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Three Dimensional Geometry of Passive-roof Duplex, Quaternary Transpression, and Hydrocarbon Traps in the Sulaiman Foreland, Pakistan

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ABSTRACT

LANDSAT & SPOT scenes combined with geological and geophysical data have been used to examine the structural style, timing of foreland deformation, and hydrocarbon trap forming geometries in the foreland of the Sulaiman fold belt of Pakistan. Seismic reflection interpretation suggests a 10 km depth for the top of the crystalline basement at the deformation front in the eastern and southern, and about 14 km in the western (Sibi trough) Sulaiman fold belt. Nearly all of the sedimentary strata, detached from the basement with floor thrust in Paleozoic strata, is uplifted several kilometers higher than its regional stratigraphic level without an exposed thrust in the foreland. Surface expression of the deformation front is of a monocline whose steeper limb dips toward the foredeep. Overall structural style is interpreted as of a passive-roof duplex with a roofthrust in Cretaceous shale (except frontal part of western Sulaiman where it is in Eocene shale). The duplexes are exposed only in the western Sulaiman fold belt due to thickening of duplex package, and friction related to drag at the lateral termination of the fold belt.

The passive-roof sequence extends over several duplexes in the foreland and shows out-of-sequence faults in the more internal parts of the Sulaiman fold belt. According to seismic reflection data, these are reverse faults with minor vertical offsets of about 1-3.5 km and are mostly restricted to the roof sequence. Some faults show dominant strike-slip displacement (about 4-5 km). Along these faults passive-roof duplex geometry is being evolved to form backthrusts and modified by strike-slip displacement in the central Sulaiman fold belt. Persistent dominant dextral displacement along strike-slip faults suggests anticlockwise rotation of discrete blocks in the Sulaiman fold belt due to its proximity to the western sinistral boundary of the Indian plate. Active nature of faults, based on seismicity and cross-section balancing, suggests onset of Quaternary transpression in the Sulaiman fold belt.Sequential evolution of structures can be interpreted as: 1) low amplitude, long- wavelength detachment folds at the tip of the decollement; 2) passive-roof duplex geometry; 3) out-of sequence faulting; and 4) onset of Quaternary transpression.

Several structural geometries form important hydrocarbon traps. Some examples include the system of fault tip-line detachment folds (Sui and Loti/Zin gas fields), fault- propagation folds (Uch gas field), fault-bend folds (Pirkoh gas field), several duplex geometries (unexplored), and secondary traps in the footwall.

INTRODUCTION

Many structural cross-sections from the frontal part of the mountain belts show a problem of uplifted stratigraphy in the absence of an exposed thrust. In a thin-skinned deformation such a problem is resolved by duplication of strata within the ground. This duplication occurs along layer parallel faults called floor and roof thrust (Dahlstrom, 1970) and multiple ramp faults between them (Boyer and Elliot, 1982; Mitra, 1986). Similar style of deformation is observed in the Sulaiman fold belt of Pakistan.

The Sulaiman fold belt represents active evolution of collision structures related to the Himalayan orogeny that extends from Burma through northern India and Nepal into Pakistan (Figure 1). It is interpreted to have a passive-roof duplex style of deformation (Banks and Warburton, 1986). The roof sequence in a passive-roof duplex is proposed to remain stationary over the foreland propagating duplex. Comparable shortening in the roof sequence is ideally accommodated by erosion at the tip of passive-backthrusts. Some examples of such a structural geometry are the southern Taiwan Thrust Belt (Suppe, 1980), eastern Rocky Mountain Foothills (Price, 1981; Jones 1982), Mackenzie Mountains, Canada (Vann et al., 1986), and north Potwar Deformed Zone, Pakistan (Jaswal, 1990; Kemal, 1991).

Three structural cross-sections from the eastern, southern, and western Sulaiman fold belt provide details

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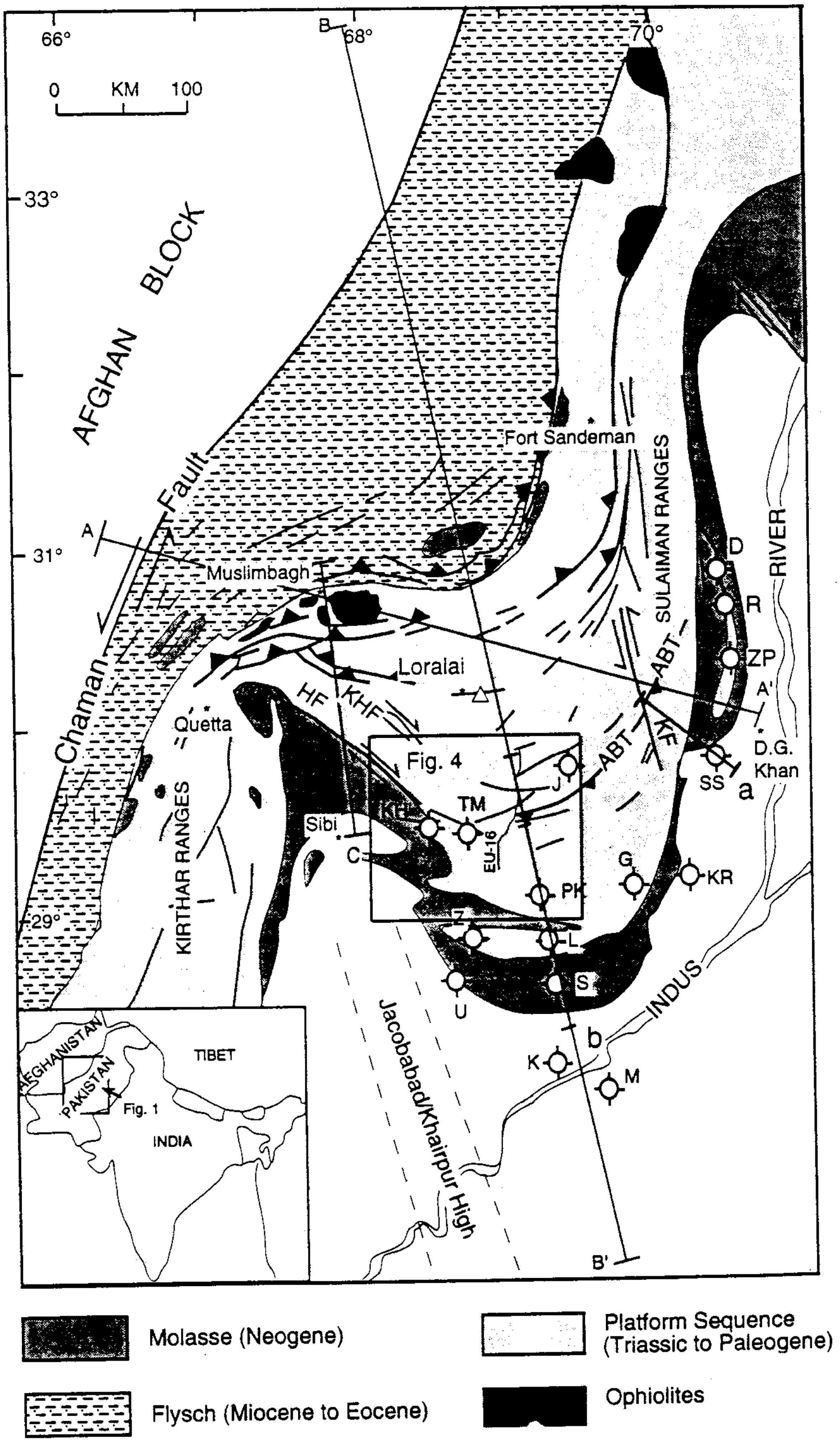


Figure 1- Simplified tectonic map of the Sulaiman fold belt at the western boundary of the Indian subcontinent. Lines A-A' and B-B' show the location of Bouguer gravity profiles modeled by Khurshid et al. (1992) and Jadoon (1992). Lines a, b, and c show the location of the cross-sections in Figure 2. Thick crooked northsouth line shows the location of a seismic line interpreted by Jadoon et al (1994a) and discussed in text. Open triangle shows the location of an alkaline intrusion (Jadoon and Baig, 1991). Box shows the location of Figure 4. Abbreviations: ABT, Andari Backthrust; HF, Harnai Fault; KF, Kingri Fault; KHF, Khakifat Fault. Well abbreviations: D, Dhodak; G, Giandari; J, Jandran; K, Kandkot; KH, Khattan; KR, Kot-Rum; L, Loti; M, Mari; Pk, Pirkoh; R, Rhodo; S, Sui; SS, Sakhi Sarwar; TM, Tadri Main; U, Uch; Z, Zin; ZP, Zindapir.

of passive-roof duplex in an active setting (Figure 2). The structural cross-sections from eastern (Humayon et al., 1991) and southern (Jadoon et al., 1994a) Sulaiman foreland are topped by an intact roof sequence. However, the duplex structures are exposed in the western Sulaiman with roof-sequence preserved only in the synclinal areas (Banks and Warburton, 1986). The roof thrust located in the Cretaceous shales changes its position to Eocene shales over frontal few duplexes from western Sulaiman fold belt (Banks and Warburton, 1986).

Foreland part of the central Sulaiman does not exhibit exposed faults (Kazmi and Rana, 1982). However, a system of active faults is exposed in the more internal parts of the Sulaiman fold belt (Kazmi,1979; Kazmi and Rana, 1982). These exposed faults with minor displacement (~2 km) in the seismic reflection data were interpreted as reverse faults, mostly rooted in the roof sequence (Jadoon et al., 1994a). Jadoon et al. (1994a) observed that long map length of these faults with minor dip displacement is inconsistent with fault-propagation theory that suggests a minimum ratio of 1/14 between displacement and map length of thrust faults (Elliot, 1976). The aim of this paper is to: (1) provide an insight into three-dimensional geometry of the passive-roof duplex; (2) explore kinematics of exposed faults; (3) propose a model for structural evolution; (4) define hydrocarbon traps.

TECTONIC SETTING

The Himalayan mountain belt evolved as a result of Cenozoic collision between Indian and Eurasian subcontinents. Its trend changes from northwest-southeast in India to northeast-southwest in north Pakistan. Further west, about 900 km long, sinistral Chaman fault makes the boundary between the Indian subcontinent and the Afghan Block (Abdul-Gawad, 1971; Lawrence et al., 1981; Khan et al., 1991; Bannert et al., 1992). The Sulaiman/Kirthar Ranges, east of the Chaman fault trend northsouth; while the Sulaiman fold belt is located between the two manifests itself as the broadest lobate feature in the entire Himalayan collision zone (Figure 1). This structural variation is attributed to the tectonic transpression along the western boundary of the Indian subcontinent (Sarwar and DeJong, 1979; Klootwijk et al., 1981, 1985; Lawrence et al., 1981).

The broad (300 km) lobate geometry and arcuate seismicity in the foreland of the Sulaiman fold belt is interpreted to be a result of rapid southward translation along a weak decollement of the tear fault bounded thrust sheets (Quittmeyer et al., 1979, 1984; Sarwar and DeJong, 1979; Klootwijk et al., 1981, 1985). The left-lateral Kingri (Rowland, 1978; Bannert et al., 1992) and right-lateral Harnai/Khalifat faults (Kazmi, 1979) may form exposed lateral ramps to the east and west respectively (Figure 1). Sedimentation and paleomagnetism in the Sulaiman foredeep suggest constant migration of deformation front towards east and south (Tainsh et al., 1959; Waheed and Wells, 1990; Ahmad and Khan, 1990; Khan and Ahmad, 1991). This is similar to the foreland translation of the Jura Mountains of Europe (Laubscher, 1981), the Pine Mountain thrust block of the central Appalachians (Rich, 1934; Harris and Milici, 1977), and the Salt Range/Potwar Plateau thrust block of north Pakistan (Lillie et al., 1987).

A thin-skinned style of deformation for the evolution of the Sulaiman fold belt is compatible with the Bouguer gravity modelling across the Sulaiman fold belt (Jadoon, 1992; Khurshid et al., 1992). The Bouguer gravity modelling suggests a thinner (about 20 km) than normal continental crust under the Sulaiman lobe and a thicker (about 57 km) crust under the Afghan Block. Overall crustal model suggests deformation partitioning with a decollement at depth of about 15 km. The model considers Afghan Block as a rigid oblique indentor (bulldozer). The Chaman fault and the Sulaiman/Kirthar Ranges are considered to accommodate transpressive deformation above the decollement, whereas distal end of the Indian subcontinent below the Afghan block may account for some of the 57 km of tectonic thickening west of the Chaman fault (Jadoon, 1992). Such a similar model of continental escape tectonics is proposed by Izatt (1990), Treloar and Coward (1991), and Treloar and Izatt (1993). More recently, Davis and Lillie (1994) attribute the broad width (300 km) and gentle topography (<1°) of the Sulaiman fold belt to the mechanical response of foreland thrusting along a weak decollement, possibly along brittle/ductile transition. The gravity and magnetic modelling from the western Sulaiman (to test the thin-skinned or thick- skinned deformation) support thin-skinned model (J. McCanns, pers. comm. 1994) over a theoretical thick-skinned model (Coward, 1994). This paper provides details critical to understand structures, neotectonics, and hydrocarbon prospects of the Sulaiman fold belt.

GENERAL OBSERVATIONS AND GEOMETRY OF FORELAND STRUCTURES

Surface and Subsurface Observations

Surface expression of foreland._ The surface expression of the Sulaiman foreland is dominated by the folds (Figures 2a-b) in about 10 km thick stratigraphic

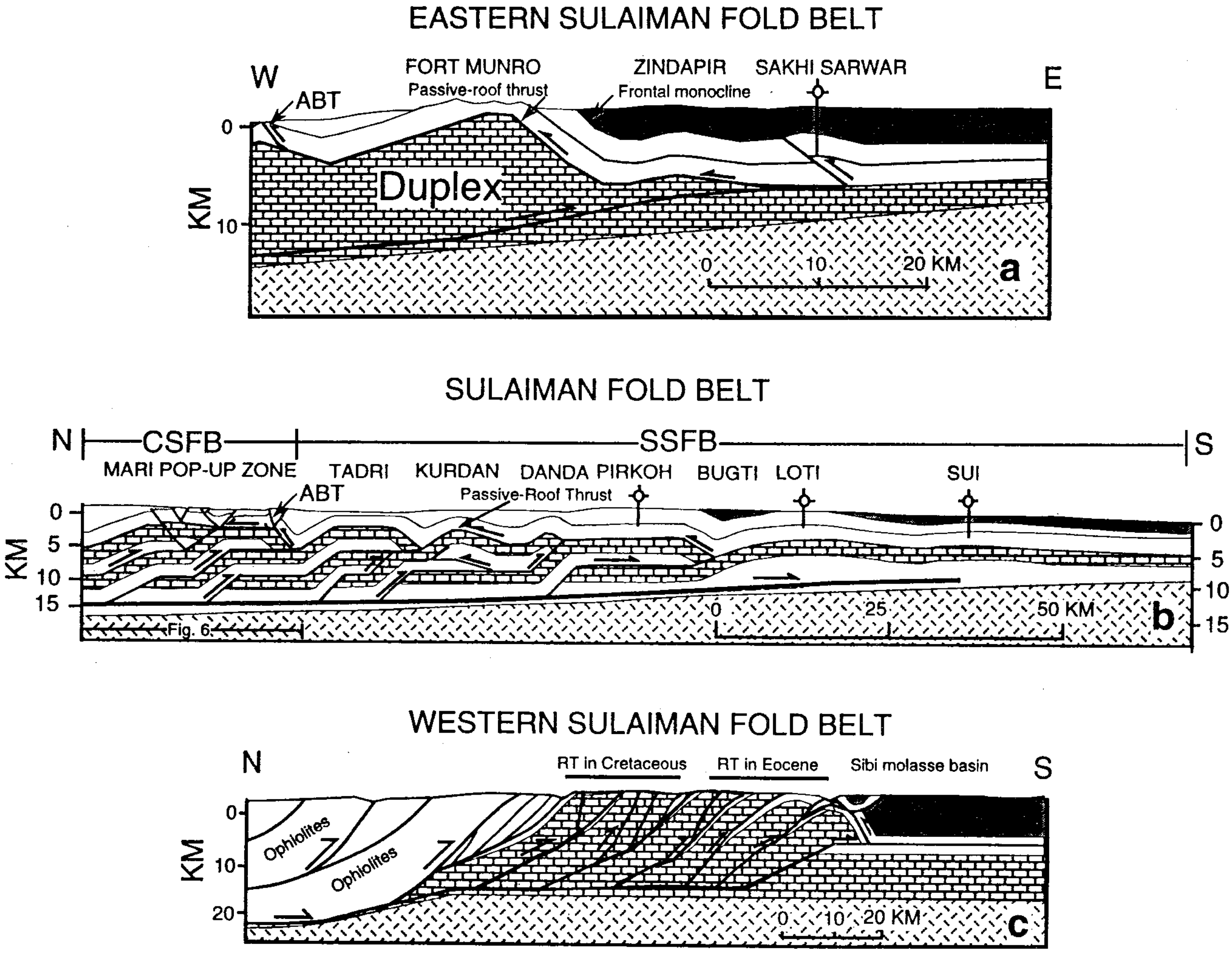


Figure 2- Lines a, b, c are from the eastern, southern, and western Sulaiman fold belt respectively. (a) The passive-roof duplex (triangle zone) geometry from the eastern Sulaiman fold belt (modified from Humayon et al., 1991) shows a passive backthrust and intact roof sequence above a stack of duplex. Notice the culmination wall of a foreland dipping monocline. (b) The passive-roof duplex (low-angle triangle zone) geometry from the southern Sulaiman fold belt (modified from Jadoon et al., 1994b) shows sequential evolution of foreland structures from the development of broad concentric low amplitude fault-tip line buckle folds, to duplex, and out-of-sequence deformation (c) The passive-roof duplex geometry from the western Sulaiman fold belt (modified from Banks and Warburton, 1986) shows frontal monocline and hinterland dipping duplexes. In this line duplexes are exposed and roof sequence is preserved only in the synclinal parts of the adjacent duplexes. In line a and b roof thrust is in Cretaceous while in c the roof thrust is in Eocene strata above the frontal few duplexes.

section of dominantly platform strata at the deformation front (Figure 3). These folds have an arcuate trend. The southernmost doubly plunging folds are broad (half wavelength 15 to 30 km) with long map traces (30 to 100 km). Two gentle (4^0 to 14^0 dips) low amplitude, and broad (half-wavelength of 25 km), doubly plunging anticlines (Sui and Loti) are exposed at the deformation front in the southern Sulaiman fold belt. Surface expression of the southerly limb of the third folded structure (Pirkoh) is of a foreland dipping monocline with dips between 30^0 to 70^0 . This is more precisely a box fold, with about 16 km of almost flat hinge zone. Such a similar surface expression is characteristic feature of many folds in the Sulaiman foreland (for example Gandar in Figure 4). These folds reflect a coherent stratigraphy with older strata progressively uplifted and exposed in the cores of more northerly, tighter anticlines (molasse in Sui, Eocene in Loti/Zin and Pirkoh, Paleocene in Kurdan, and Cretaceous in Tadri anticline; Figure 2b). This coherent stratigraphy is first disrupted by the emergent faults 100 km north of the deformation front in the southern Sulaiman fold belt.

Subsurface expression of foreland._ Subsurface expression of the fold belt is constrained by variable degree of seismic reflection and borehole data from the foreland and internal part of the Sulaiman fold belt. The seismic reflection interpretation suggests a northwestward dipping (about 3^o) planer basement in the foredeep (Humayon et al., 1991; Jadoon et al., 1993). Basement is drilled in wells at depth of about 2.5 km nearly 200 km east of the deformation front. However, stratigraphic thickness increases to about 10 km over the basement at the deformation front in the southern and eastern Sulaiman fold belt (Figure 3). The Stratigraphic sections from eastern and southern Sulaiman include about 3 km of synorogenic molasse sediments compared to about 7 km of similar strata from the Sibi trough in the western Sulaiman fold belt (Banks and Warburton, 1986; Ahmed et al., 1992). Humayon et al. (1991) infer a depth of about 14 km for the projected top of the crystalline basement below Kingri Fault (Figure 2a). Jadoon et al. (1994a) infer a depth of about 15 km for the projected top of the crystalline basement below Kohlu syncline (Figure 2b). Decollement and basement depth is deeper than 5 s of two-way travel time data (EU-16 in Figure 4) under the Kohlu syncline. The stratigraphic column shows the favourable location of detachment horizons in Paleozoic, Cretaceous, and Eocene strata (Figure 3). Generally, monoclinal dips of the exposed strata is a uniform surface expression of the Sulaiman foreland.

Style of Deformation

Eastern Sulaiman fold belt._*The structural cross-section from the eastern Sulaiman fold belt, constrained by seismic reflection data in the foredeep (Humayon et al., 1991), shows a basal decollement in Paleozoic strata and a structural relief of about 8 km of the base Cretaceous below the Fort-Munro anticline (Figure 2a). The monoclinal dips of the eastern limb of the anticline and coherent uplifted Cretaceous strata are recognized to form oblique culmination wall above a duplex stack. The hinterland dipping duplexes of Jurassic and older strata are separated by a passive-roof thrust from the overlying Cretaceous and younger strata. The exposed Cretaceous strata completely overlaps the duplexes, along nearly 25 km half wavelength across strike of the Fort-Munro anticline. The west limb of the anticline remarkably displays a gentle dip (<20^0*) of layered stratigraphy for about 20 km. An incipient backthrust (ABT) is located about 50 km west of the deformation front. The Zindapir and Sakhi Sarwar are interpreted as active blind fault tip-line folds. Some examples of similar structures, described by Jones (1982) are Turner Valley, Rice Creek, and Grease Creek from the Alberta foothills; northern Brooks Range, Alaska; molasse basin in Switzerland; and Carpathian foothills, Romania.

Sedimentologic (Waheed and Wells, 1990; Khan and Ahmad, 1991) and magnetostratigraphic (Ahmad and Khan, 1990) studies provide insight into the progressive evolution of the eastern Sulaiman foreland. Paleocurrents indicate a westward dispersion of preorogenic Cretaceous sandstone, consistent with a northwestward dipping passive margin of the Indian subcontinent (Humayon et al., 1991). A change in the dispersion pattern of sediments, is recorded from west (Cretaceous) to southeast during Paleocene/Eocene times, indicating slope reversal of the Cretaceous shelf. Paleocurrent data from synorogenic lower molasse strata shows that rivers during the deposition of sediments, paralleled the modern Sulaiman Range in the north and flowed obliquely into it in the south (Waheed and Wells, 1990). This suggests active deformation and constant migration of deformation front towards south and east as a result of foreland thrusting, similar to the Himalayan foreland in north Pakistan (Johnson et al., 1986).

Paleomagnetic studies (Ahmad and Khan, 1990) show that upper molasse (Litra and Chaudhwan) strata were deposited between 1.5 M.a. to 50,000 yr B.P., at the site of modern deformation front (Zindapir and Sakhi Sarwar in Figure 2a) in the eastern Sulaiman fold belt. The alluvial fan deposits, overlying molasse strata, are tilted due to crestal uplift of the Zindapir and Sakhi Sarwar anticlines. Besides, petromict conglomerate of

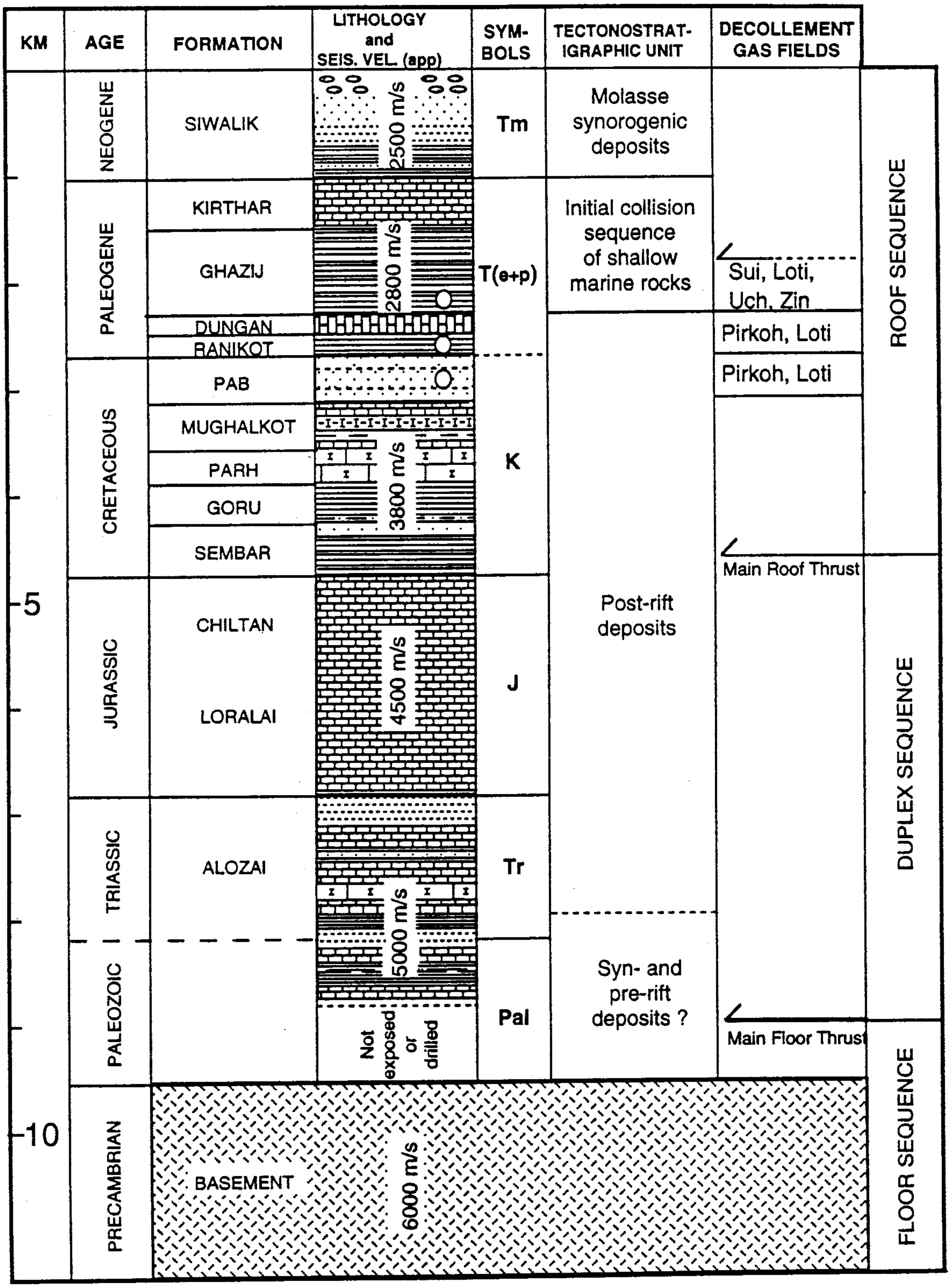


Figure 3- Simplified stratigraphic column of Sulaiman fold belt (modified from Jadoon et al., 1992). Notice tectonostratigraphic position of major floor and roof thrust and stratigraphic position of producing gas fields (open circles).

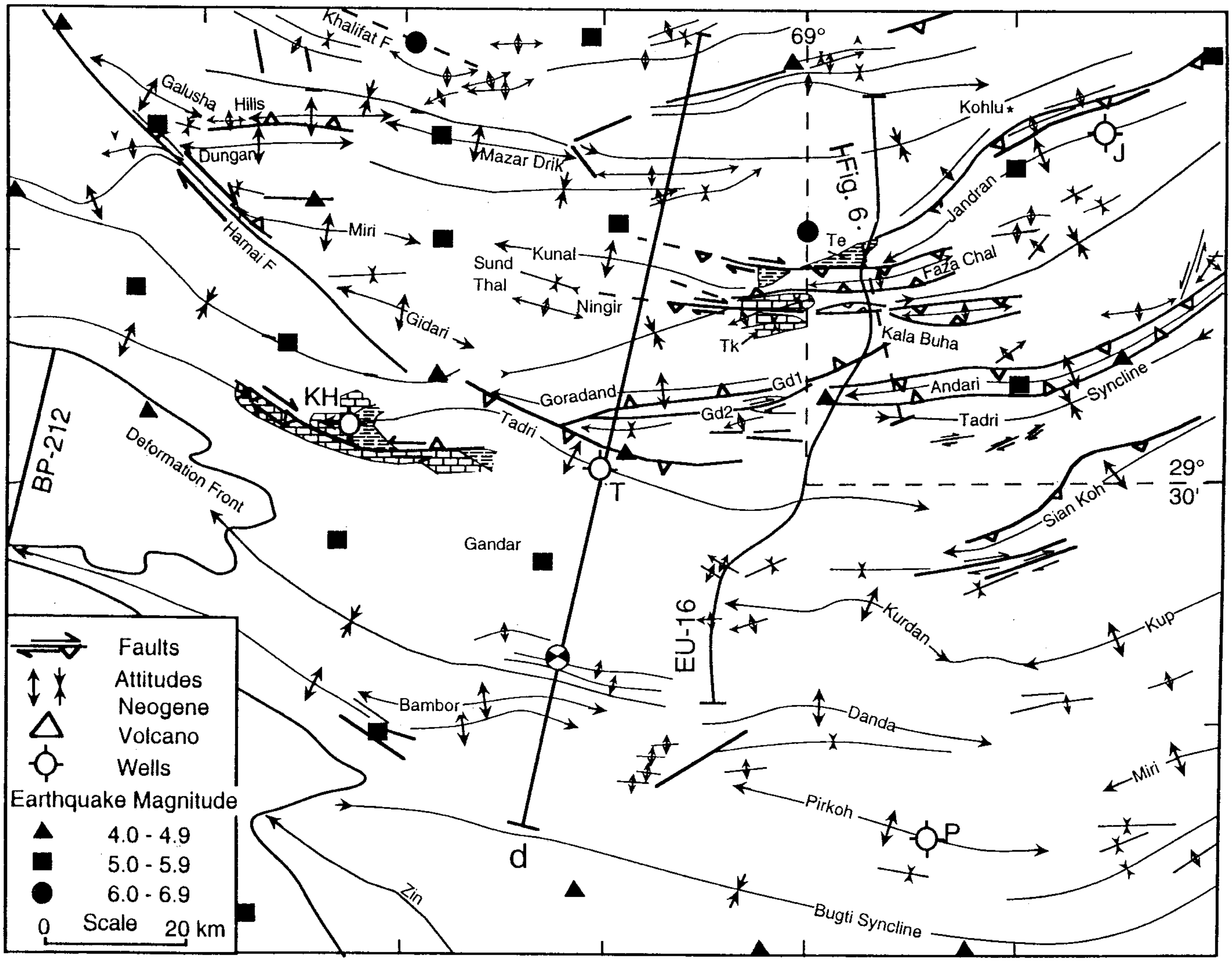


Figure 4- Generalized geological map of the west central Sulaiman (See Figure 1 for location of the map). Mapping is compiled interpreting LANDSAT and SPOT scenes (1:50,000) supplied by Tullow Oil modifying the geological map based on air photo interpretation by Jones (1961) on a scale of 1:2,53,400; published (3 sheets, 1:50,000) and unpublished (1: 2,50,000) maps of the Geological Survey of Pakistan. See location of seismic reflection profiles (EU-16 and BP-212). EU-16 provides critical control for the structural interpretation, and depth penetration of some exposed faults (Jadoon et al., 1994a). Line d is shown in Figure 7.

Chaudwan Formation (deposited between 0.7 M.a. to 50,000 yr B.P.; Ahmad and Khan, 1990) shows a source from westerly Fort-Munro anticline. This suggests incipient evolution (50,000 yr. B.P.) and acute uplift of fault tip-line structures in the eastern Sulaiman fold belt.

The Bouguer gravity anomaly of about -116 mgals above D.G. Khan (eastern foredeep) to about -70 mgals close to the Kingri fault in the eastern Sulaiman fold belt are modeled, in part to evaluate above interpretation (Khurshid et al., 1992). The results support thin-skinned duplex style of deformation and show a transitional crust (20-30 km) preserved below the Sulaiman fold belt. This is consistent with the presence of enormously thick (7 km) platform strata at the deformation front (Humayon et al., 1991). Presence of transitional crust, unlike north Pakistan where a full thickness crust is modeled south of the collision zone (Duroy et al., 1989), suggests an early stage of evolution of the Sulaiman fold belt.

Southern Sulaiman fold belt._The structural cross-section from southern Sulaiman fold belt, constrained by seismic reflection data (Jadoon et al., 1992) shows a decollement in the Paleozoic strata and a passive- backthrust in Cretaceous shales (Figure 2b). The location of the roof and floor thrust is similar to that in the eastern Sulaiman fold belt. However, structural variation from a prominent culmination wall over a duplex stack behind an incipient fault- bend (Zindapir) and a fault-propagation (Sakhi Sarwar) fold in the eastern Sulaiman to a relatively less prominent culmination wall behind two low amplitude, broad (about 25 km half wavelength) concentric detachment folds (Loti and Sui) is observed in the southern Sulaiman fold belt. This structural variation may be related to considerable friction in the eastern Sulaiman fold belt during foreland thrusting of an oblique duplex (Davis and Lillie, 1994). The entire section underlain by duplexes in the southern Sulaiman is topped by a hindward-vergent passive-roof sequence. At and south of Tadri (about 60 km from the tip of the first duplex in the southern Sulaiman) and Kingri fault (about 50 km from the tip of the first duplex in the eastern Sulaiman), passive-backthrusts do not cut the section above Cretaceous strata, and fault-related folds predominate in the foreland (Figure 2). The Bouguer gravity modelling along this section supports a thinner (about 25 km in the foreland) than normal continental crust similar to the observations from eastern Sulaiman fold belt (Jadoon, 1992).

Western Sulaiman fold belt._The duplex style of deformation from the western Sulaiman fold belt is in agreement with former sections (Figure 2c). The cross-section shows hinterland dipping duplexes. The hinterland dipping duplexes with close spacing of the adjacent ramps and relatively tight folds may be related to the friction due to drag along western termination of the fold belt. Duplexes are primarily exposed due to increasing uplift and erosion in the western Sulaiman fold belt. The roof thrust is located in the Eocene strata over frontal few duplexes, unlike, southern and eastern Sulaiman where it is located in Cretaceous strata. Active deformation is manifested by variable degree of tilt (gentle to overturned) in the Quaternary Dada conglomerate from the western Sulaiman and northern Kirthar Ranges.

7 s of two way travel time data (line BP-212 in Figure 4) shows only layercake stratigraphy with about 7 km of synorogenic molasse strata from the foredeep basin (Sibi trough). Compressive deformation in the molasse strata is accommodated by fault-related folds (Banks and Warburton, 1986). Ahmed et al. (1992) interpret similar structures due to basement involvement. Gravity and magnetic modelling of a part of the western Sulaiman fold belt and Sibi trough, however, supports thin-skinned style of deformation (J. McCann, Pers. Comm. 1994). Considering Mesozoic rift-related structures in the Sulaiman foredeep (Raza et al., 1989b; Kemal et al., 1991), role of basement in influencing thin-skinned deformation is not precluded.

CENTRAL SULAIMAN FOLD BELT

The roof sequence is breached by faults in the more internal parts (Mari-Bugti Hills) called as central Sulaiman fold belt (Figures 1, 4). These faults show variable degrees of map length (Jones, 1961; Kazmi and Rana, 1982). Some faults are shown to have long map traces (Bannert and Raza, 1992; Bannert et al., 1992). Further north, faults have an imbricate geometry. The imbricate set of faults converge laterally and are pinned northeast of Quetta towards west and near Fort Sandeman towards east (Figure 1). The arcuate geometry and lateral pinning of the faults is typical of thrust systems (Elliot, 1976).

More recently, exposed faults in the central Sulaiman fold belt are recognized as paired foreland and hinterland vergent faults (Jadoon et al., 1994a). Along these closely spaced faults, mostly Cretaceous strata in the core of tight, symmetrical anticlines are juxtaposed with Eocene Ghazij and Kirthar Formations (Figure 5). According to interpretation of a seismic reflection line EU-16 (Figure 4), these are reverse faults of minor throw (1-2 km) mostly rooted in the roof sequence (Figures 2, 6). As a result Cretaceous strata bounded between apparent reverse faults are exposed at the surface in the cores of tight anticlines as pop-up structures. Many of these faults may be active (Kazmi, 1979). This conclusion is also based on active seismicity (Quittmeyer et al., 1979; Verma and Chandra, 1986), tilted gravel beds, offset of streams, and fold axes (Rowland, 1978).

The long map length and apparent minor displacement along exposed faults in the central Sulaiman fold belt is recognized to pose a problem of their origin (Jadoon et al., 1994a) considering fault-propagation theory (Elliot, 1976). The fault-propagation theory suggests a linear relationship between thrust displacement (d) and map length (l) as d=kl, with most faults having k values of about 1/14. The

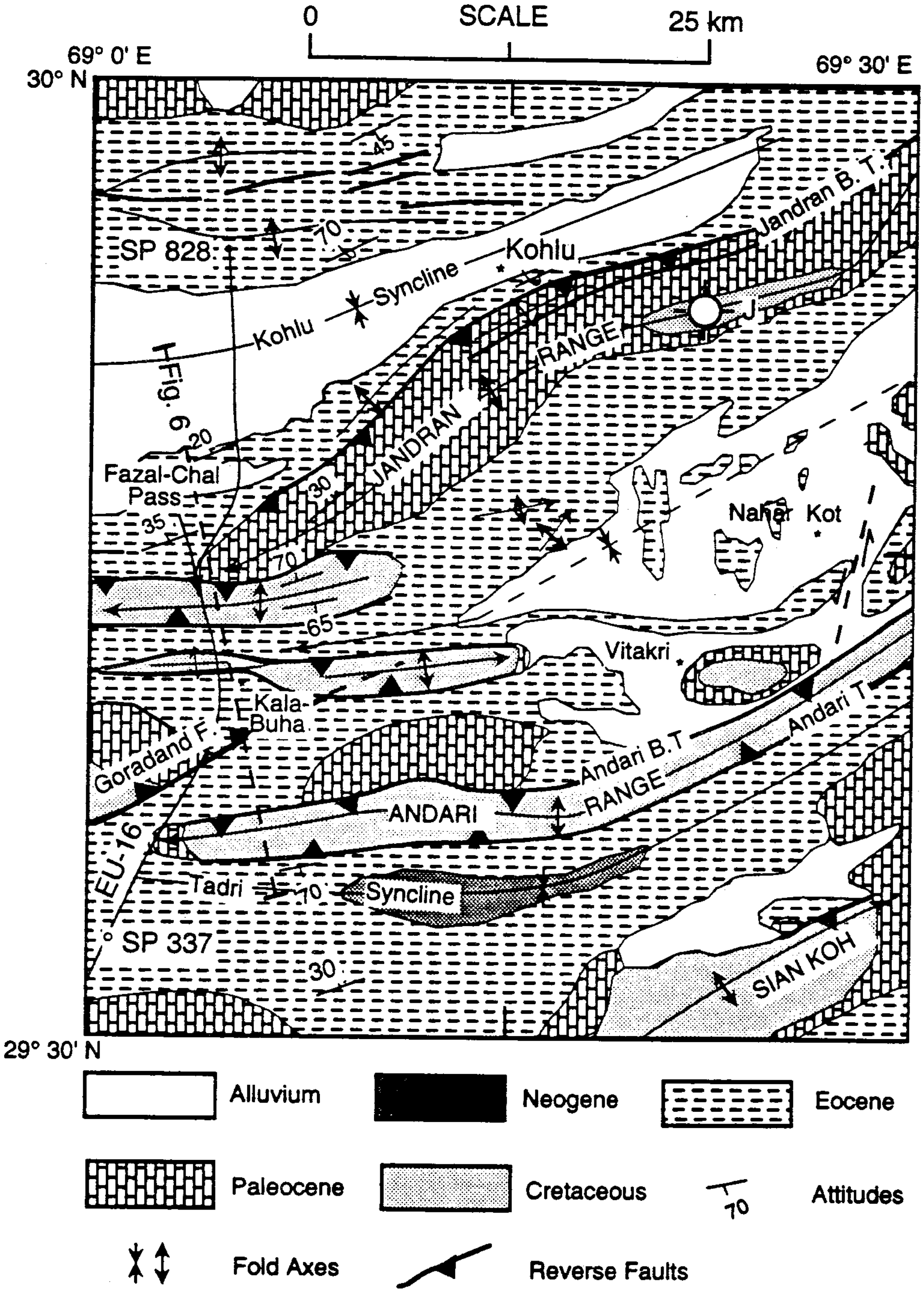


Figure 5- Geological map of a part of the central Sulaiman fold belt (from Jadoon et al., 1994a). See Figure 4 for location of the map. EU-16 shows the location of seismic reflection line discussed in the text.

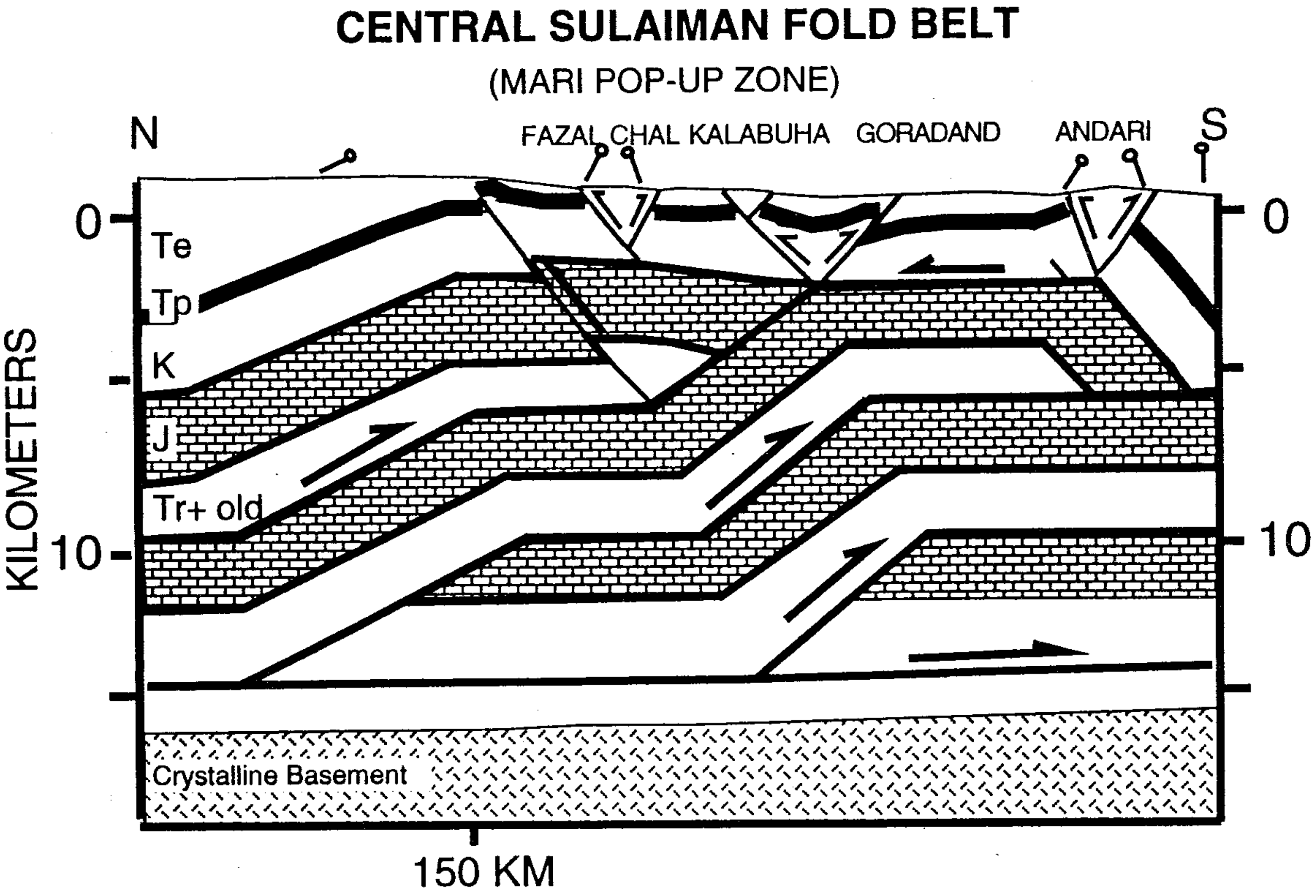


Figure 6- A line from the central Sulaiman fold belt (from Jadoon et al. 1994a). See bold dashed line in Figure 5 for location. Line is partially constrained with seismic reflection data (EU-16 in Figures 4 and 5). Notice minor displacement along exposed reverse faults bounding pop-ups. Symbols are the same as in Figure 3.

largest of above faults is the Andari backthrust. It is observed to extend continually for about 170 km and is displaced laterally by the active Kingri fault in the eastern part of the Sulaiman fold belt (Figures 1, 4). Humayon et al. (1991) mapped it as a single fault (about 60 km map trace) east of the Kingri fault and has shown a throw of nearly 1 km along the fault (Figure 2a). Similar degree of displacement is observed along section from the central Sulaiman fold belt (Figures 2b, 6). Thus, the exposed faults in the central Sulaiman fold belt with a relatively high k value appear to violate the fault-propagation theory. Jadoon et al. (1994a) inferred the presence of smaller faults in comparable structural positions, similar to faults in the southern Appalachians (Diegel and Wojtal, 1985; Geiser, 1988). The apparent long map trace of the reverse faults may similarly be a result of the linkage of two or more faults. However, herein, some of these faults are more thoroughly investigated for their kinematics and evolution based on analyses of LANDSAT and SPOT scenes (1:50,000) integrated with observations from seismic reflection interpretation.

Figure 4 highlights tectonic elements of the central and western Sulaiman fold belt. A set of paired north and south vergent reverse faults (discussed above) bounding Fazal Chal, Kalabuha, and Andari Range pop-ups extends westward as Fazal Chal/Kunal, Kalabuha, Goradand-1 and Goradand-2 faults. Apparent minimum map length of these faults is 40, 22, 45, and 30 km respectively. The first two have a backthrust sense of vergence. The Kalabuha fault, demonstrably shows a dextral slip of about 5 km with displacement of Goradand synclinal axis and the Eocene Kirthar and Ghazij Formations. Along this fault, early Eocene Ghazij shale is emplaced over late Eocene Kirthar limestone, implying a backthrust vergence to the oblique fault. Its westwards termination is manifested by broadening of the synclinal flat (from km near the surface termination of the faults to 13 km towards west) between Kunal and Goradand anticlines and by the development of a small anticline (Ningir) and syncline near the tip of the fault (Figure 4). Similarly, Fazal Chal/Kunal and Goradand-2 display 4-5 km dextral slip by the offset of stratigraphic units (Kirthar) and structural trends. Goradand-1 juxtaposes Cretaceous and late Eocene strata along 29 km of its total 45 km length, and may dominantly be a reverse fault. The Goradand and Kunal anticlines are parallel to the Goradand-1 and Kunal faults respectively. Strike-slip displacement along Goradand-1 fault is hard to predict based on LANDSAT and SPOT data. To the south, a pair of hinterland and foreland vergent faults bound the western part of Tadri anticline. Both of these faults are about 34 km long. Along these faults Paleocene/Cretaceous strata from the core zone of Tadri anticline juxtaposes Eocene strata in the adjacent synclines. The southern one (Khattan) shows along strike variation in vergence and sense of displacement (it shows both dextral and sinistral slip). This suggests a dominant strike- slip nature of the fault or alternately it may be due to a set of two oblique faults (north and south vergent) at comparable stratigraphic positions at the surface. The dextral slip of 1.0 km and backthrust vergence is observable along Khattan fault by the offset of Paleogene Kirthar and Neogene molasse strata. The sinistral slip may be due to westward thrusting of Tadri anticline over the lateral ramp (consistent with a thrust fault earthquake focal mechanism solution; Verma and Chandra, 1986). The north vergent Tadri backthrust is inferred to have a dextral slip based on drag of bedding and folds axes in the footwall. Previously these faults of apparent long map traces were recognized to show minor throw with an average k value of 1/22, inconsistent with fault-propagation theory. Herein, some of these are interpreted as strike-slip and oblique slip faults. However, recognition of dominant strike-slip displacement suggests them to be oblique faults. More detailed investigation of these structures based on field mapping is critical to resolve their nature. A balanced cross-section (Figure 7), is drawn to understand the relationship between surface and deep structures in the central Sulaiman fold belt.

BALANCED STRUCTURAL CROSS-SECTION

A balanced structural cross-section is one that can be retrodeformed, providing an opportunity to judge if the solution is geologically reasonable. Surface folds, faults, and axial surfaces may be interpolated and extrapolated below and above the topographic surface in an area of limited subsurface control to draw complete cross-sections (Dahlstrom, 1969; Woodward et al., 1989). A line-length balancing technique is applied to the cross-sections (Figure 7). The balanced structural cross-section (across strike) extends from Zin/Bugti syncline to the Butar syncline over a distance of 96 km across strike (Figure 4). Seismic reflection line EU-16 (Figures 1, 4) shows eastward control on the subsurface structures. The entire 5 s of two way travel time data shown in this line are layered sedimentary strata; basement and the decollement are deeper than this section. Jadoon (1994a) infer a depth of about 14 km for the projected depth of the crystalline basement below Tadri. Two wells drilled to a depth of about 2454 and 1825 m at the Jandran and Tadri structures respectively (Figure 4) penetrated a normal stratigraphic sequence from Cretaceous (Mughalkot) through Jurassic (Chiltan). The Khattan shows the location of shallow wells drilled to a depth of about 46 m in 1886 on oil seepages (Kemal and Malik, 1987). These produced about 20,000 barrels of oil and were abandoned for economic reasons.

Plot of surface geology along profile allowed to recognize discrete flats and ramps (Figure 7). At and north of Tadri, the relatively tight folds are related to the faults rooted in the Cretaceous roof thrust at depths less than 5 km (except Tadri). The roof thrust is preferably located in the Cretaceous strata, due to deformation of Cretaceous and younger strata as a single structural unit in the seismic reflection profile (EU-16). As a result, Cretaceous and younger strata, with true synclines, is detached and exposed mostly along oblique reverse faults. Tadri backthrust and Khattan fault is interpreted to penetrate into the duplex to a depth of about 9 km. The Tadri backthrust shows a dip slip of 2.5 km and map trace of about 34 km. The Goradand anticline, north of Tadri, is interpreted as a fault-propagation fold related to Goradand-1 fault that soles out in the passive backthrust. It shows a maximum dip-displacement of about 3.5 km (Figure 4) which decreases eastward to less than 2 km (Figure 6) close to lateral termination of the fault. In seismic reflection line (EU-16 in Figure 4) flat geometry of footwall with massive Dungan (Paleocene) limestone marker located at depth less than 1 s on two way travel time data, allows to constrain throw between cut off points along this fault (Jadoon et al., 1994a). The Goradand-2 shows relatively much smaller dip displacement of about half km along its length of 30 km, and is dominantly a strike-slip fault. It appears to extend eastwards at concurrent position along lateral termination of the Goradand-1 fault, obliterating thrust related structures. Towards north, an overall broad syncline of about 13 km between Goradand and Kunal is due to westward termination of the Kalabuha set of faults (Figures 4, 7). This can be interpreted as transfer of displacement from Kalabuha pop-up towards east on the Kunal anticline and Goradand-1 fault towards west, similar to as described by Dahlstrom, (1969) and Elliot (1976) from the Canadian Rockies and shown by analog modelling (Dixon and Liu, 1992).

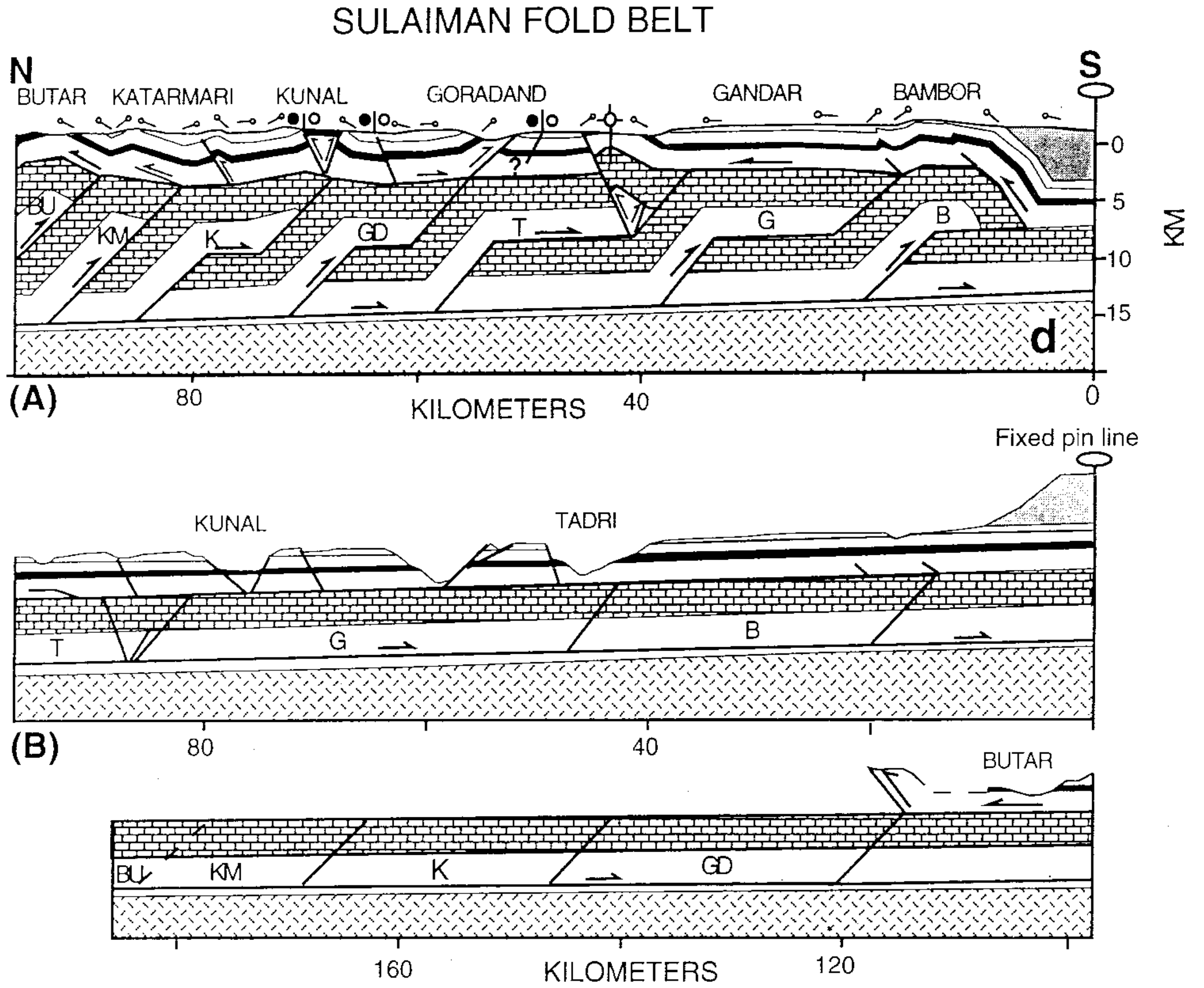


Figure 7- Actual and restored, NNE-SSW geological cross-section of the west-central Sulaiman fold belt of the active Himalayan Mountains system in Pakistan. The 96 km long deformed section (A) restores to 186 km (B), which gives a maximum shortening of 90 km. Relative shortening between roof and duplex is 44 km (Figure 8). 13 km of the relative shortening is accommodated by exposed folds and faults. The remaining 31 km of the relative shortening is interpreted to have been removed primarily by erosion along a passive backthrust north of the section (Jadoon et al., 1994b; see text for discussion). Out-of-sequence exposed faults show dominant dextral strike-slip displacement. Filled circles show movement of blocks away from reader. Patterns are the same as in Figure 6. Letters identifying the individual horses in the duplex sequence are from the individual mountains located above duplexes (shown on Figure 4). From south to north these are B, Bambor; G, Gandar; T, Tadri; GD, Goradand; K, Kunal; KM, Katarmari; and B, Butar.

South of the Tadri anticline, surface expression of the deformation front is of a foreland dipping monocline related to the emplacement of Bambor duplex. Between Tadri and Bambor anticlines, Gandar is a unique plateau type structure, similar to the Pirkoh,with flat Eocene strata extending over a distance of about 17 km. The dips remain less than 6^0 along the length of the flat. Balanced structural cross-section shows that 17 km long broad hinge area of the Gandar is the surface expression of a fault-bend fold (hanging wall flat of a duplex horse; Suppe, 1983) along a blind thrust. Thus, an anticline is predicted below an apparent surface syncline between the Bambor and Tadri anticlines. The structural position of Gandar, behind Bambor, is laterally comparable with Danda/Kurdan horse located behind the Pirkoh duplex (Figures 2b, 7). Unlike the Gandar, Pirkoh is located at the tip of the duplex with surface expression of a box fold in the southern Sulaiman fold belt. However, broad crestal area along both structures reflect a crestal broadening stage of a fault-bend fold development

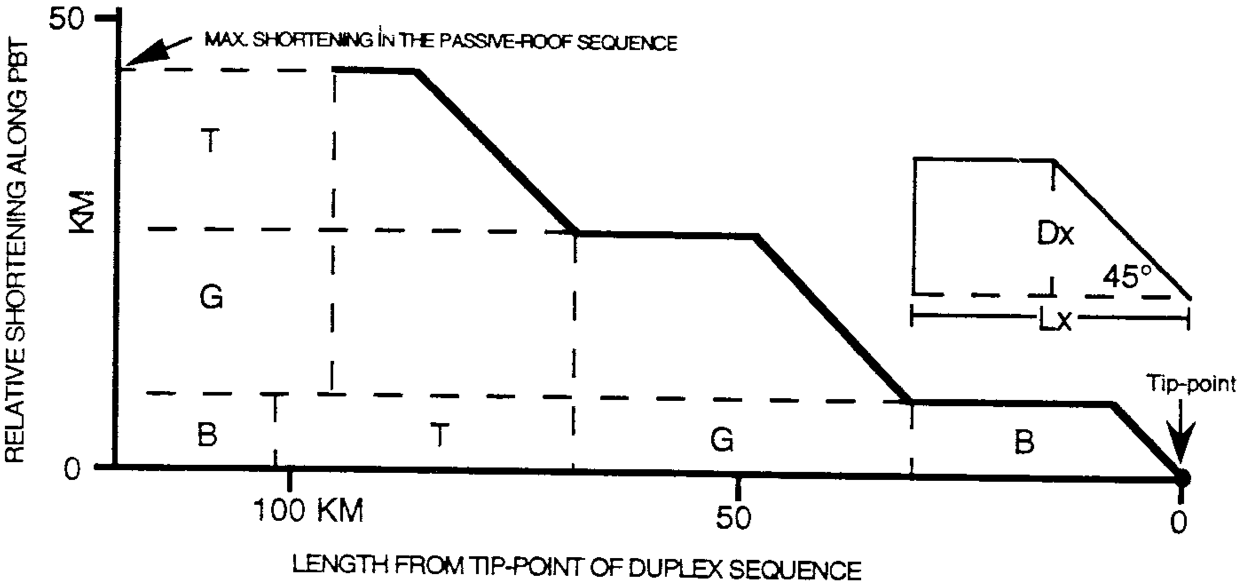


Figure 8- Plot of the cumulative length of the duplex horses against the cumulative displacement from the tip of the duplexes, to determine relative displacement along passive backthrust. Notice 44 km relative displacement between roof and duplex along 96 km length of the passive backthrust decreases to 31 km subtracting 13 km shortening along main fold and faults in the roof sequence. Total length/displacement (34/22) of Tadri horse is corrected (28/18) to make it compatible with total length (96 km) of the passive-roof thrust. Letters identifying individual horses are the same as in Figure 7. Abbreviations: Lx, Length of individual duplex horse, Dx, Displacement of individual duplex horse.

(Shaw et al., 1994), unlike Sui and Loti frontal anticlines that are going through early stages of crestal uplift.

Towards north, Tadri is relatively a tight anticline bounded between a pair of faults of opposite vergence. In the balanced section, Tadri backthrust penetrates to a depth of about 9 km in the duplex sequence. Whereas, Khattan at the same depth is shown as a blind fault that is exposed westwards. These faults are modifying the flat roofed geometry of the Tadri anticline into a hindward vergent fault-propagation fold and a pop-up. These faults die out eastward and true geometry of the Tadri anticline can be seen along seismic reflection profile EU-16 (Jadoon et al., 1992; Figures 2b, 4). Further north, flat roofed and hinterland dipping duplexes are interpreted to fill the space below the roof sequence and true geometry of deep structures is subject to modification with the availability of hard subsurface data.

Shortening

The deformed section is 96 km long. It restores to an undeformed length of about 186 km below the roof sequence, which gives a maximum shortening of about 90 km (48%). This shortening is similar to the 52 % shortening along central line of the Sulaiman section (Jadoon et al. 1994b), 51% in the eastern Sulaiman (Humayon et al. 1991) and 50 % in the Kohat Plateau south of the main Boundary thrust in north Pakistan (McDougal & Hussain, 1991).

Although roof sequence in our balanced section is 96 km long, however, relative shortening between roof and duplex is only about 44 km (Figure 8). Minimum of 13 km of this is accommodated by the exposed and blind faults in the balanced section. A small component of displacement may still be accommodated by small detachment folds, similar to Brooks Range of Alaska (Wallace and Hanks, 1990). Analog modelling of fold belts (Dixon and Liu, 1992) suggests that a significant amount of shortening in the upper layers is accommodated by layer-parallel shortening which still has to be tested in the Sulaiman fold belt. This suggests that minimum relative shortening of 0 km at the tip of the duplex may accumulate to significantly less than 31 km along the north end of the passive-backthrust in Figure 7. Thus, less than 31 km of shortening must be accommodated by the backthrust at its north end and not the total 90 km seen in the duplex structures. This implies that a passive backthrust over several duplexes in the foreland (before collapse of the roof sequence and evolution of ancipient backthrusts) may account only a fraction of shortening that takes place along youngest duplexes, and not all the shortening observed in the underlying duplexes (as older duplexes may evolve prior to their emplacement below the roof sequence at the mountain fronts). The balanced section (Figure 7) shows active deformation and incipient backthrusting above Bambor and along Tadri anticline during present stage of the Sulaiman structure evolution. A fully emergent backthrust is configured (Jadoon et al., 1994b) north of study area that is in agreement with the interpretation of an allochthonous and autochthonous sequence north and south of the Loralai Valley respectively (Kazmi, 1981; Figure 1). The emergent backthrust shows about 86 km of maximum relative shortening (including about 20 km along folds in the roof sequence) between duplex and roof sequence along its length of about 150 km. The fraction of relative displacement accommodated by layer-parallel shortening is not known. However, presence of any such component may considerably reduce the relative shortening of about 66 km (excluding 20 km along folds in the roof sequence) as discussed above. Duplex style of deformation is also interpreted from the Kohat and Potwar Plateau (Jaswal, 1990; Kemal, 1991; McDougal and Hussain, 1991) and seems to be a major mechanism of foreland deformation in Pakistan.

KINEMATICS AND MECHANICS OF THRUSTING

Throughout its length, the deformation front of the Sulaiman lobe is characterized by a moderate to steeply forelandward dipping sequence of mostly Tertiary molasse and platform sequence . In addition, Cretaceous to Eocene platform strata in the core zones of frontal folds is uplifted and exposed several kilometers higher than their regional stratigraphic level. This sequence of Cretaceous to Eocene strata is not disrupted by a significant thrust fault and is interpreted to be a result of thin-skinned duplex style of deformation whose floor (basal detachment) and roof (upper detachment) thrusts are mostly in Paleozoic and base Cretaceous respectively. The roof thrust in this case is a hindward-vergent passive-backthrust. The duplex sequence is actively propagating toward the foreland as a core wedge bounded by a triangular shaped geometry of the limiting faults (triangle zone of Gordy et al., 1977).

A typical triangle zone can be composed of stacked thrust sheets bounded between a hinterland vergent backthrust at the foreland margin of the thrust belt and a floor thrust that terminates updip in the backthrust (Figures 2a and 9a) and are common structures in various parts of the Canadian Rocky Mountains (Price, 1981, 1986; Jones, 1982), the Mackenzie Mountains, Canada and the Peruvian Andies (Vann et al., 1986) and other mountain belts. A systematic arrangement of the stacked thrust sheets with breached roof sequence by backthrusts (Figure 9b) in a triangle zone geometry is termed as a "passive-roof duplex" by Banks and Warburton (1986) with examples from the northern Kirthar and western Sulaiman fold belts of Pakistan.

A passive-roof duplex sequence is a normal stratigraphic sequence separated from the duplex by a passive backthrust that remains stationary relative to the foreland propagating duplex structures. As a mechanism to accommodate comparable shortening, roof sequence may be imbricated by multiple passive backthrusts (Figures 9b and 10). This mechanism limits the passive displacement of 10-20 km along a single backthrust and is kinematically a viable mechanism. However, in other cases a continuous roof-sequence, 10's to over 100 km long, is mapped in various fold belts (Jones, 1982; Price, 1981, 1986; Hobson, 1986; Morley, 1987; Vann et al., 1986; Geiser, 1988; Wallace and Hanks, 1990). Such a triangle zone structure with long bounding backthrust is termed as a low-taper triangle zone (McMechan, 1985). Three dimensional geometry of passive-roof duplex in the Sulaiman fold belt closely resembles to a low-taper triangle zone that can be questioned considering mechanical stability of such structures (Jamison, 1993). However, their existence invokes a more thorough investigation of such structures.

The apparent low-taper triangle zone (passive-roof duplex) structure of the Sulaiman fold belt is going through active out-of-sequence faulting. The descriptive model in Figure 11a suggests an emergent passive backthrust and pop-ups in an extended roof sequence. The segment of backthrust north of pop- up structures may primarily be inactive, based on lack of seismicity in the Sulaiman hinterland (Quittmeyer et. al., 1979). Whereas, the segment below and south of pop-up structures is seismically active (Figure 4) and may represent sequential evolution of backthrusts. Future geometry of the Sulaiman structure (Figure 11b) may be anticipated similar to as seen in section of the Athabasca Valley, Alberta Foothills, Canada (Figure 8b). It may be noted that the cross section constructed by Banks and Warburton from western Sulaiman (Figure 2b) does not preserve most of the roof sequence due to deeper erosion. Their model suggesting multiple backthrusts each originating from the tip of a new duplex, may not be completely applicable to the western Sulaiman fold belt. In their section (Figure 2c) loss of roof sequence by deeper erosion can easily lead to an incorrect interpretation. Presence of intact roof sequence over several duplex horses in the Sulaiman and other fold belts suggests that an extended backthrust can be a feature of passive-roof duplex geometry (Figure 11a) as long as backthrust wedge remains in the critical wedge limits. The simplified model in the Figure 11a shows that backthrust wedge in the Sulaiman fold belt is presently below the stable wedge configuration. Thus, active out-of-sequence deformation may be due to synchronous deformation within the wedge to create critical taper for foreland thrusting (Davis at al., 1983), and to create a mechanically stable backthrust wedge configuration (Jamison, 1993).

Discussion and synthesis of the geological and geophysical data (above) provides insight into the sequential evolution of the Sulaiman foreland structures.

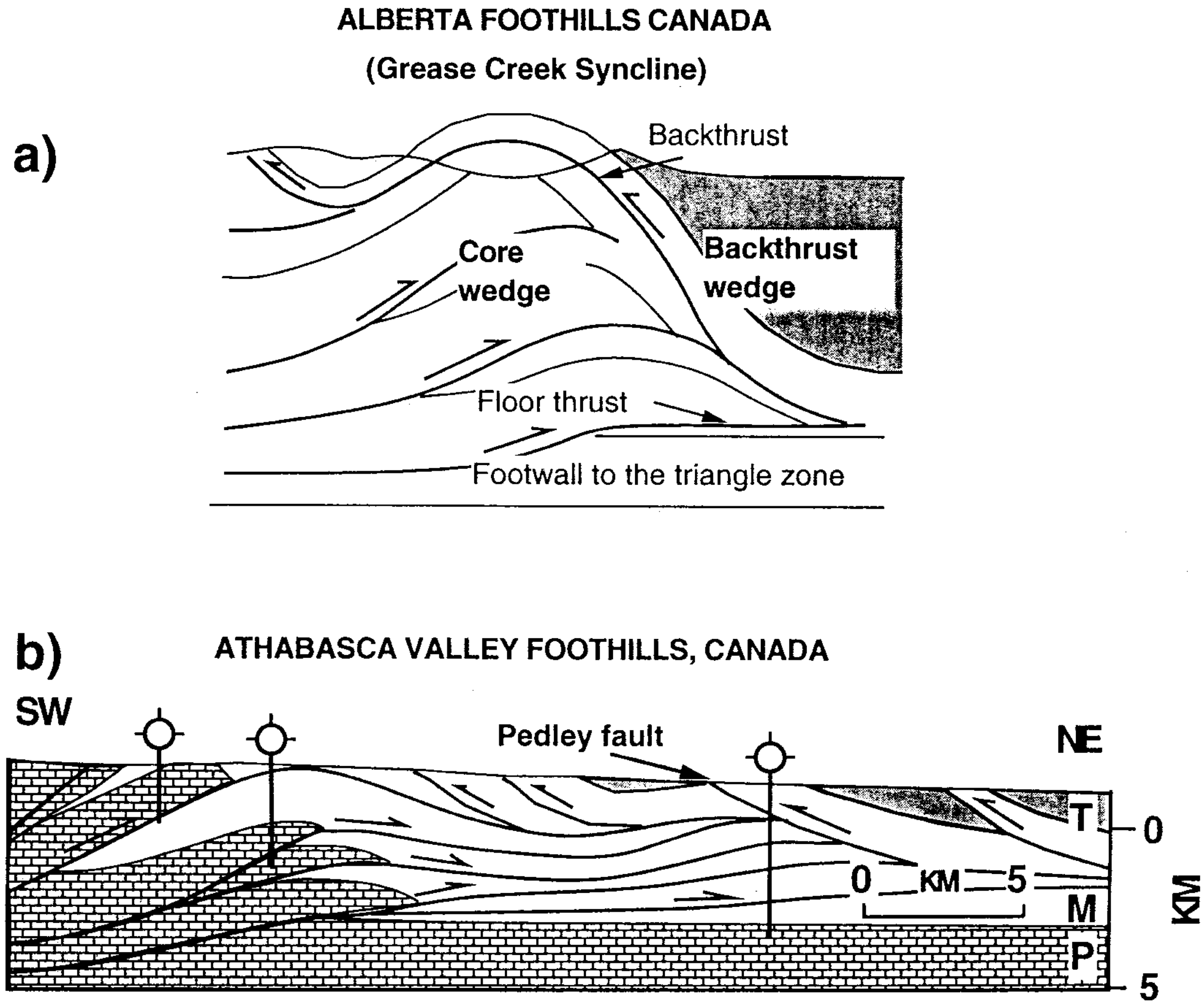


Figure 9- (a) Line of Grease Creek syncline, eastern foothills, Canada to show simplified geometry of a triangle zone (modified from Jones, 1982). The basic components are a backthrust, a floor thrust that terminates into the backthrust, and an emergent thrust that breaches the erosional surface (shown in Fig. 11). Notice the overlapping backthrust and similarity of this structure with Fort Munro Anticline shown in Figure 2a. (b) Cross-section in the Athabasca Valley, Alberta foothills (modified from Jones, 1982). This section shows multiple backthrusts over the duplex.

It has evolved with a passive-roof duplex geometry dominantly by compression since about 21 M.a (Jadoon et al., 1994b). Progressive evolution of compression related structures can be interpreted in terms of concentric long wave-length buckle folding at the tip of the decollement; development of duplex structure by sequential detachment, fault-propagation and fault-bend folding (Jadoon et al., 1993); and out-of-sequence thrusting in the internal portion of the fold belt (Figure 2b, 11).

TECTONIC TRANSPRESSION

Out-of-sequence faults in the central Sulaiman fold belt showing 1-3.5 km of throw and several km of lateral displacement can be recognized as reverse and strike-slip faults as discussed above. Dextral displacement is dominantly observable along strike-slip faults. Thrust faults and one dextral slip focal mechanism solution (Quittmeyer et al., 1979; Verma and Chandra, 1986) are in agreement with the exposed faults (Figure 4). In some cases, eastwest trending faults more precisely can be defined as oblique faults obliterating former thrust structures in their present stage of evolution.

The strike-slip faults with dominant dextral displacement can be interpreted to evolve due to anticlockwise rotation of discrete blocks in the Sulaiman fold belt along the western sinistral plate boundary of the Indian subcontinent (Figure 12). The balanced structural cross-section suggests that the surface structures in the central Sulaiman fold belt have evolved since about 0.72

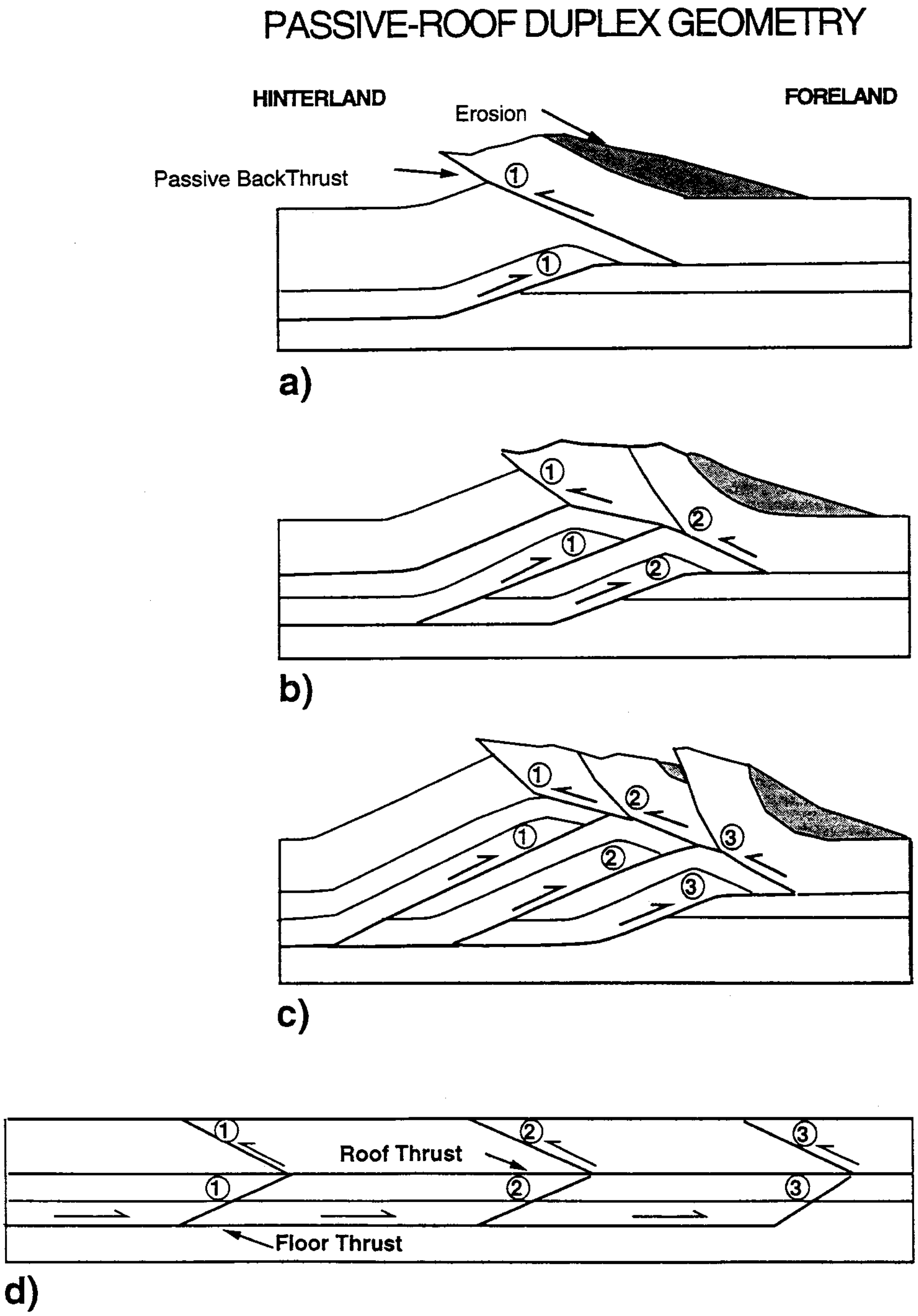
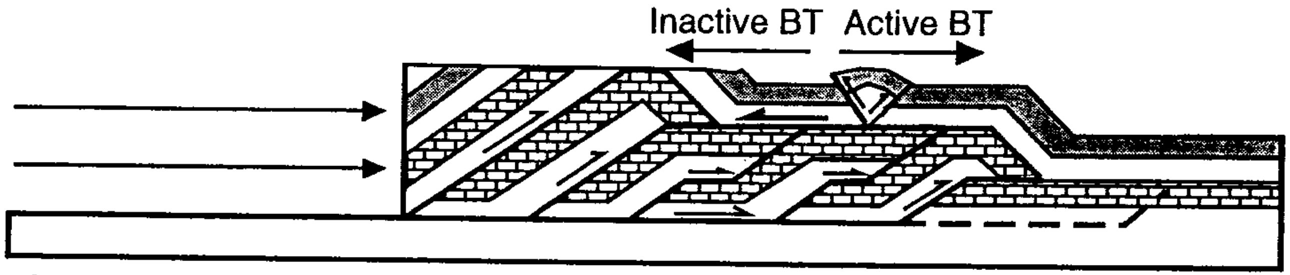


Figure 10- Schematic development of a passive-roof duplex (modified from Banks and Warburton, 1986; Humayon et al., 1991). Text for discussion.

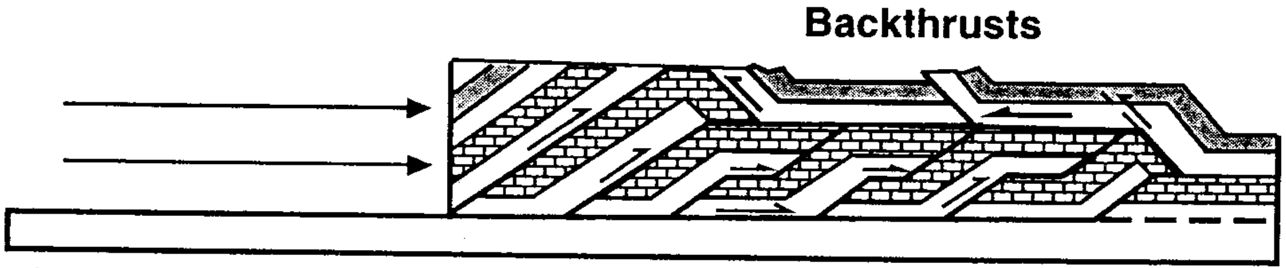
M.a (13 km of shortening with a rate of 18 mm/yr). This implies onset of Quaternary transpression in the Sulaiman fold belt bounded between northsouth trending Kirthar and Sulaiman Range. Eastwest trending strike-slip faults have also been recognized further north in the Kohat Plateau (Pivnik and Sercombe, 1993).

According to the present data, strike-slip faults are apparently restricted to the sedimentary wedge above the basement. However, more thorough investigation

PASSIVE-ROOF DUPLEX GEOMETRY



a) Early Stage: Low angle triangle zone and pop-ups



b) Advanced Stage: Over-step backthrusts

Figure 11- Simplified diagram to show progressive evolution of the Sulaiman fold belt from a low-taper triangle zone and out-of-sequence deformation in a mechanically unstable backthrust configuration (A) to a passive-roof duplex with multiple emergent backthrusts in a mechanically stable backthrust wedge configuration (B).

based on hard data is required to learn depth penetration of these faults. An alkaline intrusion is reported from the hinterland of the Sulaiman fold belt (Jadoon and Baig, 1991). Alkaline intrusions are related to extension of the crust. At present, no dating control is available on the timing of the alkaline intrusion. It may be very young. Age dating of this intrusion may provide more clues to understand neotectonics of the Sulaiman thrust system.

HYDROCARBON TRAPS

The Sulaiman fold belt with more than 60,000 km^2 of the exposed Paleogene to Triassic platform strata is one of the main petroleum zones of Pakistan. The 7 km thick Paleogene to Paleozoic strata has potential source and reservoir rocks for the generation and accumulation of the hydrocarbons (Kemal and Malik, 1987; Raza et al., 1989a). Presently gas is being produced from the Eocene, Paleocene, and Cretaceous reservoirs. Five gas fields with Sui being the first and largest have been discovered in the area since 1952. Increasing consumption and demand of energy requires to intensify exploration effort in the Sulaiman fold belt.

Successful exploration, evaluation, and exploitation of hydrocarbons demand detailed structural, stratigraphic, and geochemical investigations to define potential areas for the acquisition of closely spaced seismic data and wildcat drilling. Although Sulaiman foreland is presently considered as a gas prone area that has contributed over 69% of the total 402.5 billion cubic feet of gas produced in the country during 1986-87 (Kemal and Malik, 1987); sizable amount of oil may be present ((Raza et al., 1989a). This can be supported by the occurrence of gas condensate in wells (Dhodak) and the seepages of oil from the western (Destangi, Khattan, Samach, Spintangi), central (Khatikkani) and eastern (Mughal Kot, Burzam, Raghasar) Sulaiman fold belt (Raza et. al., 1989a and 1989b).

An important prerequisite for the accumulation of hydrocarbons is the entrapment mechanism. That is how hydrocarbons after expulsion from the source strata migrates to the reservoir where they can be caught by structural, stratigraphic, or combined traps of different kinds. Three- dimensional geometry of passive-roof duplex shows structural traps of three general types. One; system of frontal detachment (Sui, Loti/Zin) and fault-propagation (Uch, Sakhi Sarwar) folds. Detachment folds are the simplest type of traps that can contain huge quantities of hydrocarbons such as Sui gas field. Two; traps in the duplex sequence. Duplex structures consist of Jurassic and older strata. Hydrocarbon potential of these strata is presently uncertain. However, Khan and Raza (1986) based on geothermal gradient of 2.4 /100 m in the Jandran well

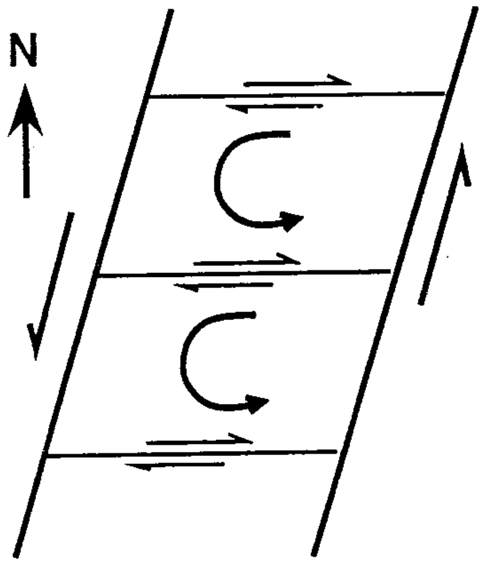


Figure 12- Simplified model for the evolution of eastwest trending, dominantly dextral faults in the central Sulaiman fold belt. The model suggests onset of transpression in the context of India/Asia collision involving rotation of discrete blocks in the Sulaiman fold belt.

suggested 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 horizons. These observations for prospects in the Jurassic are favoured by the organic geochemistry (Raza et al., 1989a). Aside from previous drilling experience and uncertainties of source and maturity of the older strata duplex structures apparently have most important hydrocarbon traps. Some examples of trap forming geometries include: (1) fault-bend folds (Pirkoh, Giandari, Bambor, Gandar, Zindapir in Figures 2a-b and 7); (2) independent ramp anticlines and fault-propagation folds (Danda, Tadri, Jandran in Figures 2b and 7); (3) intraplate folds (Kurdan); (4) plane- roofed and hinterland dipping duplexes (Fort Munro system in Figures 2a; Goradand, Kunal, Katarmari, Butar in Figure 7, and system of mountains between Galusha Hills and Miri in the western Sulaiman (Jadoon in preparation); and anticlinal stacks (Mari, Tadri in Fig. 2b). Three; traps in the roof sequence structures. Roof sequence of Cretaceous and younger strata has relatively well studied source and reservoirs that have been tested. Of these, some fields are on production (Sui/Pirkoh Gas Fields etc). Some examples of the trap forming geometries in the roof sequence include: (1) fault-bend folds (Pirkoh, Bambor, Tadri); (2) fault-propagation folds (Jandran, Tadri); (3) pop-ups (Kunal in Figure 7); (4) upturning of the footwalls adjacent to faults (Figures 6, 7); (5) culmination wall of the duplex may turn out as the most suitable location for the sizable hydrocarbon reserves.

Existence of traps prior to hydrocarbon influx is important for the entrapment. Due to active development of foreland structures, it is possible that many structural traps may have not yet accumulated sufficient quantities of hydrocarbons (D. Bannert, pers. comm. 1994) and so are severely underfilled (Kemal and Malik, 1987). In other cases young strike-slip faults may be providing seals or conduits for lateral and vertical migration of oil resulting in surface seepages. This paper is an effort to provide an insight into the 3-dimensional geometry, kinematics, and evolution of the Sulaiman fold belt. As Sulaiman fold belt is an evolving mountain system, I expect to see more geological, geophysical, and geochemical data to understand its structure and evolution and to calculate its hydrocarbons potential.

CONCLUSIONS

Passive-roof duplex geometry is interpreted as the style of foreland deformation in the Sulaiman fold belt that is now under the influence of dominant transpressive deformation. The duplex sequence is covered by an intact roof-sequence that measures some 150 km across strike.

This intact passive-roof sequence differs from the model of passive-roof duplex geometry developed for the western Sulaiman by Banks and Warburton (1986), which is characterized by multiple overstep-backthrusts that ideally originate from the tip of each foreland propagating duplex to accommodate shortening strain in the roof sequence.

The intact roof sequence in the Sulaiman fold belt covers several duplex horses. It shows out-of-sequence faulting (probably an early stage of evolution of overstep-backthrusts), but none of the faults is observed to show a significant displacement at the present stage of their evolution. The passive-roof sequence is however fully emergent further north in the hinterland, thus implying that a significant amount of relative displacement (about 66 km) between roof and duplex sequence must be accommodated by a single passive-backthrust over the underlying duplexes. The passive-roof duplex of the Sulaiman fold belt bears some resemblance to the low-taper triangle-zone model proposed for the northern Canadian Rocky Mountain Foothills Belt (McMechan, 1985).

The long roof sequence in a low-taper triangle zone model raises question of stability of the backthrust wedge. However, presence of intact roof sequence over several duplex horses in the Sulaiman and other fold belts suggests that an extended backthrust can be a feature of passive-roof duplex geometry as long as backthrust wedge remains in the critical wedge limits. The backthrust wedge in the Sulaiman fold belt appears to be below the stable wedge configuration. hus, active out-of-sequence deformation in the central Sulaiman can be interpreted to create a mechanically stable backthrust wedge configuration. Active shallow seismicity in/south and lack of seismicity north of the central Sulaiman supports this hypothesis.

96 km long balanced section in this paper shows relative shortening of only 44 km between roof and duplex sequences. 13 km of this is accommodated by out-of- sequence fault and folds. How much of remaining 31 km is accommodated by layer-parallel shortening is not known. Subtraction of this component should reduce the amount of relative shortening that must be accommodated by the backthrust. Thus, an extended backthrust over 96 km of relative shortening between roof and duplex sequences.

Some of the exposed faults in the central Sulaiman fold belt are recognized as strike-slip faults, which show consistent dextral displacement. They can be interpreted to evolve by anticlockwise rotation of discrete blocks in the Sulaiman fold belt due to its close proximity with the western sinistral boundary of the Indian subcontinent. This suggests onset of dominant Quaternary strike-slip deformation in the Sulaiman fold belt. Three-dimensional structures of the Sulaiman foreland allows to predict sequential evolution of active structures in terms of low-amplitude concentric folds at the tip of the decollement, to duplex and out-of-sequence faulting, and onset of Quaternary transpression.

Structural geometries form several important hydrocarbon traps. Some examples of trap forming geometries in the Sulaiman fold belt include: (1) detachment folds (Sui and Loti/Zin gas fields); (2) fault-propagation folds (Uch gas field); (3) fault-bend folds (Pirkoh gas field); (4) several duplex geometries (unexplored); and (5) secondary traps in the upturned end of the footwalls.

Many studies with consideration of style of deformation, seismic and gravity interpretation, mechanics, seismicity, sedimentation, and paleomagnetism are consistent with thin-skinned foreland thrusting of the Sulaiman fold belt. Plio. Pleistocene transpression in the eastwest Kohat Ranges has been reported to influence thrusting consistent with this study (Pivnic and Sercombe, 1993). This paper is an effort to provide an insight regarding the three-dimensional geometry, kinematic evolution, and hydrocarbon potential of the Sulaiman foreland. However, as the Sulaiman is an evolving mountain system, we expect to see more useful details in future to evaluate structure of the Sulaiman fold belt for more successful exploration.

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