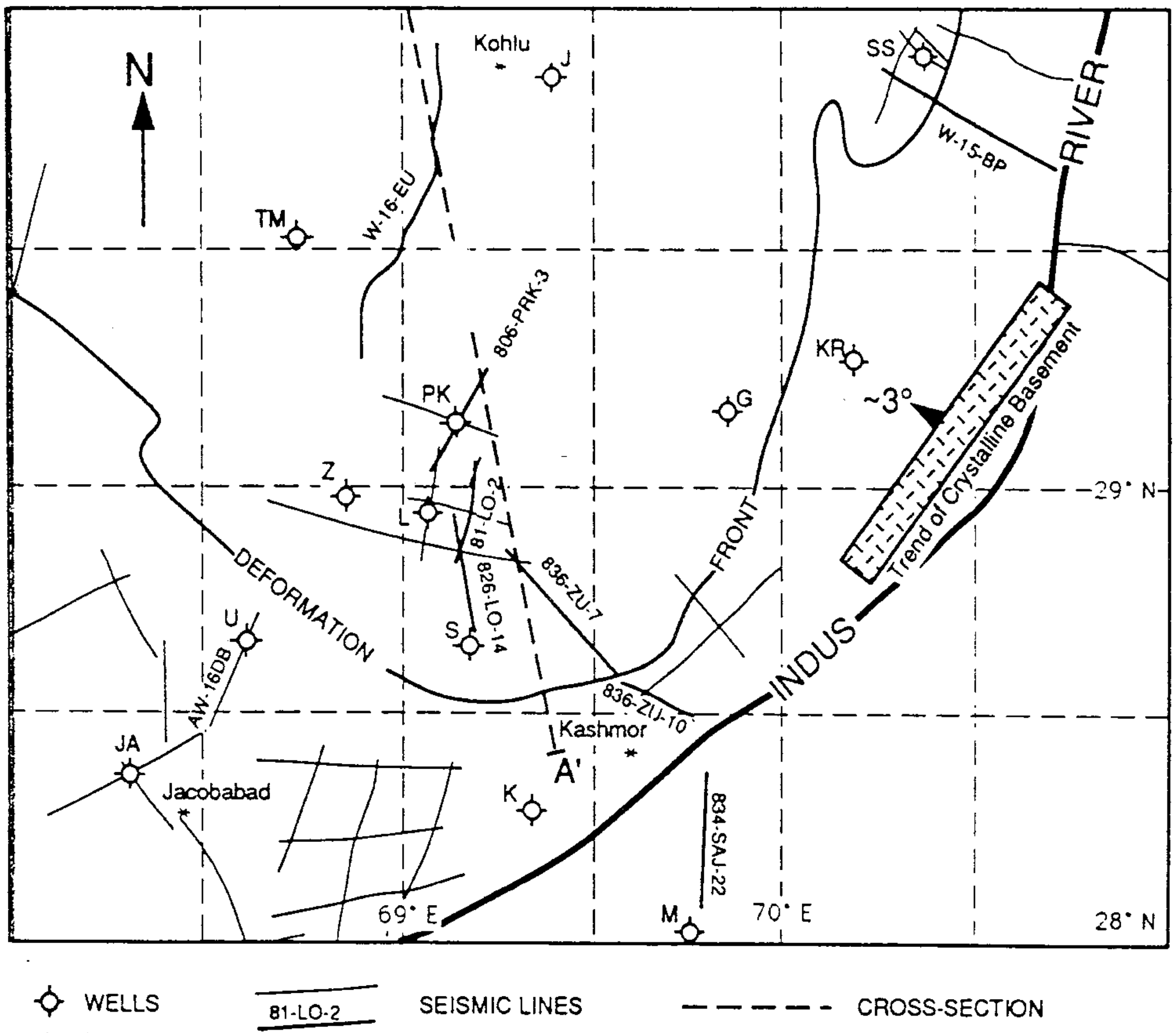


Figure 3– Map of seismic reflection and well data coverage. Bold lines were used to project subsurface data onto the balanced cross-section A-A′ (Figure 9). The crystalline basement can be seen on seismic lines 834-SAJ-22 and W-15-BP. Well abbreviations are same as in Figure 2. Data were released by Oil and Gas Development Corporation of Pakistan (OGDC), Amoco, and Texaco overseas.

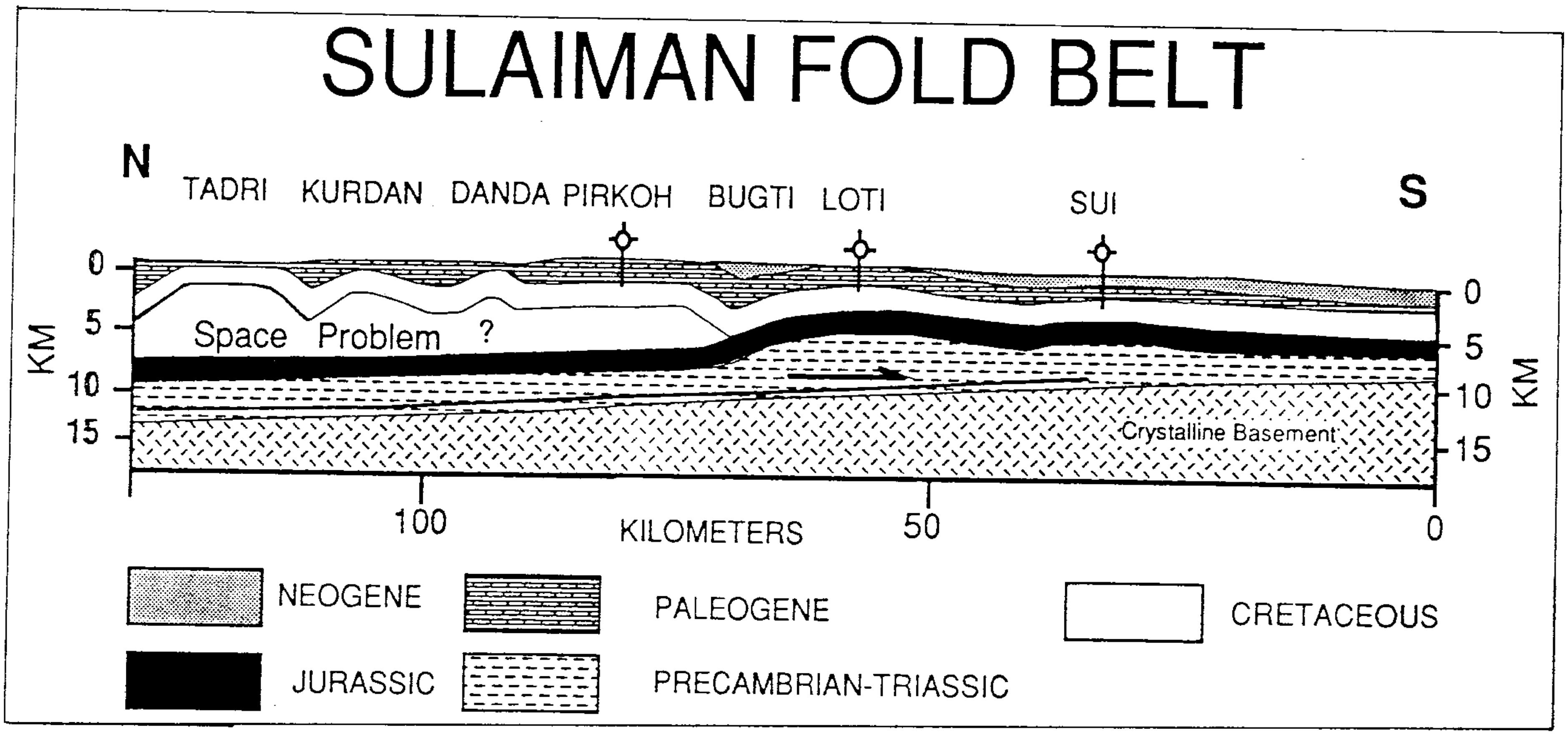


Figure 4– Partial geological cross-section of the southern Sulaiman foreland. See Figure 6 for location. The cross-section (Jadoon et al., 1992) is based on the seismic reflection, borehole, surface geology, and LANDSAT data. It shows the extrapolated top to the crystalline basement, decollement zone, and a space problem due to tectonic uplift of Cretaceous and younger strata as a coherent slab, over the older strata. Notice concentric folding is the structural style of the broad Sui and Loti anticlines. The space in the cores of these folds (Sui and Loti) may be filled by ductile flow within the decollement zone at a depth of more than 10 km. Text identifying the individual folds at the surface are from the individual mountains.

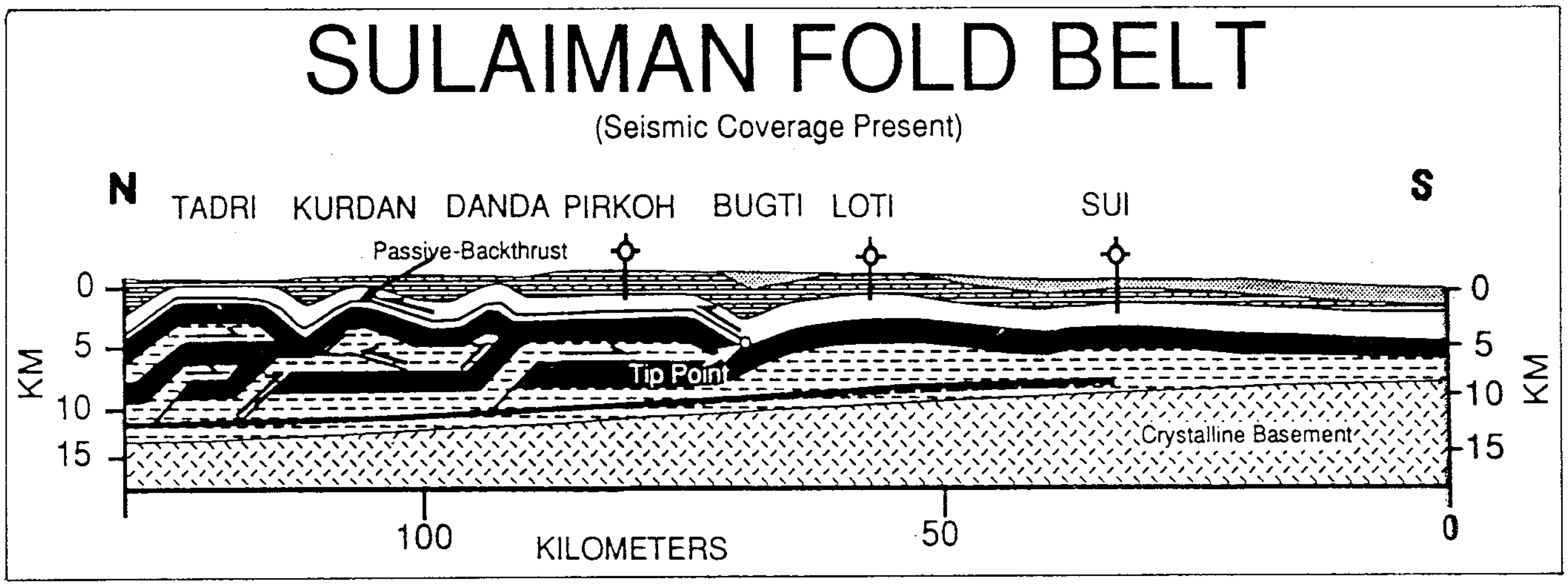


Figure 5– Complete geological cross-section of the southern Sulaiman foreland (from Jadoon, 1991a). It suggests duplex style of deformation to solve the space problem in Figure 4. The duplex sequence of Jurassic and older rocks is bounded between a floor thrust (decollement) above the crystalline basement and a roof thrust (passive-roof thrust) in Cretaceous Sembar shales. Folds at the surface reflects the shape of the duplex horses below. See Figure 4 for the patterns.

(Jadoon, 1991a; Jadoon et al., 1992). The crests of these folds are cut only by small-scale normal faults. Seismic reflection profiles show that northwards from the Bugti syncline rocks exposed at the surface are structurally elevated by the over thickened, active wedge. The resultant structural relief is 4 to 8 km from south to north in the foreland (Figure 4). Interpretation of seismic reflection data (Jadoon, 1991a; Jadoon et al., 1992) suggests that structural relief is due to duplexes at depth (Figure 5).

(5) The Central Sulaiman lobe exhibits an extensive system of faults (Figure 6). These are interpreted as reverse faults mostly restricted to the roof sequence. Tight anticlines between paired faults with hinterland and foreland vergence are interpreted as pop-ups (Figure 7).

(6) The Northern Sulaiman lobe shows the structure of a triangle zone between hindward emergent passive-roof fault and forward vergent Loralai thrust (Figures 8 and 9).

(7) Overall structural style is of hinterland dipping duplexes bounded between a floor thrust near the base of the sedimentary section and a passive-roof thrust in thick Cretaceous shales. In the foreland broad and gentle folds (Sui and Loti), half wavelength about 20 km, may be primarily formed as a result of ductile flow of material in the core of the anticlines at a depth of about 10 km (Figures 5).

(8) Total shortening parallel to the direction of tectonic transport along the duplex structures and the broad frontal folds is estimated as 378 km. Shortening in the roof sequence is accommodated by erosion at the emergent tip of passive-roof (Figures 9 and 10D) and overstep back thrusts (Figure 10C).

(9) Duplex geometry implies that petroleum producing Cretaceous and Eocene horizons may not be present in the lower plate for drilling. It suggests to determine the prospects for hydrocarbons in the Jurassic for drilling in the favourable duplex structures.

The details of these structures are discussed below in the context of seismic reflection profiles and the balanced structural cross-section A-A' (Figures 2 and 9). This is followed by discussion of the palinspastic restoration, style of deformation, timing and rate of deformation, and hydrocarbon prospects.

DATA, AND BALANCED STRUCTURAL CROSS-SECTION

Surface Geology and Landsat Data

Geological maps (1:250,000) by the Oil and Gas Development Corporation of Pakistan (OGDC) of the frontal folds, unpublished maps (1:250,000) in the Geological Survey of Pakistan (GSP) from the central Sulaiman (Marri Bugti area), and the Hunting Survey Corporation maps (1:253,440) along with Landsat data (1:125,000), provide surface geology coverage. This data set is used to construct a balanced structural cross-section across the western collisional boundary of the Indian Subcontinent (A-A' in Figure 2). Field checks

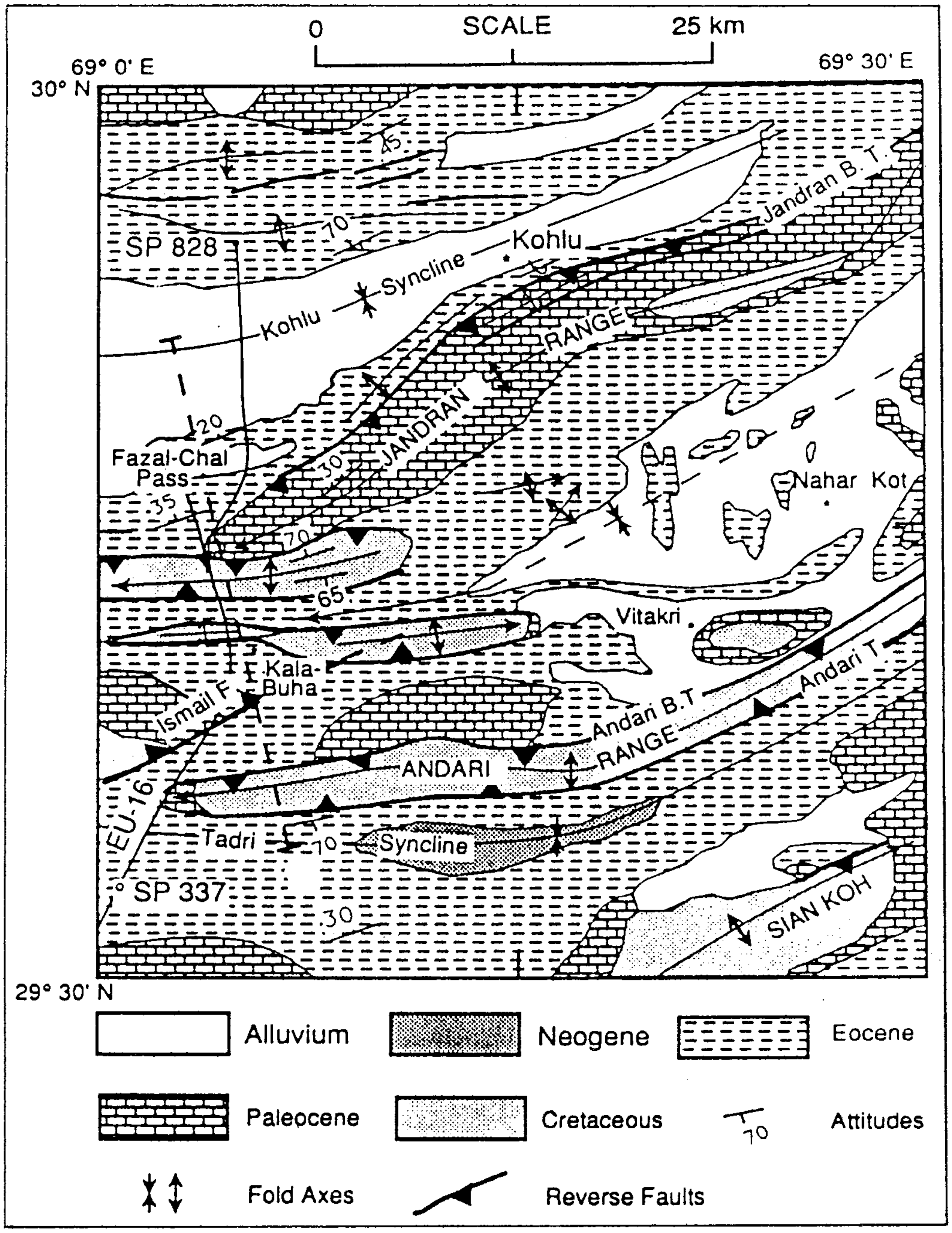


Figure 6– Geological map of the central Sulaiman fold belt. See Figure 2 for location in the Sulaiman lobe. Compare the surface (secondary) structures in this map to the deep (duplex) structures in Figure 7. Dashed line between Kohlu and Tadri synclines show the location of Figure 7. Curved line (EU-16) shows the location of a seismic reflection line.

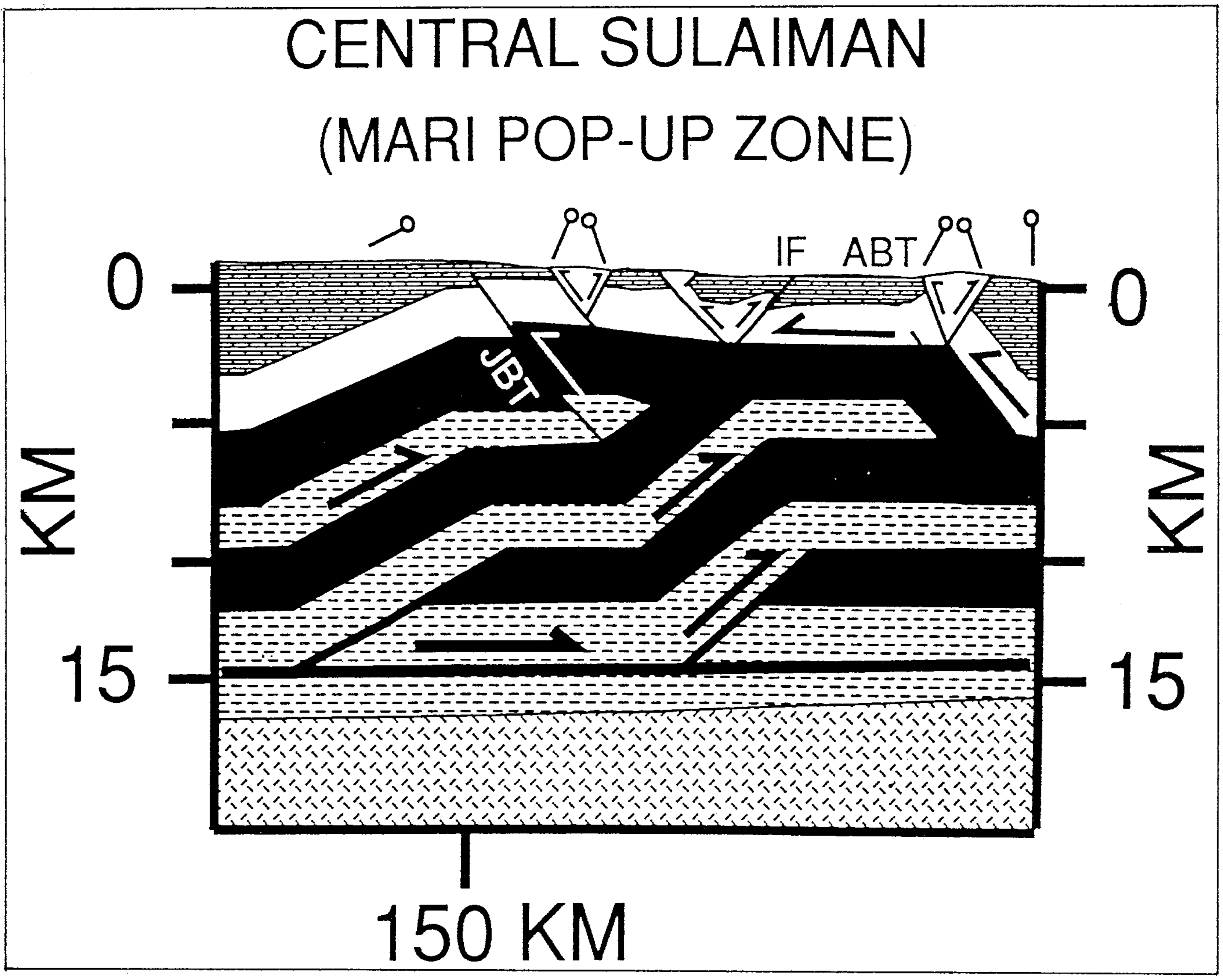


Figure 7– Structural cross-section of part of the central Sulaiman fold belt. See Figure 6 for location. Notice pop-ups and associated reverse faults with minor throw of the top Cretaceous, Paleocene, and Eocene. These secondary faults emerging from the passive-roof thrust, may represent an early stage of development of overstep-backthrusts. Symbols in above section represent dips measured in the field. See Figure 4 for the patterns.

were done along the cross-section in two seasons during the fall of 1988 and winter of 1990.

Main Structural Zones of the Sulaiman Lobe

Study of the geological maps shows simple to complex surface structures from the foreland towards the hinterland. This variation is related to the active evolution of the Sulaiman fold belt. For simplicity of discussion in this paper, the broad (>300 km) Sulaiman fold belt is divided into different structural zones along a regional, 349 km long balanced cross-section (A-A′ in Figure 2).

Southern zone.– The southern Sulaiman lobe consists of an area from the Sulaiman foredeep to Tadri and Sian Koh anticlines. See Jadoon (1991a) for a geological map of this area. This area mainly consists of Tertiary molasse and Paleogene to Cretaceous platform sedimentary rocks. It is dominated by broad, east-west trending, doubly plunging surface folds whose axes rotate toward the north-south at the edges of the fold belt.

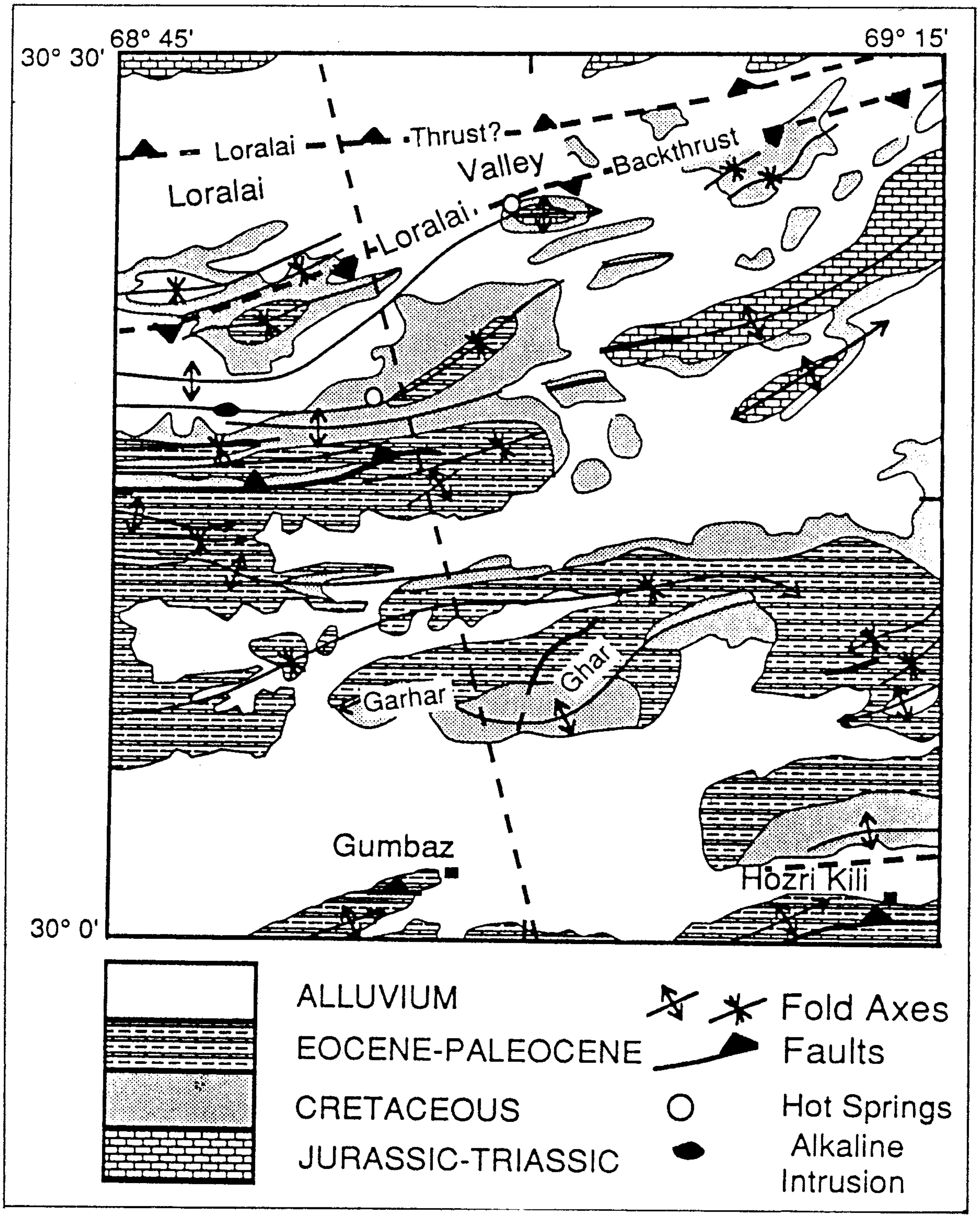


Figure 8– Geological map of the northern Sulaiman fold belt (modified from Hunting Survey Corporation, 1961; Bhatti et al., 1984). See Figure 2 for location in the Sulaiman lobe. Dashed line shows the location of a part of the balanced cross-section A-A′ (Figures 2 and 9) on this map. Notice the consistent uplift of the older rocks toward the north, widespread Cretaceous strata, and the hot springs in the broad Loralai valley.

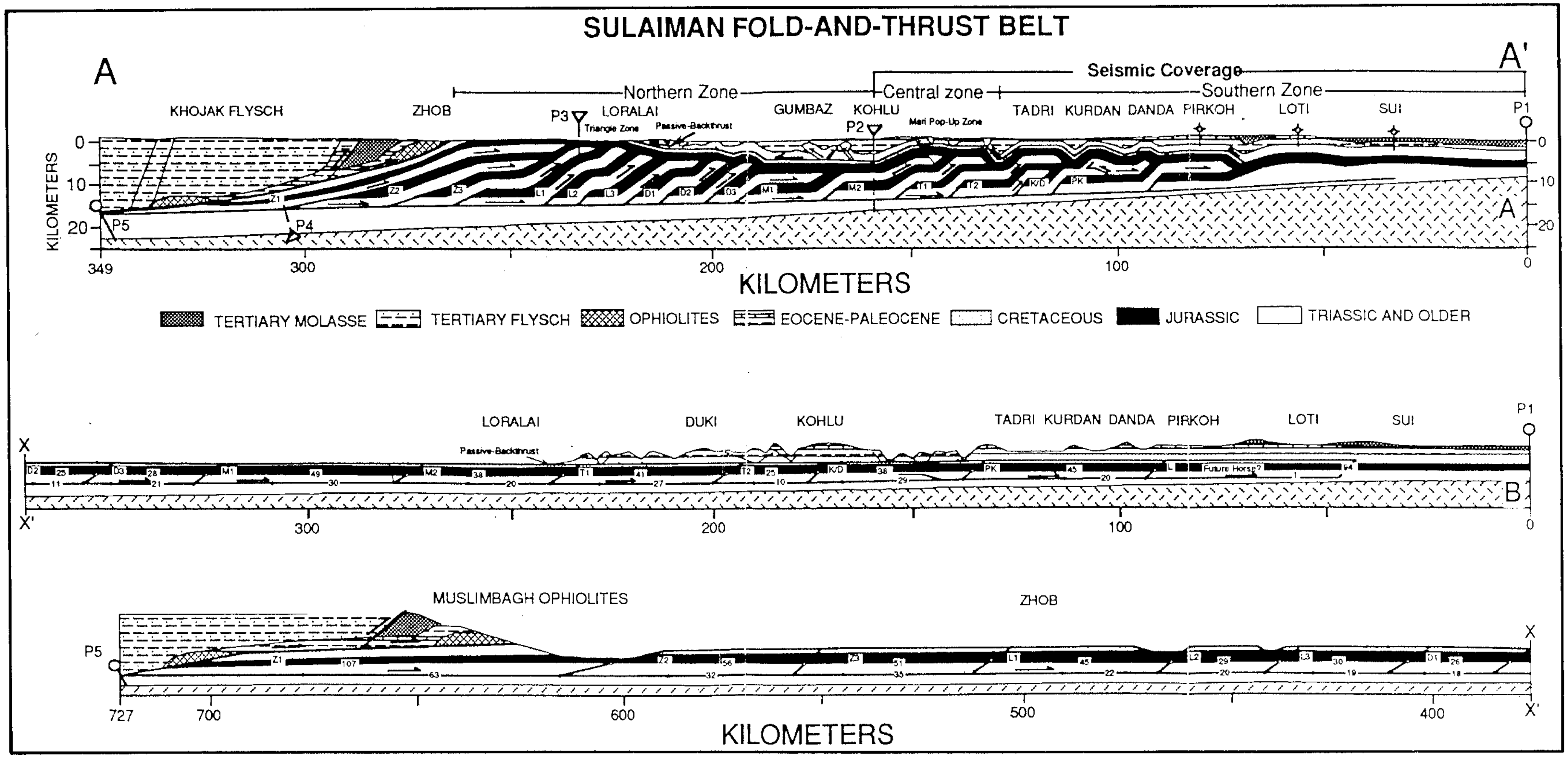
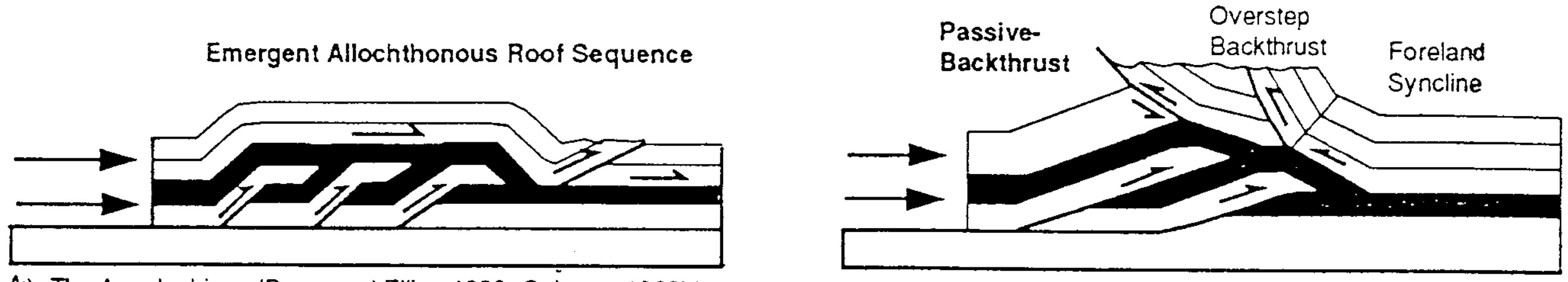


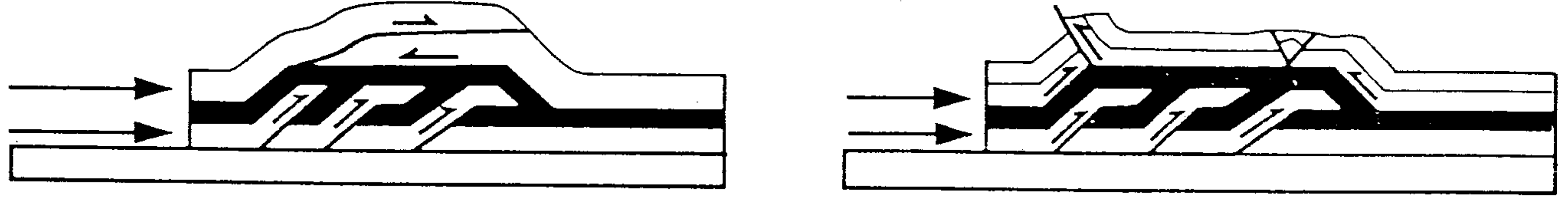
Figure 9– Balanced (A) and retrodeformed (B) structural cross-sections from the Sulaiman lobe in Pakistan. See Jadoon (1991a) and Jadoon et al. (1993) for seismic coverage from southern and central zone. See Figures 5 and 7 for structural details of southern and central zone. 349 km long deformed section (A) restores to 727 km (B) which gives maximum shortening of 378 km related to Himalayan collision at the western terminus of the Indian subcontinent. Missing roof-sequence is interpreted to be removed primarily by erosion along a major passive-backthrust. Letters identifying individual horses in the duplex sequence are from the individual mountains and from the geographic domains. From north to south these areas are Z1-Z3 = Zhob valley, L1-L3 = Loralai valley, D1-D3 = Duki Valley, M1-M2 = Mari, T1-T2 = Tadri, K = Kurdan, D = Danda, P = Pirkoh, L = Loti (future horse). Numbers between the white dots and the black dots within the individual horses in the retrodeformed section show the length of the horse and the associated displacement in kilometres.



Emergent Allochthonous Roof Sequence

A) The Appalachians (Boyer and Elliot, 1982; Geisser, 1988b)

C) Western Sulaiman/Kirthar ranges, Pakistan
(Banks and Warburton, 1986)



Superficial decollement in the Roof-Sequence

Major Passive-Back Thrust

B) Main Brooks Range Thrust Sheet, Alaska
(Vann and others, 1986)

D) Central Sulaiman Fold Belt, Pakistan
Papua, New Guinea Fold Belt (Hobson, 1986)

Figure 10– Multiple interpretations of duplex geometry (A) emergent allochthonous roof sequence, (B) superficial decollement in the roof sequence, (C) passive-roof sequence with multiple overstep backthrusts, and (D) passive-roof sequence with limited backthrusts. Different models illustrate shortening in roof sequences based on practical examples around the world.

Central zone.– The central Sulaiman fold belt consists of an area between the Tadri and Kohlu synclines (Figure 6). This area is dominated by foreland and hinterland verging faults. These thrust/reverse faults juxtapose Cretaceous against Eocene rocks. Folds in the central zone appear to be related to these faults.

Northern zone.– The northern Sulaiman fold belt consists of an area between the Kohlu syncline to Muslimbagh (Zhob valley) ophiolites (Figures 2 and 8). The exposed rocks are progressively older (Paleogene to Triassic) toward the north. South of the Loralai valley, structures are dominated by symmetrical folds (wavelength about 10 km), e.g. the Garhar Ghar anticline (Figure 8). These folds become much tighter (wavelength less than 2 km) as the Loralai valley is approached (see maps of Hunting Survey Corporation, 1961). These tight folds may be interpreted as detachment folds with a decollement in thick Cretaceous shale that is extensively distributed in the Loralai valley.

Faults are present in the northern zone but are not as abundant as in the central zone. Two main faults are inferred in the Loralai valley (Figure 8) based on an abrupt facies change and structural interpretation along the balanced structural cross-section. One fault, the Loralai thrust, is inferred due to distal pelitic facies of Jurassic limestone against shallow water massive limestone of the same age. Structures in the dominantly pelitic sequence are kink and box folds. The other fault, the Loralai backthrust, is based on the structural interpretation to be discussed below.

Zhob (Muslimbagh) ophiolite zone.– The northern zone is overlain by Zhob (Muslimbagh) ophiolites. These ophiolites composed of pillow basalts, sheeted dykes represent pieces of oceanic crust (Asrarullah et al., 1979; Abbas and Ahmad, 1979; Gansser, 1979; Farah and Zaigham, 1979), tectonically emplaced on the Sulaiman passive margin shelf and platform sequence during the Paleocene to Eocene time (Allemann, 1979; Otsuki et al., 1989).

Khojak flysch zone.– The Khojak flysch represents a deep-water submarine clastic sediment fan. This fan, probably analogous to the present day Indus fan, was deposited on the oceanic crust mostly during Eocene to Oligocene in response to the first deformation episode of Himalayan orogeny (Lawrence and Khan, 1991). Subsequently most of the deformation of the Khojak flysch occurred in the Oligocene to Miocene, as evidenced by an increase in sea-floor spreading velocities about 30 Ma (Lawrence and Khan, 1991). Presently, it is found in the Makran Ranges and between the Chaman fault and shelf sediments of the Indo-Pakistan plate. Ophiolites are present along both sides of the Khojak flysch. To the south and east are the well known ophiolites of Waziristan, Muslimbagh, and

Las-bela (Asrarullah et al., 1979; DeJong and Subhani,1979; Otsuki et al., 1989). To the north and west, ophiolites are scattered along the Chaman fault, in the Ras Koh (Hunting Survey Corporation, 1961), and in the Kabul block (Lawrence and Khan, 1991; Khan et al., 1991). Fragments of ophiolites along the Chaman fault were probably emplaced during the late Cretaceous/Paleocene contemporary with the Kandahar andesitic arc (Lawrence et al., 1981b; Debon et al., 1986).

Subsurface Data and Depth to the Decollement

Extensive seismic reflection and borehole data from the frontal part of the Sulaiman fold belt and the adjacent foredeep (Figure 3) have been provided to the Oregon State University by the Oil and Gas Development Corporation of Pakistan (OGDC), the Hydrocarbon Development Institute of Pakistan (HDIP), Amoco and Texaco oil companies. The seismic profiles provide good coverage from the southern Sulaiman foredeep and extend about 160 km to the north into the fold-and-thrust belt from the deformation front. Humayon et al. (1991) provide seismic coverage from the eastern Sulaiman foredeep.

The seismic profiles are used to resolve: (a) trend and depth to the top of the crystalline basement to constrain stratigraphic and tectonic thicknesses and Bouguer gravity modelling (Jadoon, 1992); (b) the major decollement; and (3) the geometry of structures along balanced structural cross-section A-A' in Figure 2. The first two constraints are vital to resolve the geometry of structures and style of deformation and are discussed by Jadoon (1991a) in detail.

Seismic reflection lines and borehole data (Figure 3) provide sufficient subsurface data to constrain the Sulaiman foredeep and the southern zone. One of the most important observations resulting from the study of the composite seismic line (bold lines in Figure 3) from the Mari well (line 834-SAJ-22) in the Sulaiman foredeep to Kohlu (line W-16-EU) in the central Sulaiman is the interpreted depth to the top of the crystalline basement. Seismic data suggest that depth to the top of crystalline basements is about 10 km at the deformation front. The basement descends northwards with a gentle inclination of about 2°-2.5° and is extrapolated to attain a depth of about 20 km in the hinterland of the Sulaiman fold-and-thrust belt. The seismic reflection profiles show that all the stratigraphic section is detached from the basement in the southernmost Sui and Loti anticlines (81-LO-14, 81-LO-2 in Figure 3). Thus, the major decollement is in Paleozoic rocks at the interface between crystalline basement and the sedimentary package at the deformation front.

BALANCED STRUCTURAL CROSS-SECTION

Section Balancing

Line length and area balancing techniques (Balley et al., 1966; Dahlstrom, 1969; Gwinn, 1970; Elliot, 1982; Woodward et al., 1989) were applied to the cross-section (A-A' in Figures 2 and 9). The southern 159 km long part of the cross-section is thoroughly constrained by seismic reflection and well data and was balanced by the line-length method except under the frontal broad folds (Sui and Loti). This technique is considered here to be invalid due to the ductility of material in the core zones of these anticlines. The northern 185 km of the cross-section north of kilometre mark 159 primarily area-balanced (Figure 9), due to lack of seismic data.

Surface and Subsurface Expression

Discussion along the 349 km long balanced structural cross-section (A-A' in Figure 2 and 9) is divided according to the structural zones described earlier.

Sulaiman foredeep and the southern zone.- The Sulaiman foreland constrained with seismic and borehole data has been discussed by Jadoon (1991a), Jadoon et al. 1992). This portion consists of broad east-west trending, doubly plunging folds. The rocks structurally uplifted to the surface in the cores of anticlines, become progressively older toward the hinterland. However, these exposed rocks everywhere show a coherent stratigraphy that is not disrupted by thrust faults (Figure 4). Boreholes in the frontal and central Sulaiman Range (Tadri and Jandran) penetrated a normal stratigraphic sequence as deep as Jurassic. These observations collectively imply that, towards the hinterland, rocks are structurally uplifted from their regional stratigraphic level by duplication along blind thrust below the Cretaceous (Figure 5).

The surface and seismic expression of the frontal part of the Sulaiman fold belt is of two broad (half wavelength about 20 km), small amplitude (1-2 km) anticlines (Sui and Loti). Limb dips do not exceed 4° on Sui and 15° on Loti (Figure 5). Nearly all the 10 km thick stratigraphic sections are detached from the basement. These folds are replaced by ramp and duplex structures with a continuing extremely deep detachment level toward the north, starting with Pirkoh anticline. Major duplexing dominates between a floor thrust just above crystalline basement and a passive-roof thrust in Cretaceous shale (Figure 5). Duplexing appears to be initiated when the buckle folds reach a limiting amplitude. The Pirkoh, Danda, and Kurdan anticlines are cored by a single horse. The Tadri anticline and the Mari anticlinal zones are cored by two horses. Tadri is fundamentally an anticlinal stack.

The entire portion of this section underlain by duplexes is topped by a passive-roof sequence (Figure 5). At and south of Tadri, faults do not cut the section above Cretaceous rocks, and fault-related folds predominate in the exposed Paleogene rocks. The surface structures (folds) in the passive-roof sequence reflect the shape of the fault-bend folds in the duplex sequence (e.g. Pirkoh anticline). This means that the roof sequence does not deform independently of the duplex sequence south of Tadri anticline. The great length of the passive-roof structure in the Sulaiman fold belt remains a significant mechanical problem.

Central zone.– North of the Tadri syncline, complicated structures appear at the surface (Figure 6). These structures are foreland and hinterland verging reverse faults, and associated small wavelength, fault-bounded anticlines. Along these faults, mostly Cretaceous rocks juxtapose Eocene rocks. At the surface, these faults are of great lateral extent (10s of km; Figure 6). The Andari backthrust that emerges from the Tadri syncline with a backthrust sense of vergence extends for about 170 km (Figures 2 and 9). Humayon et al. (1991) recognized the backthrust sense of vergence along the Andari fault in the eastern Sulaiman Ranges and interpreted it to emerge from the passive-roof thrust. Critical observation of seismic data (Jadoon, 1991b; Jadoon et al., 1993) shows minor throw (1-2 km) mostly of top Cretaceous, Paleocene, and Eocene rocks along these faults (Figure 7). These observations suggest that the faults are secondary structures (out-of-sequence thrusts of Morley, 1986 and 1988), mostly restricted to the passive-roof sequence. One exception is the Jandran backthrust that cuts through the upper duplex horse (M1). Tight, short wavelength anticlines associated with these faults are interpreted as pop-ups (Mari pop-up zone) in the roof sequence (Figures 6 and 7). Parry (1978) and Mitra (1987), and Ahmed and McElroy (1991) have shown similar structures in cross-sections from the Appalachian foreland in West Virginia and the Himalayan foreland in Kohat Plateau respectively. Active shallow seismicity (about 5 km) in the central Sulaiman Range (Quittmeyer et al., 1979, 1984; Kazmi, 1979), tilted gravel beds, and landslides in the Mari pop-up zone suggest that some of these faults may be active. This interpretation suggests that north of the Tadri anticline, structures (tight) in the roof-sequence are different from the deep (relatively broad) structures in the duplex sequence.

Although the passive-roof sequence is disrupted by reverse faults in the central zone, it is not emergent due to minor throw along these secondary faults (Figure 7). These out-of-sequence reverse faults may represent an early stage in the development of one or more overstep backthrusts emerging from the passive-roof thrust. This suggests that multiple backthrusts which were proposed to serve as a mechanism for the shortening strain in the passive-roof sequence (Banks and Warburton, 1986) are not present or are only incipiently present at the current stage of the central Sulaiman deformation.

Northern zone.– Seismic data do not exist from the northern zone. Basement and the decollement surface (Figure 9) are extrapolated as they descend northwards from the central and southern zone. The structural profile (A-A') intersects an east-west Bouguer gravity profile (E-E') in the Loralai valley (Figure 2). Crystalline basement along this Bouguer gravity profile (E-E' in Figure 2) is extrapolated (Khurshid et al., 1992) by the seismic reflection data from the eastern Sulaiman foreland and associated foredeep (Humayon et al., 1991). Depth to the crystalline basement at the intersection of two profiles is about 18 km. Surface geology is mostly from the Hunting Survey Corporation (1961) at a scale of 1:253,440 and Bhatti et al. (1984) at a scale of 1:25,000 for the Gumbaz area in Figure 8. Geology was field checked by the first author where possible during the field season in the fall of 1988 and winter of 1990. The plot based on surface geology leaves a space of more than 10 km thickness below the Loralai and Zhob areas. This space is hypothetically filled by duplexes of Jurassic and older rocks, analogous to those from the southern and central zones (Figure 9).

Important structural elements of the northern zone are a structural depression (Gumbaz in Figure 9), emergent passive-roof sequence in the Loralai valley along a passive-backthrust, Loralai triangle zone and the Muslimbagh ophiolites emplaced over the marginal facies (Figures 8 and 9). Triangle zone is a region between extensive faults of opposing vergence (Gordy et al., 1977). Such zones are reported from Canadian Rockies (Bally et al., 1966; Jones, 1982; and Vann et al., 1986), and the northern Potwar Plateau (Lillie et al., 1987, Baker et al., 1988; and Jaswal, 1990). In the active Sulaiman fold belt however, the triangle zone is in the hinterland. This implies that the triangle zone structures initially due to structural uplift may develop in the hinterland and subsequently with increasing shortening migrate towards the foreland.

The balanced section (A-A' in Figure 9) shows an intact passive-roof sequence about 150 km long. Such a long, continuous passive-roof sequence poses the problem of a mean to accommodate shortening strain in the roof sequence. However, structures of similar magnitude are reported in the literature from the Appalachians (Roeder et al., 1978; Berg et al., 1980; Boyer and Elliot, 1982), Papua New Guinea (Hobson, 1986); and the Brooks Range, Alaska (Wallace and Hanks, 1990). Relatively tight folds in the roof sequence (Hunting Survey Corporation, 1961; Bhatti et al., 1984) in the northern zone are interpreted as detachment folds in the passive-roof sequence. These folds accommodate a fraction of shortening in the roof sequence.

In the Loralai triangle zone of the Sulaiman fold belt, massive, shallow water Jurassic (Chiltan) limestone (Iqbal and Shah, 1980) crops out at the surface in nearly symmetrical anticlines (Figure 8). North of the Loralai triangle zone, massive Chiltan limestone is replaced by more distal, slope and rise facies (medium bedded limestone and intercalated shales) of Jurassic and Triassic age. The structure changes from a duplex geometry to simple ramp-and-flat geometry, and is dominated by detachment folding (box and kink folds; see maps of Hunting Survey Corporation, 1961). It is presumed that a fault with considerable shortening must be present in the Loralai valley (Loralai thrust in Figure 8), to emplace the more distal Jurassic facies and older rocks against the shallow water Jurassic limestone. A similar interpretation is suggested for this facies change by Kazmi (1981). This part of the balanced section is primarily the area balanced. Complex folds (Hunting Survey Corporation, 1961) above the major flat (Z1) south of the Zhob ophiolite is not shown because they are too small for the scale of the cross-section (Figure 9). The Zhob thrust sheet (Z1) is overlain by Muslimbagh ophiolites in the Zhob valley. Paleocene to early Eocene emplacement of the ophiolites (Allemann, 1979; Otsuki et al., 1989) over shelf strata records the first event of collision along the passive margin. Subsequently, much of the Khojak flysch was deposited and deformed during the Eocene to Miocene, probably as a submarine fan on oceanic crust of the closing Neo-Tethyes ocean (Lawrence and Khan, 1991).

Palinspastic Restoration

The balanced and retrodeformed cross-section (Figure 9) have 2 pinlines, P1 and P5, starting in the Sulaiman foredeep and ending at an arbitrary cutoff point at the Muslimbagh allochthon, and three intermediate reference lines, P2, P3, and P4. The northernmost point is at the edge of early emplaced ophiolites and melange, the shortening of which is not dealt with in this study. These pin and reference lines are selected to reflect variations of the seismic coverage, stratigraphy, and other uncertainties along the balanced cross-section (Figure 9A). P1, through the undeformed rocks, is in the Sulaiman foredeep. P2 is through the M1 and M2 duplex sheets at 159 km at the limit of the seismic coverage. Thus P1 to P2 is the area with good subsurface control and the most confident reconstruction. P3 is through the footwall of the Z3 duplex sheet at the northernmost limit of exposure of massive (platform) Jurassic limestone in the Loralai valley. P4 is through the footwall cutoff of Z2. Buried rocks between P3 and P4 may include the Jurassic transitional slope facies that are onlapped by the Loralai thrust (Figure 8). There is no thickness control on units in this area and constant thicknesses unlikely shelf sediments are extrapolated in the reconstruction. North of P4 shortening and structures are poorly constrained and the P4 to P5 portion is included mainly to show the possible complete section across the reconstructed Mesozoic margin. Due to the multiple uncertainties in the northern section, no effort has been made in the retrodeformed section to include a realistic continental margin geometry. The northern part of Figure 9 is intended only for shortening estimates.

It is important to point out that the base of the Jurassic limestone is picked to calculate the total shortening. This horizon is part of the duplex structure that has never been emergent or eroded except in the northern part of the Loralai triangle zone (Figure 9A). Thus, the problem of eroded section length uncertainties is negligible, as little or no erosion has occurred. Thus, the retrodeformed cross-section (Figure 9B) of this study provides a maximum estimate of shortening. This is in contrast to most shortening estimates from balanced sections which are minimal estimates due to missing sections along emergent faults (Coward and Butler, 1985).

The deformed section between the pin lines P1 to P5 (Figure A) is 349 km long. The frontal half part of the section between km marks 0 to 159, P1 to P2, is constrained by seismic reflection data (Jadoon et al., 1992; Jadoon et al., 1993) and is balanced by the line-length method except frontal concentric folds. This part restores to an undeformed length of 280 km for a shortening of 121 km. The second part of the cross-section, between kilometer marks 159 to 349, P2 to P5, is 190 km long and restores to an undeformed length of 447 km, that gives maximum shortening of 257 km. This part is primarily area balanced maintaining the stratigraphic thickness documented below Kohlu syncline by seismic data and using the documented thickness in the field for the section north of the Loralai. All together the 349 km long deformed section across the Sulaiman fold belt (Figure 9A) restores to a maximum undeformed length of 727 km (Figure 9B), which gives a maximum shortening of 378 km. Only a fraction of shortening (<1 km) is accommodated by the broad frontal folds (Sui and Loti), over a distance of about 55 km. Shortening within the passive-roof sequence is 20 km. This is accommodated by surface faults and folds. All additional shortening in the roof sequence is taken up by emergent passive-backthrusts/roof thrust in the Loralai triangle zone in this interpretation.

The 52% shortening in the central portion of the Sulaiman fold belt is similar to 50% in the Kohat Plateau south of the Main Boundary thrust (McDougall and Hussain, 1991). However, it is smaller than the about 60% shortening estimated along cross-section C-C' in Figure 2 for the western Sulaiman (Banks and Warburton, 1986). Smaller amount of shortening (52%) along cross-section A-A' compared to C-C' (60%) (Figure 2) could be explained in two ways: (1) the central Sulaiman is translated farther south onto the foreland, that is, the length of the deformed section between the pin lines is about 3.5 times greater in the central Sulaiman Range (349 km : 100 km); (2) the Sulaiman lobe along the edge of the Indian subcontinent (Figure 2) may experience variable shortening due to transpression.

STRUCTURAL STYLE AND GEOMETRY

In this study the Sulaiman fold belt is interpreted to have a passive-roof duplex style of deformation. This is consistent with interpretations from the western (Banks and Warburton, 1986) and eastern (Humayon et al., 1991) Sulaiman Ranges. However, it is contrary to simple ramp-and-flat geometry for the evolution of the Sulaiman fold belt (Bannert et al., 1989).

Duplex structures

Below the roof sequence, the deep, major structures of the thrust system are duplexes. The retrodeformed cross-section (Figure 9B) shows that the individual duplex horses are of variable length and relative displacement. This results in folds of variable symmetry, geometry, and tightness in the foreland (Jadoon et al., 1992). The main structures are described below using terminology from Dahlstrom (1970), Boyer and Elliot (1982), Butler (1982), Suppe (1983); Banks and Warburton (1986), Boyer (1986), Mitra (1986), and Groshong and Usdansky (1988).

In the southern zone, Sui and Loti are broad, concentric frontal folds (Dahlstrom, 1970) formed at the tip of the decollement, primarily by buckle folds over the ductile rocks along the detachment horizon. Liu and Dixon (1990) and Dixon and Tirrul (1991) experimentally produced such folds in front of the duplexes. These folds are forelandward of ramp and duplex structures which start with the Pirkoh anticline (Figure 9A). The Pirkoh anticline forms a significant topographic front. Much of seismic activity from the southern zone (Quittmeyer et al., 1979) is probably located along blind faults below this topographic front.

From Pirkoh to Tadri (Figures 9), the geometry of the surface folds reflects the shape of the duplex related fault-bend folds at depth. From south to north, Pirkoh, Danda, and Kurdan are interpreted as a fault-bend fold, overlap ramp anticline, and an intraplate fold, respectively. Unlike Pirkoh and Danda, which have foreland vergence, the intraplate Kurdan fold formed as a result of displacement along a passive-backthrust within the Kurdan duplex sheet (Jadoon et al., 1992).

Deep structures below the Tadri anticline and the central zone are anticlinal stacks (overlapping ramp anticlines). In each case space of about 8 km below the roof sequence is filled by two duplex horses. Note the monoclinal dip of the roof sequence in front of M2 duplex horse (Figure 9A). The foreland vergent monoclinal dip of the M2 duplex horse could lock the hinterland vergent passive propagation of the roof sequence. The secondary structures at the surface between the Tadri anticline to Kohlu syncline may then develop due to increasing strain in this region. This zone of complicated surface structures called as the Marri Bugti pop-up zone (Jadoon et al., 1993) is similar to structures shown in the roof-sequence in West Virginia of the Appalachian foreland-fold belt (Parry,1978; Mitra, 1987) and the Kohat Plateau of Himalayan foreland system in Pakistan (Ahmed and McElroy, 1991).

The northern zone has a planar-roofed duplex below the Gumbaz structural depression and hinterland verging duplexes farther north. The excess space between decollement and roof sequence below the Gumbaz structural depression does not require two duplex horses to form an anticlinal stack. Instead it can be filled by a single duplex horse (Figure 9). This suggests that the Gumbaz structural depression in the roof sequence was produced by a change in structural style from anticlinal stacks in the central zone to fault-bend folding in the northern zone. The length of the M1 duplex horse and displacement along this horse below the Gumbaz structural depression is much larger than that on the preceding duplex horses (Figure 9). This may be due to presence of relatively weak decoupling (along salt?) that resulted in greater translation and hence produced a change in structural style as that weak surface was overrun. Alternatively, relatively strong decoupling in the central and southern zone may be due to a decrease in depth of the decollement that steps up from a ductile interface into the brittle/ductile transition.

To the north, a change in structural style from plane-roofed duplexes to hinterland dipping duplexes is suggested. This change results from choices of ramp spacing, relative displacement, and final position of the D2, D3, and M1 duplexes (Figure 9). Figure 9 illustrates their relationship as the emplacement of a hanging wall ramp of the D2 duplex (Garhar Ghar in Figure 9) over the footwall flat of moderately north-dipping D3 that is itself emplaced over the footwall ramp of the M1 (next duplex). Thus, Garhar Ghar is an overlap anticline similar to Danda to the south. At Loralai valley, the passive-roof thrust emerges over a series of hinterland dipping duplexes (L1, L2, and L3) to form a triangle zone structure (Gordy et al., 1977; Price, 1981).

Passive-roof sequence

A passive-roof sequence remains stationary over a duplex sequence. It was first described by Banks and Warburton (1986) with example from the western Sulaiman and Kirthar Ranges in Pakistan. Subsequently, it was recognized from eastern (Humayon et al., 1991) and frontal (Jadoon et al., 1992) Sulaiman lobe. The duplex style of deformation with a continuous overlap roof sequences extending over several duplex horses are reported from the Brooks Range of Alaska (Vann et al., 1986; Wallace and Hanks, 1990), from the Appalachians (Geiser, 1988a and 1988b), and the Papua, New Guinea, thrust belt (Hobson, 1986). A continuous overlap roof sequence is geologically an unrealistic solution. The Sulaiman lobe is one of the clearest examples in which the apparently unbroken surface sheet extends large distance toward the hinterland. This study suggests a continuous passive-roof sequence of about 150 km in the Sulaiman fold belt of Pakistan (Figure 9A). A mechanical problem with such geometries is how an equal amount of shortening strain can be accommodated in both the roof and duplex sequences. Various models involving backthrusting (Banks and Warburton, 1986), layer parallel shortening (Geisser, 1988a and 1988b), detachment folding (Wallace and Hanks, 1990) of the roof sequence and/or passive behavior of the roof sequence attempt to resolve this problem.

Boyer and Elliot (1982) reported a kinematic model for the development of duplexes with floor and roof thrusts with motion only towards the foreland (Figure 10A). This duplex geometry provides one logical solution to explain the structurally duplicated orogenic wedges whose surface expression lacks faults with significant shortening on the ground. The model suggests large displacement, foreland-verging fault, along which roof sequence is emergent to accommodate shortening (Boyer and Elliot, 1982; Vann et al., 1986; Geiser, 1988b). Examples are the Jura and Swiss Plain, and the Mackenzie Mountains area of Canada. As proposed, this model involves no backthrust motion, however, if the roof sequence moves forward more slowly than the duplexes, a passive-backthrust component of motion can be introduced. Another model suggests a superficial decollement in the roof-sequence (Figure 10B) similar to that in the main Brooks Range thrust plate south of the Romanzof Mountains in Alaska (Vann et al., 1986). In active fold and thrust belts, this may be recognized by an anomalously thick roof sequence. This model restricts backthrust motion to the leading portion of the foreland system. Banks and Warburton (1986) proposed "passive-roof duplex geometry" with several overstep-backthrusts emerging from a passive-roof thrust (upper detachment), all with a backthrust sense of vergence. In each case the backthrust emerges from the tip of a duplex. The emplacement of the duplex uplifts and rotates the roof sequence passively without any significant forward translation. Uplift and rotation in rocks over the foreland propagating duplex horse creates steep monoclinal dips to the roof sequence rocks at the foredeep margin. As a result, the roof sequence becomes emergent along a backthrust and is removed primarily by erosion (Figure 10C). Very long preserved roof sequences are precluded by this geometry.

None of the above mentioned processes appear to operate as a main shortening mechanism for the long passive-roof sequence of the central Sulaiman Range (Figure 9). Instead of this 150 km long, intact passive-roof sequence is emergent along a major passive-roof thrust in the Loralai valley. This is the longest passive-roof sequence we have found in the literature (Hobson, 1986, shows about 120 km). No significant break in this fault has been recognized from its southern tip line to the Loralai valley which implies that backthrust motion on similar fault must be equivalent to the forethrust motion in the originally underlying duplex sequence. The minimum relative displacement on the passive-roof thrust under the roof sequence is 106 km (Jadoon, 1991b). Thus, in the early stages of structural development, a hindward emergent continuous passive-roof sequence may extend over several duplex horses (Figure 9A). North of Loralai, the roof sequence has largely been removed by erosion and is no longer a continuous sheet. How this motion is accomplished mechanically remains a significant problem and needs to be modelled.

The descriptive situation is a very long passive-roof sequence that has an emergent backthrust at its northern termination along which material has been removed by erosion (Figure 10D). This is similar to Figure 10A in that both have an intact roof sequence over a greater distance, but it is different from Figure 10A in that the emergent fault is a passive-backthrust in the hinterland of the Sulaiman fold belt instead of a foreland verging fault in the foredeep basin. Mechanically, it could pose serious problems if rugged topography is present as this would make continued relative displacement of the roof sequence difficult. However, the Sulaiman fold belt may be an exception due to gentle (<1°) topography and the presence of very thick shale (Sembar Formation) at the decollement horizon. More than 1700 m of Sembar shale have been drilled in the Giandari well from the Sulaiman foreland (Figure 2). This shale is extensively distributed along the emergent Loralai backthrust in the broad (>15 km wide) Loralai valley (Figure 8). The descriptive situation in Figure 10D could be evaluated in context of critical wedge model (Davis et al., 1983; Davis and Engelder, 1985) and Anderson's theory of faulting.

Evolution of emergent overstep-backthrusts in long roof sequences

The roof sequence in the Sulaiman lobe does show secondary hinterland and foreland verging faults and associated pop-ups. Displacement along secondary faults never exceeds more than 2-3 km. Due to minor throw, the roof sequence nowhere becomes emergent along these faults (Figure 7). An overstep backthrust is one that emerges from the passive-roof thrust (upper decollement) and does show considerable shortening (Banks and Warburton, 1986; Figure 10C). The Mari pop-up zone (Figures 6 and 7) occurs just south of the Gumbaz structural depression and can be interpreted as the early stages of development of an emergent overstep-backthrust in this area. This would be the first overstep-backthrust observable in the central Sulaiman lobe as presently configured. Seismic control (Jadoon, 1991b; Jadoon et al., 1993) demonstrates that only the Jandran fault cuts into the duplex sequence, and even it has only small displacement. The area is seismically active, probably at least in part on the Jandran fault. This structure is probably developing in response to the tight Tadri syncline in the passive-roof sequence which apparently locks the passive-backthrust. Secondary thrusting, the pop-ups, probably occurs when increasing strain exceeds the strength of the rocks in the locked roof sequence. We suggest that these secondary faults represent the early stages of development of an overstep-backthrust that may eventually have substantial out-of-sequence displacement. Out-of-sequence structures are commonly interpreted occurring in through the entire duplex wedge (Jaswal, 1990) in order to increase taper and thus driving force. The Mari pop-up structures, as interpreted here, offer an alternative source of out-of-sequence activity in the interior of a thrust system.

Timing and Rate of Deformation

Deformation of the northwestern margin of the Indian subcontinent, the future Sulaiman area, started by the Paleocene to early Eocene emplacement of the Muslimbagh ophiolites (Allemann, 1979; Otsuki et al., 1989; Jadoon, 1992). This event is constrained by the emplacement of ophiolites over Maastrichtian shelf sediments and onlap of Eocene platform rocks (Allemann, 1979; Otsuki et al., 1989). Emplacement of the Muslimbagh ophiolites was followed by deposition of the Khojak flysch on remaining oceanic lithosphere between the Eocene and late Oligocene with the early Himalayan uplift as the most likely sediment source (Lawrence and Khan, 1991). Continued shortening in the late Oligocene to early Miocene (25±5 Ma?) resulted in the final closure of the ocean, the initiation of the left-lateral strike-slip Chaman fault system, and deformation of the Khojak flysch (Khan et al., 1991). Shortening in the cover sediments of the Indian subcontinent south of the Muslimbagh ophiolites allochthon probably became significant during the Miocene (20±5 Ma?) with the beginning of deposition of the continental molasse deposits. Since then, about 378 km of shortening has occurred in the cover strata of the Indian subcontinent (Figure 9). Ongoing, prograde deformation consistently reworked the molasse strata so that the center of deposition migrated to the south and east. Presently, active deformation is suggested by recent unconformities from the southern Sulaiman Range (Tainsh et al., 1959) and local seismicity. Age dating by magnetostratigraphy (Ahmad and Khan, 1990) shows that continental Siwaliks, deposited between 0.7 Ma to 50,000 yr, are overlain by alluvial fan deposits. The later are tilted along the eastern Sulaiman front. Shortening estimates in the cover sediments of the Sulaiman fold belt of about 378 km over 21 Ma suggest a shortening rate of about ~18 mm/yr. This number compares with shortening estimates of 9-14 mm/yr in the Salt Range/Potwar Plateau regions (Leathers, 1987; Baker et al., 1988), and 10-15 mm/yr in the sub-Himalaya in India (Lyon-Caen and Molnar, 1985). Further magnetostratigraphic studies in this area should be very productive in providing more refined control on the deformation chronology.

The amount of shortening in the Sulaiman fold belt represents about 50% of the average plate convergence rate of about 37 mm/yr between the Indian subcontinent and the Afghan block almost parallel to the Sulaiman vector determined above (Minster et al., 1974; Minster and Jordan, 1978; Jacob and Quittmeyer, 1979). Continental basement is not found to be involved in the deformation in the Sulaiman fold belt (Jadoon, 1992). Therefore ductile deformation in metamorphosing basement in the hinterland of the orogen is not yet contributing to shortening. Additional shortening may be accommodated by the left-lateral strike-slip Chaman fault system. Khan et al. (1991) suggest 450±10 km of left-lateral strike-slip displacement along the Chaman fault over about 25 Ma, for a rate of about 18 mm/yr. If the Chaman vector is resolved into the component parallel to the plate motion vector it is about 15 mm/yr. Thus the sum of the Sulaiman (~18 mm/yr) and Chaman (15 mm/yr) displacement rates of 33 mm/yr is closely comparable to the plate rate of 37 mm/yr since Miocene.

Present estimates of shortening related to the western Himalayas in northern Pakistan are 475-500 km (Coward and Butlėr, 1985), and 570 km (Izatt, 1990). Malinconico (1989) approached the problem of the shortening with estimates of crustal volume and suggested crustal shortening between 570 and 1,140 km. All of these are still less than the 2,000 km of shortening since Eocene time calculated for the central Himalaya/Tibitean Plateau region largely from paleomagnetic data (Molnar, 1984; Patriat and Achache, 1984; Klootwijk et al., 1985). The Himalayan collision zone appear to show a part of the total shortening. The additional shortening may be taken up by extrusion tectonics along strike-slip faults and lose of section by partial melting at the leading edge of the Indian subcontinent (Molnar and Tapponier, 1975; Lyon-Caen and Molnar, 1985; Hefu, 1986; Armijo et al., 1989).

Hydrocarbon Prospects

The Sulaiman fold-and-thrust belt with over 60,000 km^2 of the exposed Paleogene to Triassic platform strata is generally considered as a gas prone area. The 7 km thick Paleogene to Paleozoic strata has potential horizons for the generation and accumulation of hydrocarbons (Raza et al., 1989a). Raza et al. (1989a) based on detailed geochemical investigations evaluated Mesozoic/Cenozoic strata for hydrocarbons prospect. They suggest that sizeable amount of oil may be present in the Sulaiman fold belt. This could be supported by the occurrence of gas condensate (Dhodak well) and the oil seepages from various places e.g. Khattan, Samach, Spintangi from the western Sulaiman and Ragha Sar, Mughal Kot, and Burzam (Drazinda area) from the Sulaiman Range (Raza et al., 1989a and b).

The Sulaiman fold-and-thrust belt was scarcely investigated. Detailed structural investigations are vital for a successful exploration, evaluation, and exploitation of the hydrocarbons. Recent structural studies has conflicting ideas about the structural evolution of the Sulaiman thrust system. One model suggests nappe structures (Bannert et al., 1989) whereas the other model suggests a passive-roof duplex geometry (Banks and Warburton, 1986; Humayon et al., 1991; Jadoon, 1991a; Jadoon et al., 1992). The nappe structure model could consider that the lower plate may be drilled for the presently producing Cretaceous and younger horizons. The duplex model rejects the presence of Cretaceous to Eocene targets in the lower plate. The balanced section (Figure 9) shows favourable structures consisting of Jurassic and older rocks in the internal part of the thrust system. Khan and Raza (1986) based on geothermal gradient of 2.4°/100 m in the Jandran well suggest an oil window at depth from 2,300 to 4,400 m. Similarly, oil window in the Tadri well is at depth of 2,100 to 4,000 m. In both the cases an oil window is suggested below the penetrated depth of the wells in the Jurassic and older horizon. These observations for prospects in the Jurassic are favoured by the organic geochemistry (Raza et al., 1989a). The duplex model requires attention for generating hydrocarbon prospects in the duplex sequence (Jurassic limestone) in areas of small surface structures (Figures 4 and 5).

CONCLUSIONS

Surface and subsurface data have been integrated to evaluate the structural form of the active Sulaiman lobe, the underlying crustal variation, and the total shortening in the cover sediments of the Indian subcontinent and across the Indian/Afghan collision zone. The important conclusions are summarized below.

(1) The style of deformation in the Sulaiman fold belt is a passive-roof duplex geometry with a floor thrust at the base of the wedge and a passive-roof thrust in Cretaceous shales. Two broad (half wavelength about 20 km) folds (Sui and Loti) are located at the southern tip of the decollement zone.

(2) A continuous passive-roof sequence is intact for about 150 km northwards from the tip of the first duplex. Eventually it becomes emergent along a passive-backthrust in the Loralai valley, where majority of the excess section has been removed by erosion. Surface structures in the southern Sulaiman lobe are fault related folds. In the central Sulaiman lobe, out-of-sequence structures (secondary foreland and hinterland verging reverse faults with minor throw of <2 km and associated pop-ups) are recognized. They may represent an early stage of evolution of an overstep-backthrust emerging from the upper detachment (passive-roof thrust). A structural depression and a triangle zone are the dominant structures of the northern Sulaiman lobe. North of the Loralai triangle zone, the duplex style of deformation is replaced by ramp-and-flat geometry. On the Loralai thrust, Jurassic shallow water limestones are overridden by deeper-water, more distal facies. This facies change probably marks the old shelf edge.

(3) Structures in the duplex rocks, starting from the foreland to the hinterland (Figure 9) are a fault-bend fold (Pirkoh), overlapping ramp anticline (Danda), intraplate fold (Kurdan), anticlinal stacks (Tadri anticline and Mari pop-up zone), plane-roofed (Gumbaz structural

depression), and hinterland dipping duplexes. Farther north the duplex structure is poorly constrained, but is adequately modelled by a simple flat-and-ramp geometry.

(4) General chronology of thrusting is as follows: (a) concentric buckle folding at the tip of the decollement; (b) the development of a passive-roof duplex; (c) foreland propagation of the duplex; (d) normal flexural faults at the frontal folds in the roof sequence and tear faults at the margins; and (e) out-of-sequence (secondary) thrusting. Existence of secondary structures may explain the active shallow seismicity at the front and in the central parts of the Sulaiman fold belts.

(5) The 349 km long balanced structural cross-section from the foreland northwards across the collision zone restores to 727 km. This gives 378 km of shortening related to Himalayan collision at the western terminus of the Indian subcontinent.

(6) The sum of the Sulaiman (18mm/yr) and the Chaman (15mm/yr) displacement rate of 33 mm/yr is closely compareable to the plate rate of 37 mm/yr since Miocene.

(7) The duplex model suggests that the producing Cretaceous and Eocene horizons in the foreland may not be drilling targets, in the lower plate, in the internal parts of the Sulaiman fold-and-thrust belt. However, relatively simple structures in the uplifted Cretaceous and younger strata (roof sequence) may be recognized for their petroleum prospects. The duplex model suggests to consider Jurassic and older rocks (duplex) for hydrocarbon potentials in the internal parts of the Sulaiman thrust system.

ACKNOWLEDGEMENT

This work in the Sulaiman fold belt is part of a cooperative project between Oregon State University (OSU) and the Hydrocarbon Development Institute of Pakistan (HDIP). Additional data were provided by Amoco, Texaco Overseas, and by Shahid Hassan Khan from the Geological Survey of Pakistan (GSP). Ishtiaq Jadoon at Oregon State University was supported by a scholarship from the United States Agency for International Development (USAID) to the Government of Pakistan. NSF grants INT-86-09914 and EAR-8816962 are acknowledged for partial support.

We gratfully acknowledge to Bob Yeats, Alan Niem, and Jon Kimerling for critical review of the preliminary manuscripts. Special thanks are due to Hilal A. Raza, Riaz Ahmed, Manshoor Ali, Jalil Ahmad, and Amjad Cheema from HDIP and Mohamad Ilyas (Assistant Commissioner, Kohlu) and many others for their cooperation, time and sincere effort in assembling the data and logistic problems. Many discussions with Mirza S. Baig and Vera Langer throughout the completion of this project are gratefuly acknowledged.

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