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The Style and Evolution of Foreland Structures: An Example from the Sulaiman Lobe, Pakistan

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ABSTRACT

Structural cross sections constrained with seismic reflection, borehole, Landsat, and surface geology in the foreland of the Sulaiman lobe provides data on the style and evolution of a specific foreland structures. Seismic reflection profiles show about 10 km thick stratigraphic section at the deformation front. Nearly all of the stratigraphic section is detached from the crystalline basement, suggesting a deep decollement at the base of the wedge. Structural uplift of 4-8 km is observed in the seismic reflection profiles, without emergent thrusts in the foreland. This is interpreted to be related to passive-roof duplex style of deformation. Duplex sequence is consists of Jurassic and older strata with a floor thrust (decollement) at the base of the section and a roof thrust (passive backthrust) in thick Cretaceous shales.

Three cross sections across the foreland show the structural variations from: (1) two broad (half-wavelength about 25 km), low amplitude (1-1.5 km) folds in front of the duplex; (2) a small wavelength (about 3.5), low amplitude (about 1 km) fault- propagation fold ahead of a broad fold and the duplex; and (3) a duplex respectively at the deformation front. This data suggests chronology of foreland structures from a fault-propagation fold to a broad concentric buckle fold to a duplex.

INTRODUCTION

In recent years, exploration for hydrocarbons has provided tremendous amount of seismic reflection and borehole data along mountain fronts. Integrated surface and subsurface data has allowed to produce well constrained geological cross sections.

These sections recognize a variety of thin-skinned foreland structures varying from concentric folding (Dahlstrom, 1970), to piggyback (Bally, 1966; Dahlstrom, 1970; Boyer and Elliot, 1982; Butler, 1982), and duplex (Jones, 1982; Vann et al, 1986; Banks and Warburton, 1986; Hobson, 1986; Evan,1989; Humayon et al, 1991). In addition, the mechanics of the mountain belts has been modelled by Davies et al (1983), Davis and Engelder (1985) and the geometry of foreland structures has been modelled by Liu and Dixon (1990), Dixon and Tirrul (1991). More detailed studies on the geometry of the individual structures show that a fold at the deformation front may be related to a fault at depth (Suppe, 1983). Such folds could be recognized as fault-bend folds with a stair-case trajectories (Suppe, 1983) to fault-propagation folds at the tip of the decollement (Suppe and Medwedeff, 1984).

In this paper surface geology is integrated with seismic reflection profiles and well data to draw three structural cross sections across the active Sulaiman Mountain front to:1) determine the style of deformation and structural variation; and 2) to understand the evolution of the foreland structures.

STRATIGRAPHY AND TECTONIC SETTING

The Sulaiman lobe (Sarwar and DeJong, 1979) southwest of the Himalayas, is a broad (300 km) fold-and-thrust belt that is tectonically active (Figure 1). Its surface geology is dominated by continental platform and shallow marine rocks bordered by ophiolites and flysch in the hinterland and continental molasse strata in the foredeep (Allemann, 1979; Kazmi and Rana, 1982; 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 (Izatt, 1990; Jadoon, 1991). The fold belt is interpreted to overlie transitional or oceanic crust of a previously extended continental margin (Khurshid, 1991; Jadoon, 1991). 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) and Bouguer gravity data (Duroy et al, 1989). In addition, basement rocks are exposed at the surface in the hanging-wall block of the Main Central thrust (LeFort, 1975).

Two different structural models have been proposed for the evolution of the Sulaiman fold belt (Banks and Warburton, 1986; Bannert et al, 1989). Geological maps of the Hunting Survey Corporation (1961) and Kazmi and Raza (1982) show thrust faults exposed as imbricate structures in the central and northern part of the fold belt. Bannert et al (1989) interpret these faults as

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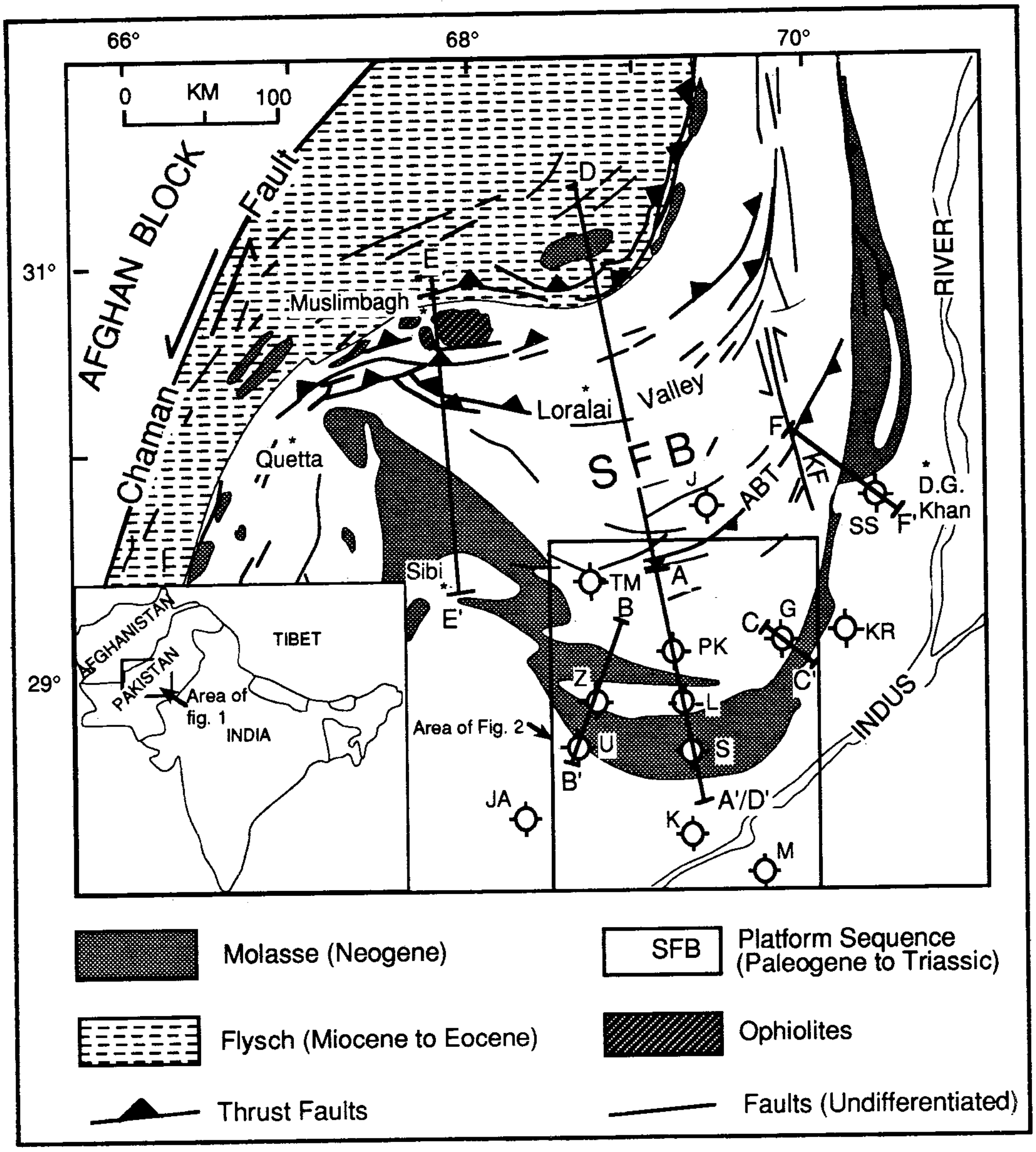


Figure 1— Location of the Sulaiman fold-and-thrust belt in Pakistan (box). Structural cross sections A-A′, B-B′, and C-C′are shown in Figures 10, 13, and 14 respectively. Cross sections D-D′, E-E′, and F-F′shows the location of balanced cross- sections constructed by Jadoon (1991), Banks and Warburton (1986) and Humayon et al, (1991) respectively. Abbreviations: ABT = Andar Backthrust; KF = Kingri fault. Well abbreviations: G = Giandari; J = Jandran; JA = Jacobabad; K = Kandhkot; KR = Kotrum; L = Loti; M = Mari; PK = Pirkoh; S = Sui; SS = Sakhi Sarwar; TM = Tadri Main; U = Uch; Z = Zin.

foreland-verging thrusts. Banks and Warburton (1986) proposed a passive-roof duplex style of deformation from western Sulaiman fold belts (E-E′ in Figure 1). A similar style of deformation is recognized from the frontal (Jadoon et al, 1991) and eastern (F- F′in Figure 1, Humayon et al, 1991) Sulaiman fold belt.

Deformation in the Sulaiman lobe probably became significant during the Miocene (205 Ma?) with the initiation of Chaman fault system (Figure 1) and the deposition of the continental molasse deposits (Lawrence and Khan, 1991). Since then, 353±25 km of shortening has occurred in the cover strata of the Indian subcontinent (Jadoon, 1991). Ongoing, prograde deformation consistently reworked the molasse strata so that the centre of deposition migrated to the south and east. This is similar to the foreland translation of the Pine Mountain thrust sheet of the central Appalachians (Rich, 1934; Harris and Milici, 1977), Jura Mountains of Europe (Laubscher, 1981) and the Salt Range/Potwar Plateau of Pakistan (Johnson, 1982; Raynolds and Johnson, 1985). Presently, active

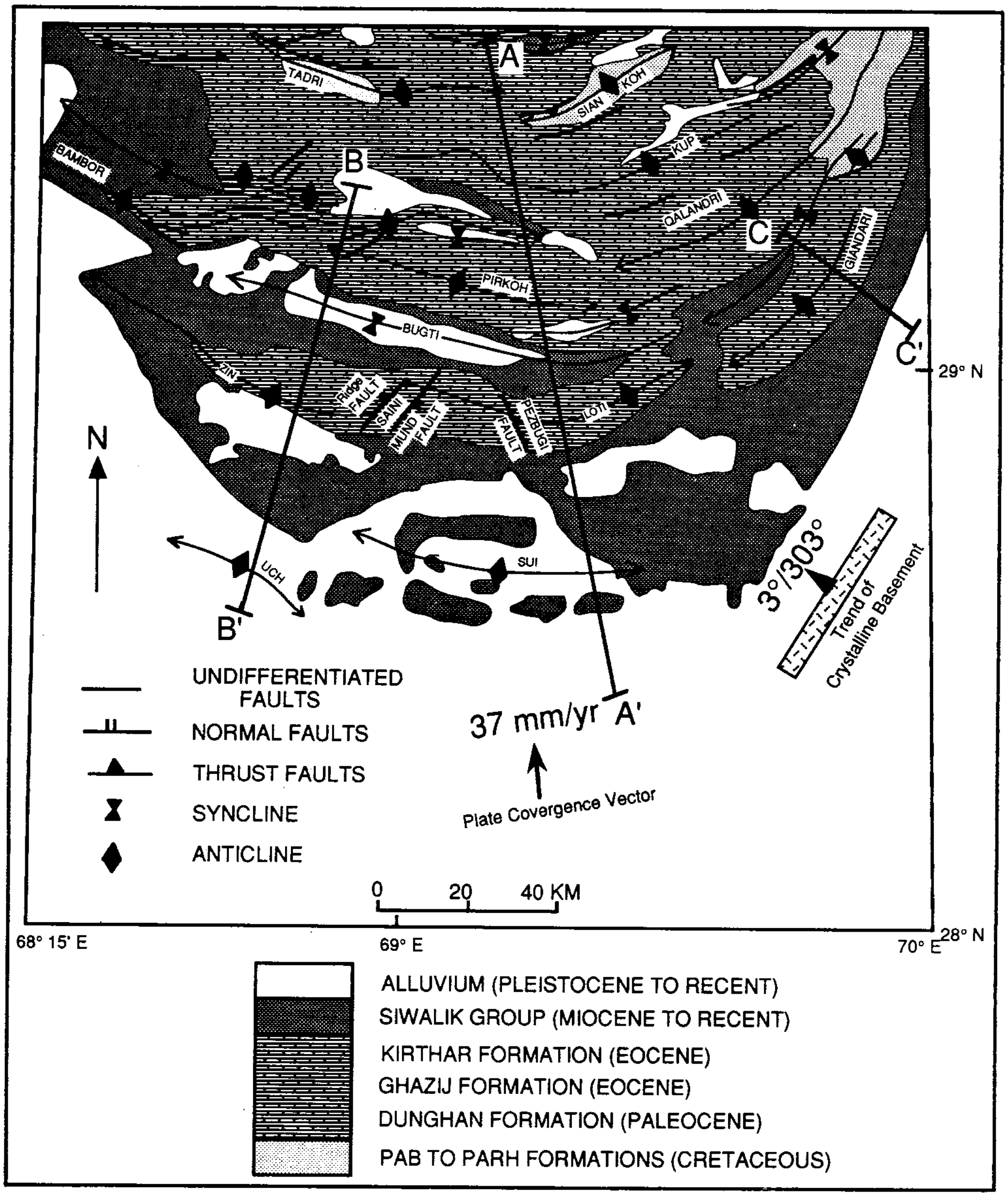


Figure 2— Generalized geological map of the southern Sulaiman lobe (modified from Jadoon et al, in press). Notice the folds as dominant foreland structures. Plate convergence vector is adopted from Minster et al, (1974). See text for the attitude of the basement. A-A′, B-B′, and C-C′ are the locations of the structural cross sections.

deformation is suggested by recent unconformities from the southern Sulaiman Range (Tainish et al, 1959) and local seismicity (Quittmeyer et al, 1979, 1984). Age dating by magnetostratigraphy from the eastern Sulaiman mountain front (Ahmad and Khan, 1990) shows that continental Siwaliks, deposited between 0.7 Ma to 50,000 yr, are overlain by alluvial fan deposits. The latter are tilted along the eastern Sulaiman front. This paper is, in part, designed to draw closely spaced cross sections at the evolving mountain front to understand the evolution of the foreland structures.

DISCUSSION OF SURFACE AND SUBSURFACE DATA

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

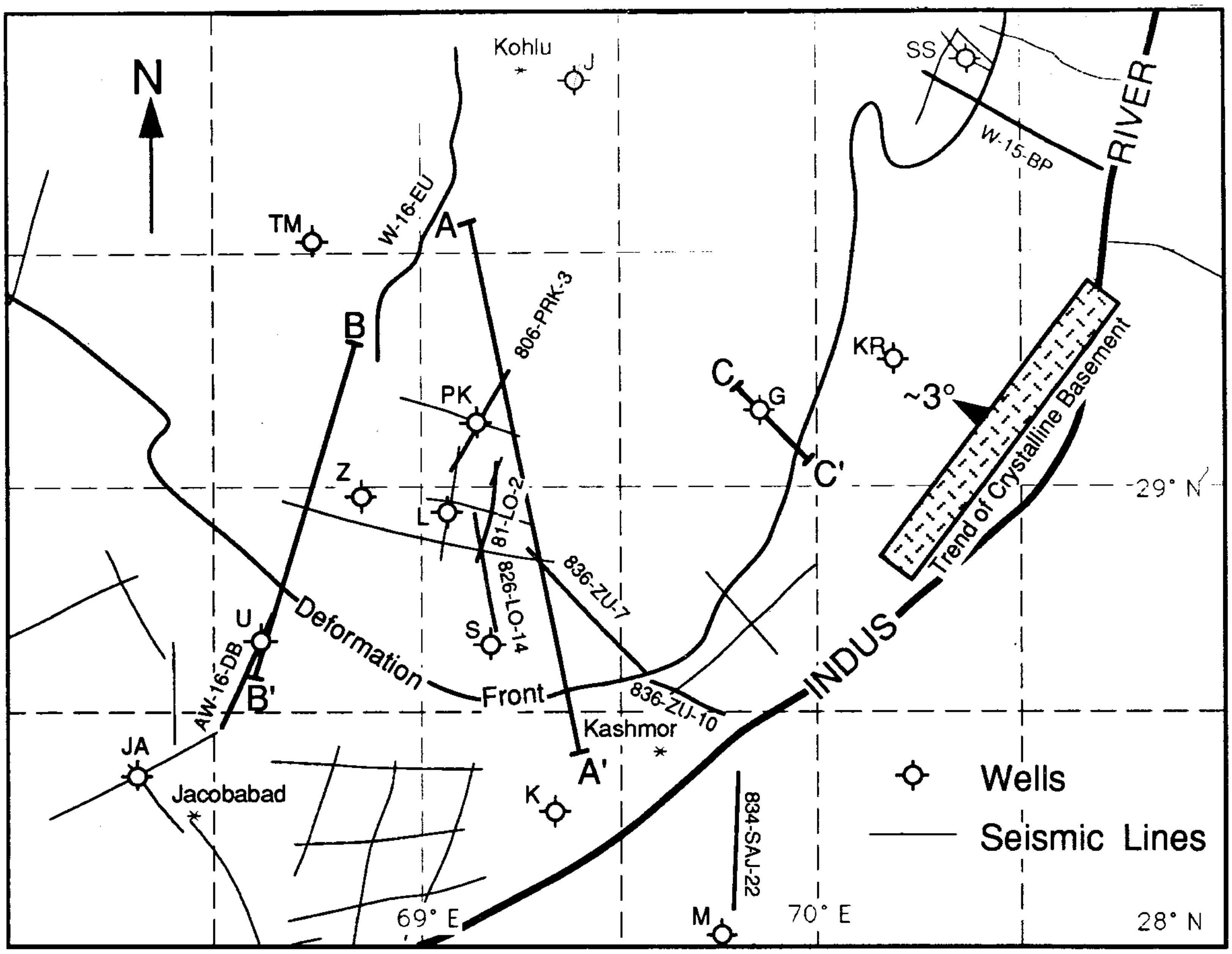


Figure 3— Seismic layout and borehole map to show the location of the seismic reflection lines available for this study. Bold lines with text show the location of composite seismic line, part of that is shown in Figure 9. A-A', B-B', and C-C' are the location of Figures 10, 13, and 14 respectively. Well abbreviations are the same as given in Figure 1.

Sulaiman (Mari-Bugti area), and the Hunting Survey Corporation maps (1:253,440) along with Landsat data (1:125,000), provide surface geology coverage. These data were used to compile a geological map of the entire Sulaiman foreland (Figure 2). This data set is used to constrain 3 structural cross sections, A-A', B-B', and C-C' shown in Figures 1, 2, and 3 across the Sulaiman foreland. Field checking was done mainly along cross section A-A' during the fall of 1988.

Surface Expression of the Foreland

The frontal Sulaiman ranges are composed largely of Neogene molasse and Paleogene shales and carbonates at the surface. Dominant structures of the foreland are mostly broad folds. Progressively older rocks are exposed in the cores of folds toward the hinterland (Figure 2). However, in the foreland, rocks at the surface show coherent stratigraphy that is not disrupted by emergent thrusts. Sui and Loti are two broad (about 25 km half wavelength) doubly plunging anticlines at the mountain front (Figure 2). Limb dips do not exceed more than 5° on Sui and 15° on Loti. Towards the north individual folds vary from eastwest trending folds (Pirkoh) in the middle to northeast (Qalandri) and northwest (Bambor) trending folds along the margins (Figure 2). Unlike gentle Loti fold, the Pirkoh anticline has a fairly steep (35°-75°) southern limb and a relatively flat hinge zone of about 15 km. Overall expression of the Pirkoh anticline is a foreland dipping monocline. En-echelon patterns along with deflection of the axes (Kup fold: Dahlstrom, 1970) are thoroughly observed in the foreland of the Sulaiman lobe (Figure 2). The Sui and Uch are relatively small douply plunging anticline. Axes of the Sui and the Uch anticlines form an en-echelon pattern (Figure 2). Like the Sui and the Uch fold in the southwestern part; axes of the Loti and the Giandari folds to the southeastern part have an en- echelon pattern. These observations may suggest laterally discontinuity of structures at depth.

In addition to folds, normal bending-movement faults are common structures in the foreland. Normal faults, the Ridge and Sani Mund faults, on the Loti structure show a

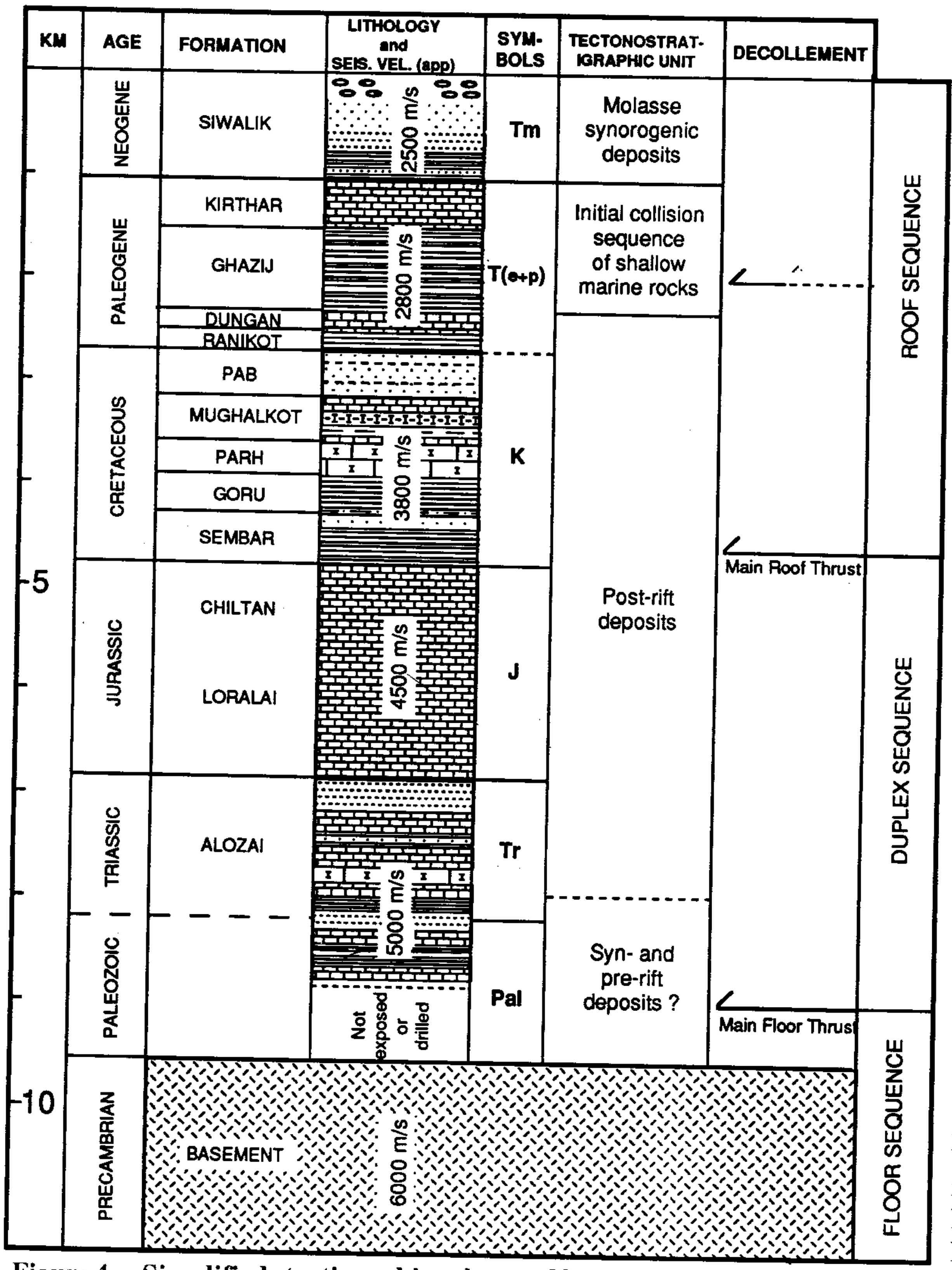


Figure 4— Simplified stratigraphic column of frontal Sulaiman fold belt (from Jadoon et al, in press). Major decollement horizons are proposed in Paleozoic, Cretaceous, and Eocene with a duplex sequence below and a roof-sequence above Cretaceous shales.

dip-slip offset of about 20 metres. These faults, more precisely are oblique bending-movement faults with a significant component of strike- slip displacement. The fold axis of the Loti anticline is displaced for several hundred metres along some of these faults (Figure 2).

Seismic Reflection Profiles and Boreholes

Extensive seismic reflection and borehole data from the frontal part of the Sulaiman fold belt and the adjacent foredeep have been used to constrain the structural cross sections A-A′, B-B′, and C-C′ (Figure 3). These data were provided to Hydrocarbon Development Institute of Pakistan (HDIP) by the Oil and Gas Development Corporation of Pakistan (OGDC). The seismic profiles provide good coverage of the southern Sulaiman foredeep and extend about 160 km to the north into the fold-and-thrust belt from the deformation front.

The seismic profiles are used to resolve: (a) trend and depth to the top of the crystalline basement to constrain stratigraphic and tectonic thicknesses; (b) the major decollement; and (c) the geometry of structures along structural cross sections. The first two constraints are vital to constrain the geometry of structures and style of deformation.

Crystalline Basement and Sedimentary Package

It is important to locate the top of crystalline basement in a fold-and-thrust belt in order to evaluate: 1) total thickness (stratigraphic and tectonic) of the sedimentary wedge above the basement; 2) location and nature of the decollement at the base of the wedge or in some younger horizon: 3) basement slope, which is important in understanding the mechanics of thrusting (Davis et al, 1983; Davis and Engelder, 1985; Jaumè and Lillie, 1988); and 4) the role of basement structures in controlling the deformation (Jackson, 1980; Lillie, 1984; Lillie and Yousaf, 1986; Baker et al, 1988).

Most of the seismic reflection lines located in Figure 3 include data to 5 seconds, 2-way travel time. Due to the extreme thickness of the sediments, basement can only be seen on lines W-15-BP to the east, and 834-SAJ-22 to the south (Figure 3). The seismic reflection data shows that the Precambrian to Quaternary sedimentary rocks are about 6 km thick in the foredeep near the Mari gas fields and that they thicken stratigraphically to about 8 km along the axis of the Indus river (Jadoon et al, 1991). At the deformation front, the basement is deeper than 5 seconds two-way travel time. However, the basement configuration is interpreted extrapolating the layercake stratigraphy into the thrust belt from the foredeep region (bold lines in Figure 3). A stratigraphic column (Figure 4) based on the seismic

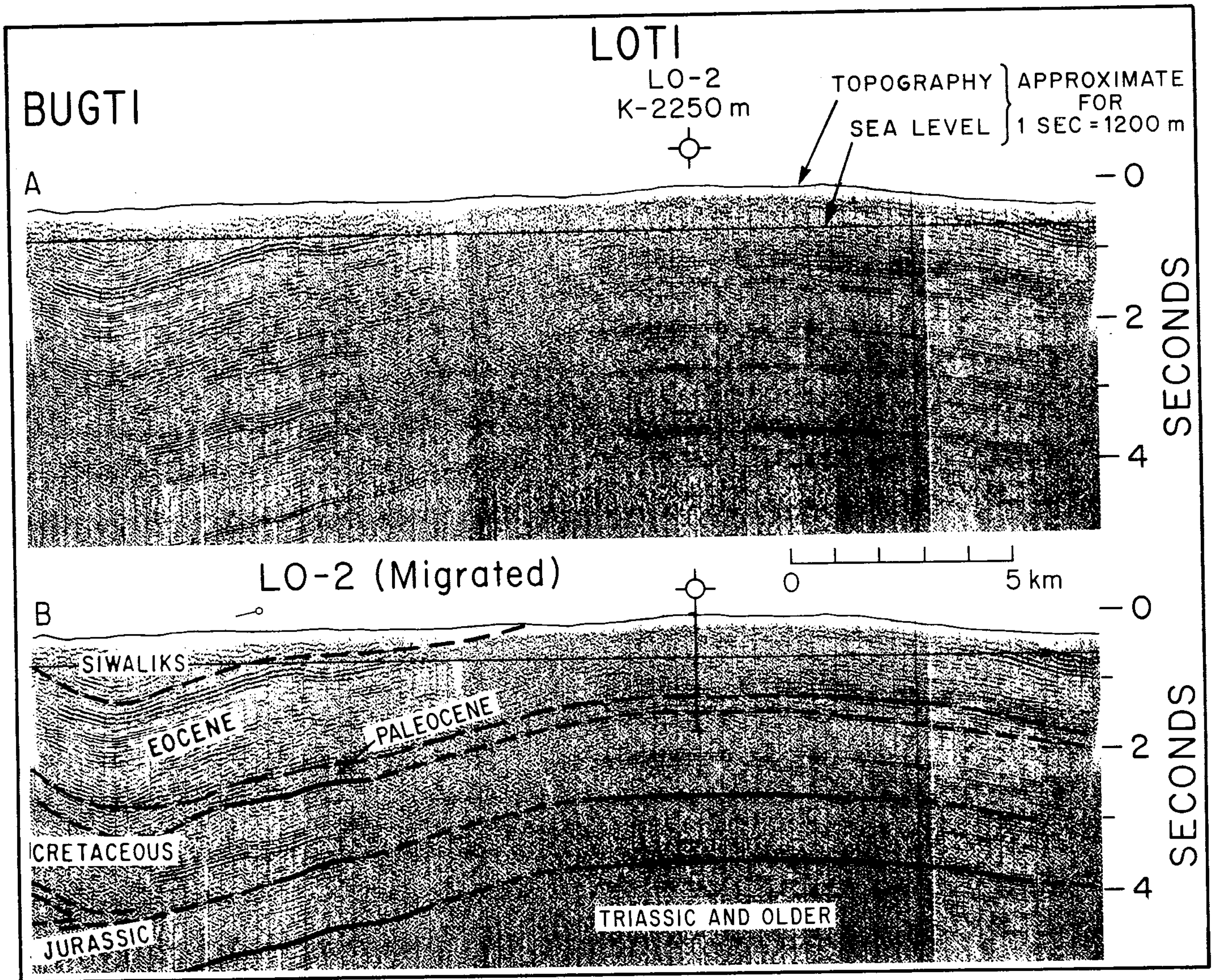


Figure 5— Uninterpreted (A) and interpreted (B) seismic reflection line (81-LO-2) over the Loti anticline along structural cross section A-A (locations in Figures 2 and 3) to show concentric frontal folding and deep decollement. Line 81-LO-2 is 24-fold, migrated, dynamite source, recorded and processed by OGDC (Oil and Gas Development Corporation, Pakistan).

reflection data shows a stratigraphic thickness of about 10 km at the deformation front of the Sulaiman fold belt. Extrapolating the top of basement dip (2°-2.5°) to the north suggests a tectonic thickness of about 20 km in the hinterland (Banks and Warburton, 1986; Jadoon, 1991). Planar stratigraphy and broad structures as far north as Bugti syncline suggest a planar basement surface. However, the presence of rift-related features is not precluded because a thin, extended crust is interpreted underneath the Sulaiman fold belt (Khurshid, 1991; Jadoon, 1991).

Seismic reflection data constrains the attitude on the top of the crystalline basement. Seismic reflection lines show that westward dipping basement in the eastern foredeep (Raza et al, 1989) is at a depth of about 8 km along the axis of the Indus River (Humayon et al, 1991; Jadoon et al, 1991). It is inferred at a depth of about 13 km underneath the Tadri anticline along cross section A-A′ in Figure 2. This data implies an attitude on top of the crystalline basement of N33°E, 3°NW. This interpretation is supported by additional 3-point problems using boreholes (Karampur, Bahawalpur East, and Marot-1) in which basement is drilled from the eastern Sulaiman foredeep (Kamran and Ranke, 1987; Humayon et al, 1991). This observation shows that the east-west trend of the folds at the southern Sulaiman lobe is oblique to the orientation of the underlying northwestward dipping basement.

Location of Major Decollement

Surface geology (Figure 2) suggests that progressively older rocks are exposed toward the hinterland in the

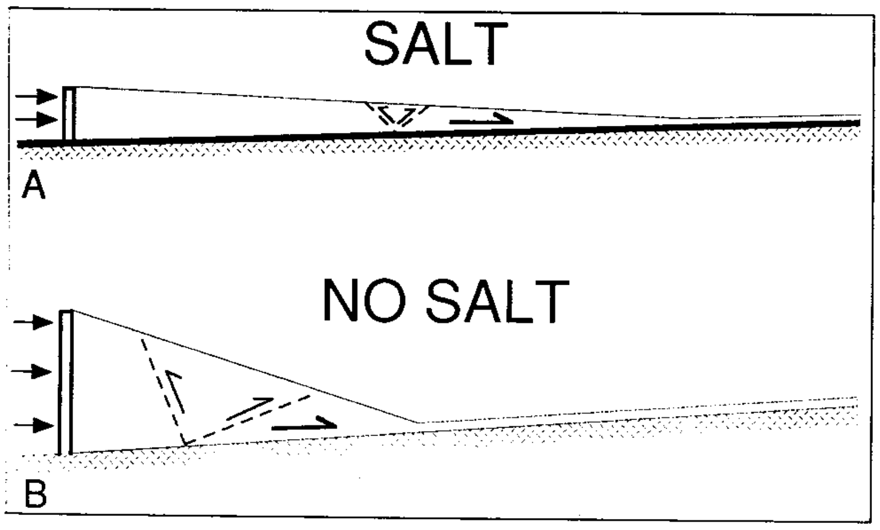


Figure 6— Critical wedge model for accretionary wedges and foreland fold-and-thrust belts (after Davis and Engelder, 1985). The model demonstratres the relationship between topography and cross sectional area of a foreland fold-and-thrust belt underlain by (A) salt or (B) no salt.

Sulaiman lobe. Stratigraphy based on seismic reflection and borehole data infers about a 10 km thick undeformed sequence of rocks at the Sulaiman mountain front (Figure 4). The stratigraphic column suggests potential decollement horizons in the Eocene, Cretaceous, and in Paleozoic rocks. At the beginning of this study, it seemed probable that a hinterland decollement surface in the Paleozoic section gradually steps up to the Cretaceous and Eocene in the foreland. However, seismic reflection profiles show that all the stratigraphic section is detached from the basement in the southernmost Sui and Loti anticlines (826-LO-14, 81-LO-2 in Figure 3). Thus, the major decollement remains in Paleozoic rocks at the interface between crystalline basement and the sedimentary package at the deformation front (Figure 5). This is consistent with the decollement interpreted at the western (Banks and Warburton, 1986) and eastern (Humayon et al, 1991) Sulaiman Range.

Nature of Major Decollement

The gross geometry of the overthrust wedge, including gentle topography ($<1^{\circ}$) and broad width (>300 km), is compatible with that proposed by Davis and Engelder (1985) for thrust belts developed over a weak decollement (Figure 6). A thin-skinned style of deformation (Sarwar and DeJong, 1979) is supported by the seismic reflection data from the Sulaiman fold belt (Humayon et al, 1991; Jadoon, 1991). However, there is evidence 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; Pennock et al, 1989) may not be present underneath the Sulaiman fold belt. This evidence includes: (a) absence of salt related diapiric structures (e.g., tight anticlines, broad synclines and disharmonic folding); (b) the closest observation of the Eocambrian evaporites in wells and seismic lines is about 200 km east of the deformation front (Humayon et al, 1991); and (c) the seismic reflection signature of the ductile zone (salt pillows) associated with the evaporites drilled in wells dies out westward before reaching the Sulaiman front. Clear evidence for evaporites has not been observed on the seismic lines from the southern Sulaiman foredeep (Jadoon et al, 1991). Alternately, Davis and Engelder (1985) suggest that carbonates at temperature more than 200°C behave similar to halite at shallow depth. Unlike the 2 to 4 km depths in the frontal Salt Range/Potwar Plateau, seismic reflection data from the Sulaiman fold belt show that the decollement is about 10 km deep at the base of the wedge at the deformation front (Figures 4 and 5). Khan and Raza (1986) and Raza et al (1989) calculate an average geothermal gradient of about 30°C/km in boreholes from the Sulaiman foreland and adjacent foredeep (Figure 7). Davis and Engelder (1985) show that with a geothermal gradient such as this, limestones at depths of about 10-12 km are as weak as evaporites. This alternate hypothesis is supported by ductility of fine carbonates in the core zones of small folds

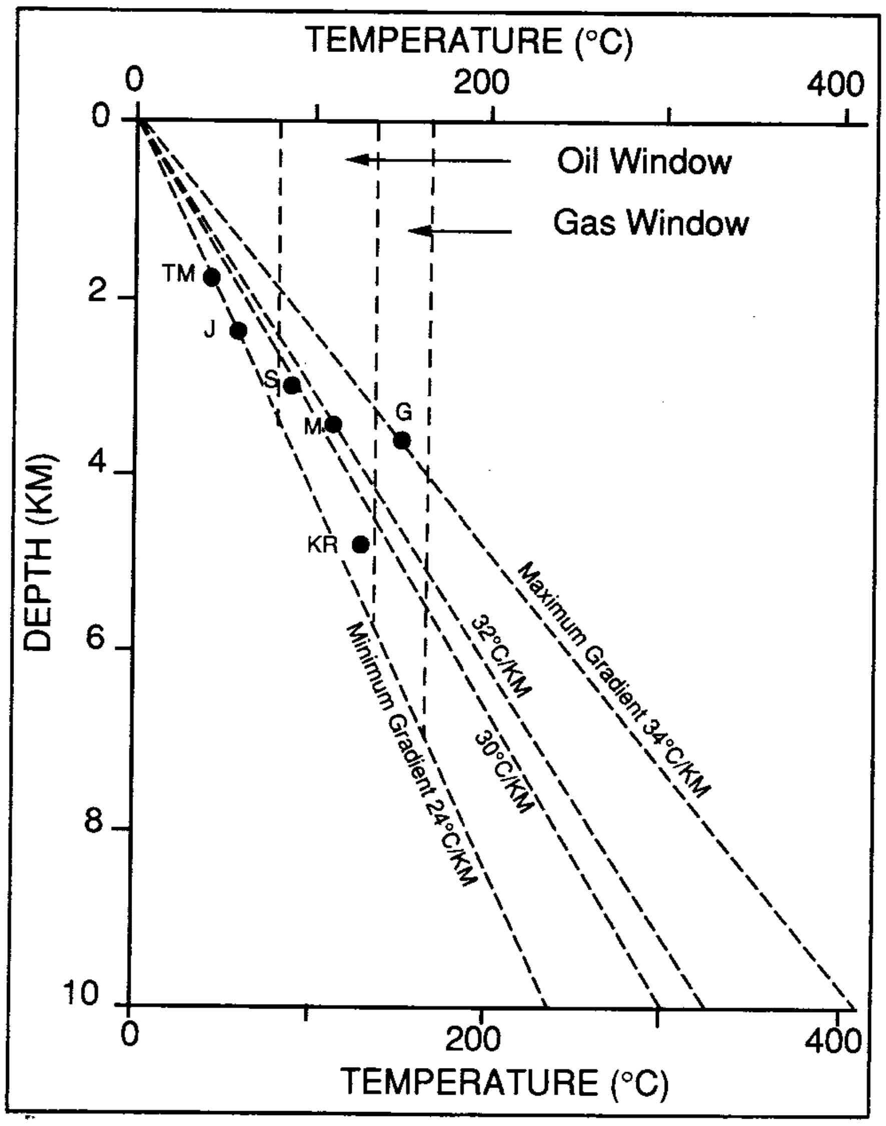


Figure 7— Geothermal gradient from the southern Sulaiman fold belt (data is from Khan and Raza, 1986; Raza et al, 1989). Average geothermal gradient of about 29°C/km suggests that at depth of 8-10 km fine carbonates may be as weak as salt (Davis and Engelder, 1985). Dots show the well data. Well abbreviations are the same as given in Figure 1.

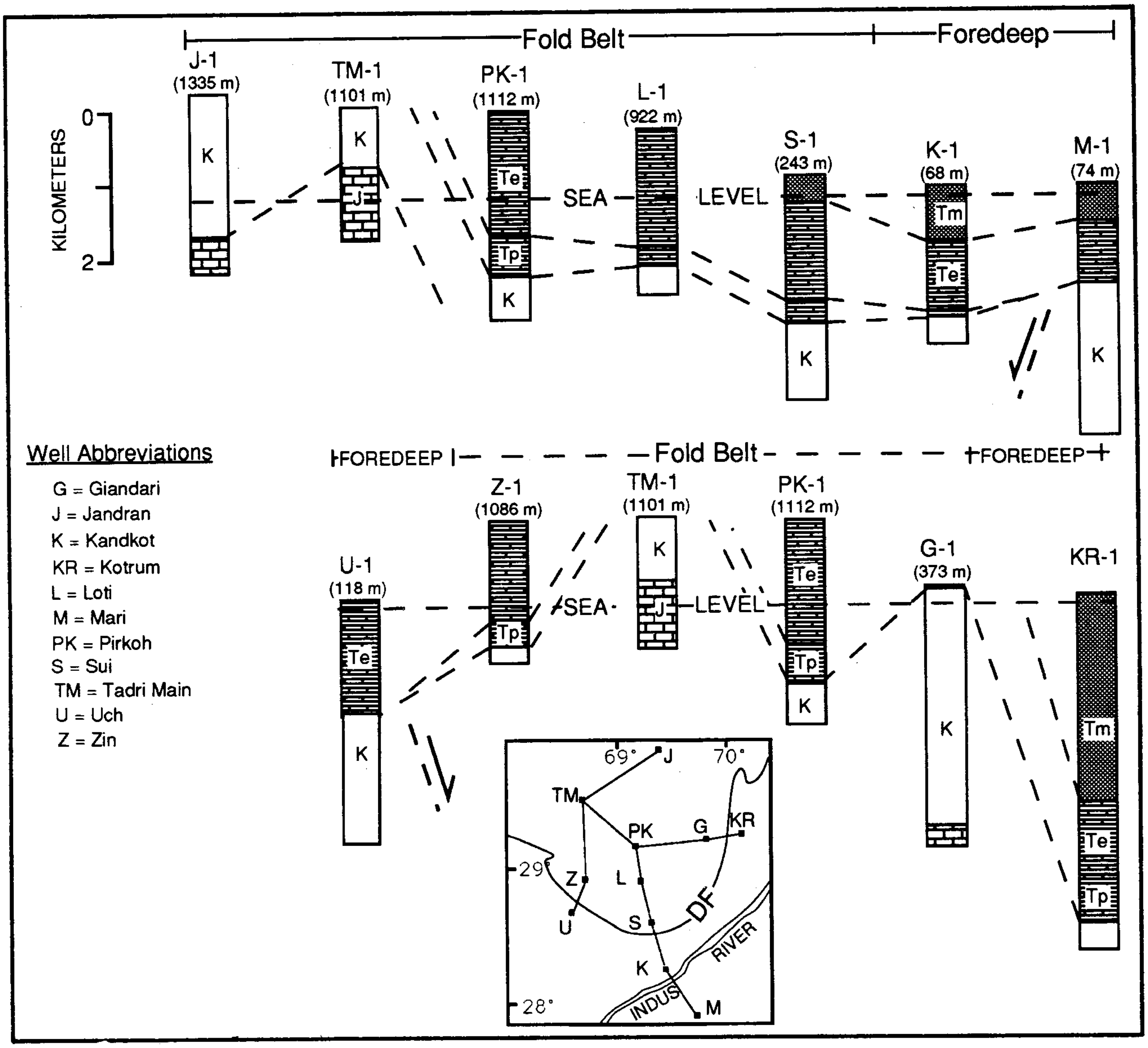


Figure 8— Well data from the Sulaiman foreland and adjacent foredeep. Notice tectonic uplift of rocks in the fold belt, coherent stratigraphy, and stratigraphic thickness variation of the platform and the Molasse strata. See Figure 4 for the symbols of stratigraphic units. DF = Deformation front.

in the hinterland of the Sulaiman fold belt, where stratigraphically deeper Triassic limestones and shales are exposed at the surface. The signature of ductile deformation is also seen on the seismic lines in the core zones of frontal anticlines (Sui and Loti). This suggests that the effective zone of weak decoupling in the Sulaiman may be in fine-grained carbonate rocks along brittle/ductile transition at depths of 10-15 km (Lillie and Davis, 1990; Jadoon, 1991). The stratigraphic section suggests abundant pelitic rocks at this level which also might provide a weak zone through dewatering and/or recrystallization. Thus at this depth fine-grained sedimentary rocks may provide a weak detachment similar to the evaporites at depths of 1 to 3 km beneath the Salt Range/Potwar Plateau region.

FORELAND STRUCTURES AND STYLE OF DEFORMATION

Seismic reflection lines (Figure 3) and borehole data (Figure 8) provide sufficient subsurface data to constrain the structures in the foreland of the Sulaiman lobe. Three structural cross sections A-A′, B-B′, and C-C′ (Figures 2

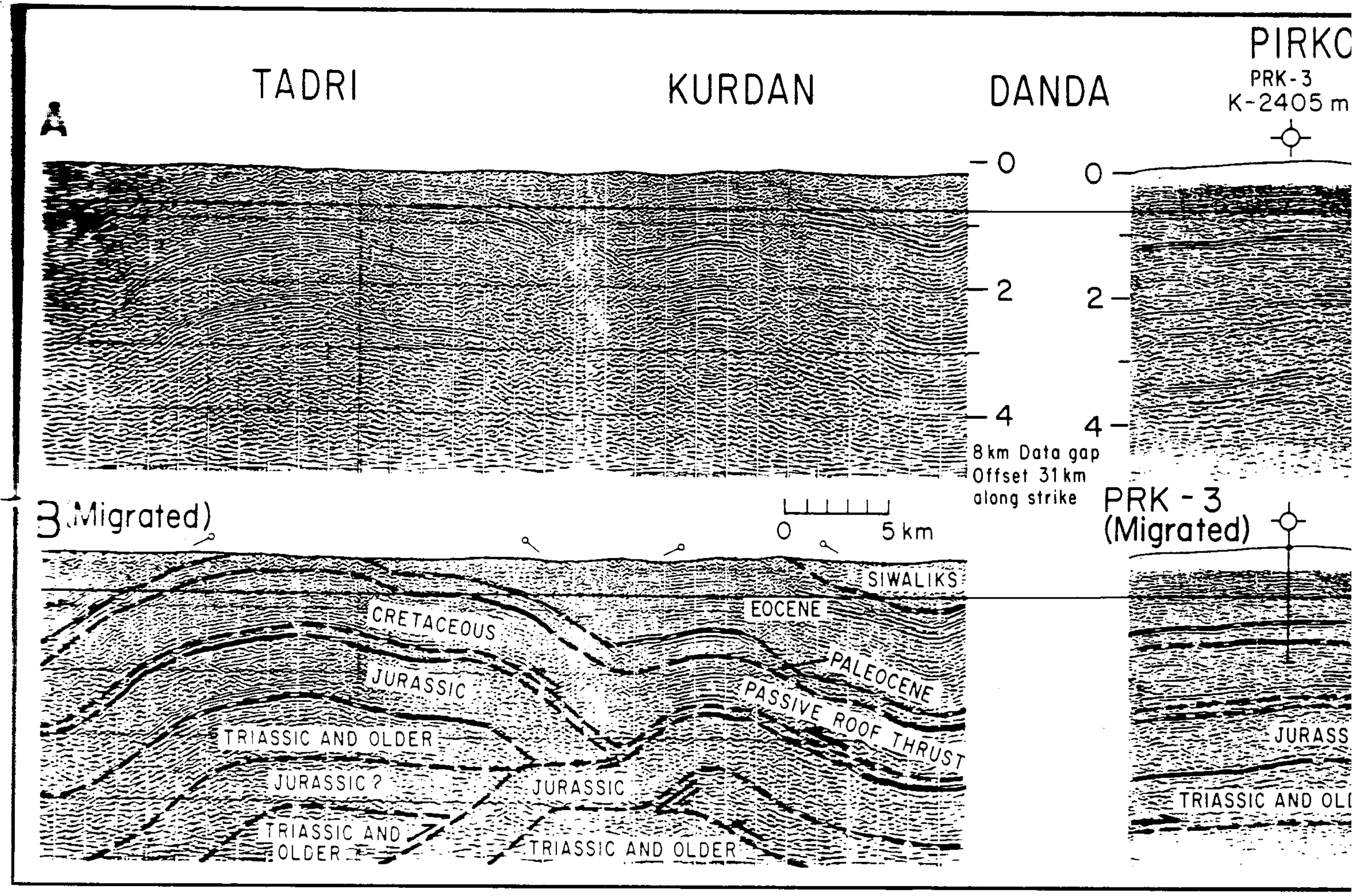
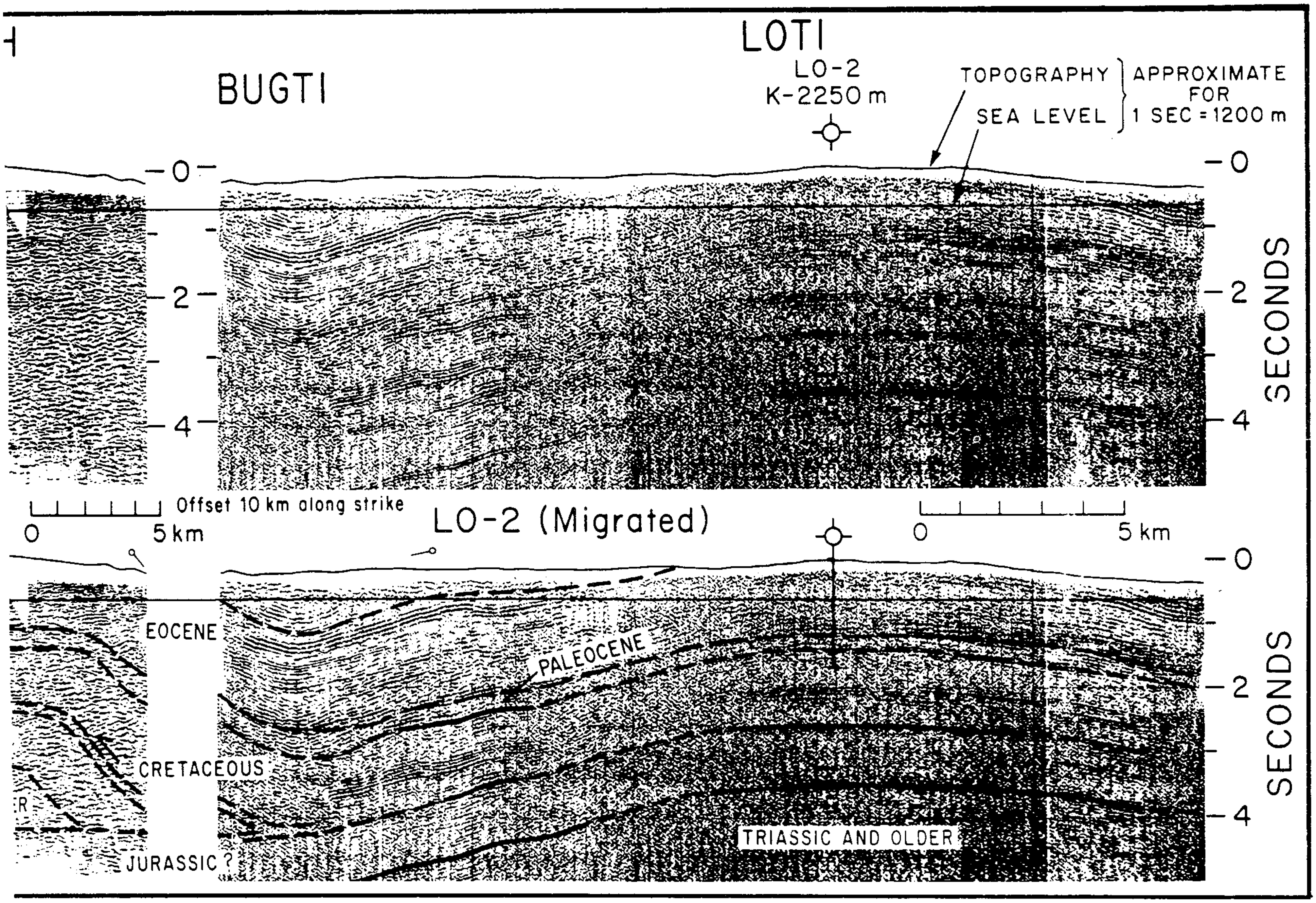


Figure 9— Composite uninterpreted (A) and interpreted (B) seismic line from southern and central Sulaiman fold belt. Basement in in Cretaceous shales and a floor thrust in Paleozoic section at the base of the wedge. Tip of the decollement extends below the broad I of material at the detachment horizon. Line 81-LO-2 is migrated, 24-fold, dynamite source, recorded and processed in 1981 by OGDC Geophysical Service Inc. Azaiba, Oman. Line W-16-EU is migrated 10-40 Hz, Vibroseis source, recorded and processed by Western G control. Horizontal scale for the lines differ.



ach case is below 5 seconds 2-way travel time. The interpretation shows a passive-roof duplex structure bounded by a roof thrust
ti and Sui anticlines (Figure 10). These structures are interpreted as concentric, buckle folds formed primarily due to ductility
ine 816-PRK-3 is migrated 24-fold, dynamite source, recorded by OGDC in December 1980 to January 1981 and processed by
physical Company in 1975. Lines are tied along strike. Data gap between 816-PRK-3 and W-16-EU is bridged by surface geology

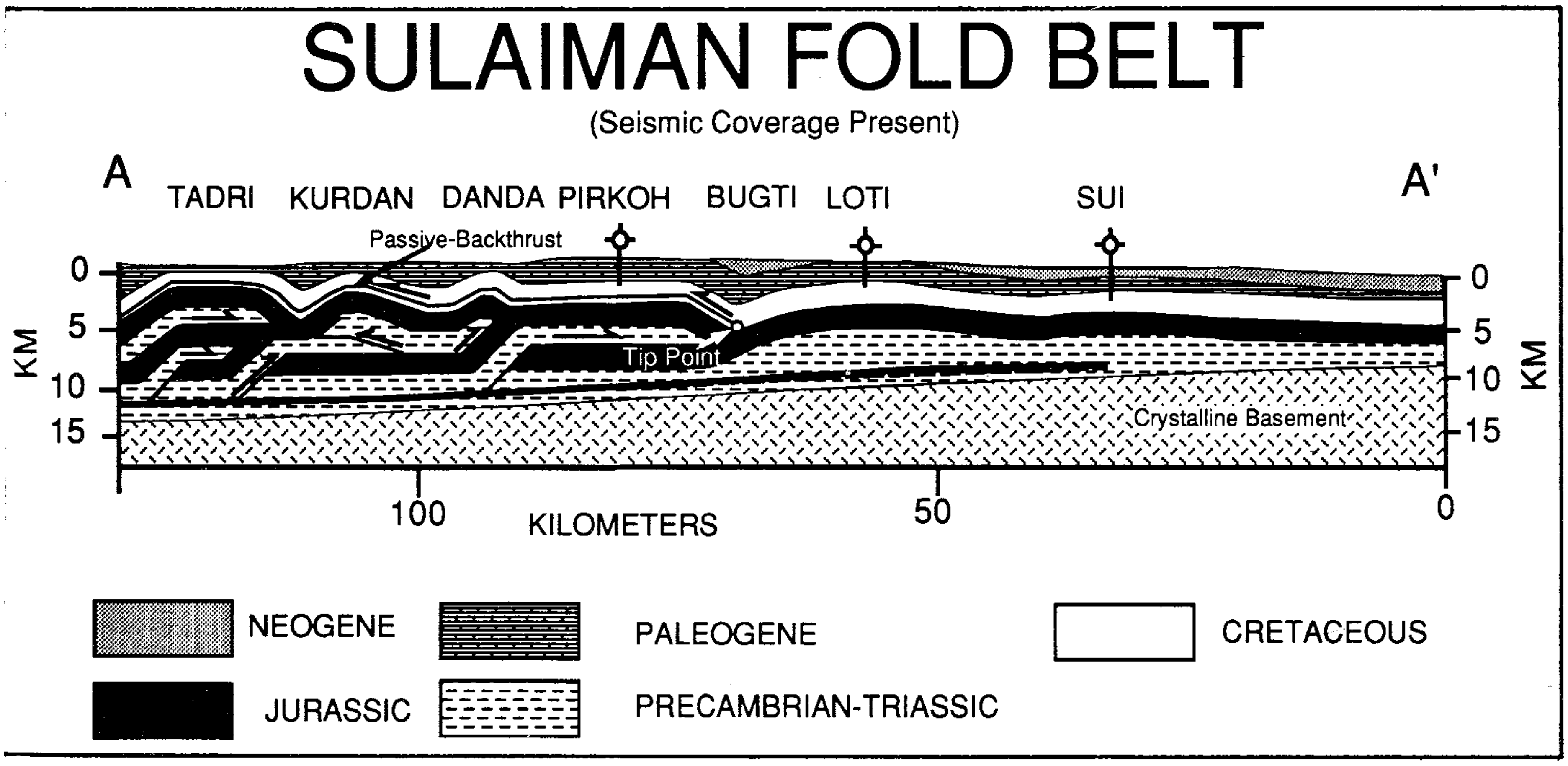


Figure 10— Actual and restored, geological cross section (A-A′) of the southern Sulaiman foreland (from Jadoon et al, 1991). Notice duplex style of deformation with folds at the surface reflecting the shape of the duplex horses below. The roof-sequence is not disrupted by faults along the cross section and is believed to extend continually for about 150 km. Eventually it is exposed in the Loralai valley where shortening in the roof-sequence is removed primarily by erosion. Notice structural evolution from broad folds at the front to duplex structures. Text identifying the individual folds at the surface are from the individual mountains.

and 3) are drawn to understand the structures of the Sulaiman mountain front. Structural cross section A-A′ is modified from Jadoon et al (1991) and is shown to elaborate the foreland structures. Two other cross sections (B-B′ and C-C′) from the southern Sulaiman foreland are added to the former to understand the evolving foreland structures.

A-A′: Sui, Loti, Pirkoh, and Tadri (Southern Sulaiman)

One of the most important observations resulting from the study of the composite seismic line (bold lines in Figures 3 and 9) 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 basement is about 10 km at the deformation front. The basement descends northwards with a gentle inclination of about 2^o-2.5^o and is extrapolated to attain a depth of about 13 km below Tadri in the central zone.

The Sulaiman fold belt exposes Neogene molasse at the deformation front; a maximum of 2400 m thickness is encountered in the southern Sulaiman foredeep (Jadoon et al, 1991). Banks and Warburton (1986) reported about 7000 m of molasse sediments from the Sibi trough within the frontal deformation zone in the western Sulaiman fold belt. Boreholes and the composite seismic reflection lines show that the molasse strata reach maximum thickness in the foredeep and thin toward both the foreland and hinterland (Figure 8). Unlike the molasse, the underlying platform strata in the fold belt thicken toward the hinterland. These strata are structurally uplifted towards the hinterland (Figure 8). In the foreland (Figure 2), progressively older rocks are exposed in the core zones of doubly plunging anticlines (e.g., the Sui anticline exposes molasse at the surface; the Loti, Pirkoh, Danda have Eocene exposed strata while farther north, the Kurdan and Tadri anticlines are cored by Paleocene and Cretaceous strata). These exposed rocks show a coherent stratigraphy as far north as the Tadri syncline, and are not disrupted by significant thrust faults (Figure 3). Boreholes in the frontal and central Sulaiman Range (Tadri and Jandran) penetrated a normal stratigraphic sequence as deep as Jurassic (Figure 8). Figure 9 shows two major structural steps; one at Pirkoh and the other at Tadri. Along these steps undisrupted strata above Jurassic is uplifted several kilometers higher than their regional stratigraphic levels. This implies that, towards the hinterland, rocks are structurally uplifted from their regional stratigraphic level by duplication along blind thrusts below the Cretaceous.

The surface geology and seismic expression of the frontal part of the Sulaiman fold belt is of two broad (half wavelength about 25 km), small amplitude (1-2 km) anticlines (Sui and Loti) at the tip of the decollement (Figures 9 and 10). Limb dips do not exceed 4^o on Sui and

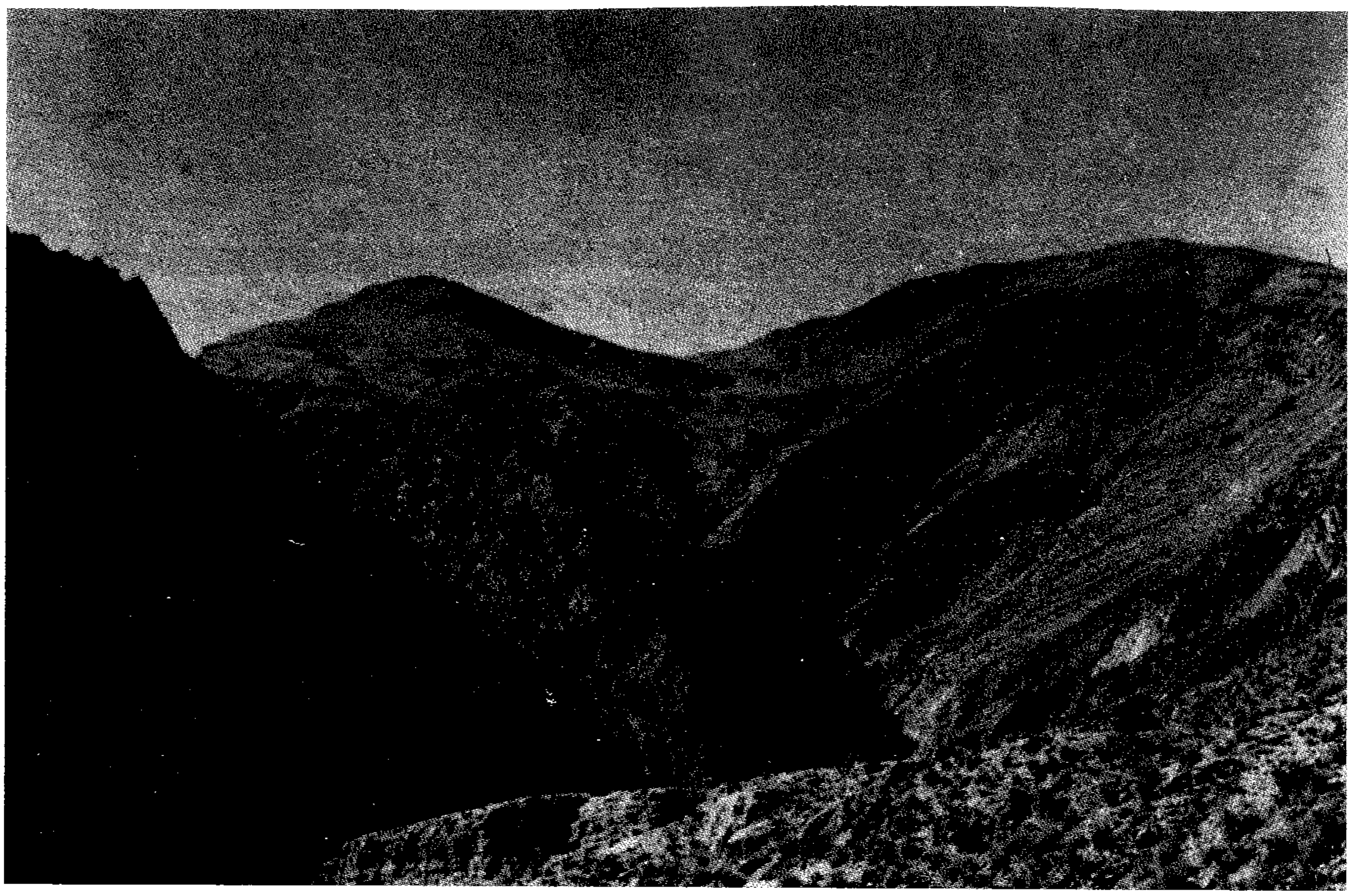


Figure 11— Hinterland dipping Mehrab Tangi (left) and Warsak Deng (right) duplexes exposed in the foreland of the western Sulaiman Range. The massive competent strata in the duplex horse is Dunghan (Paleocene) limestone. The Dunghan limestone in the hinterland (Banks and Warburton, 1986) and the central Sulaiman lobe (A-A′ in Figure 10) is interpreted as a part of the roof sequence.

15° on Loti. The Sui and Loti are concentric folds that maintain their layer parallel thickness and wavelength on the seismic lines, unlike typical concentric folds (Dahlstrom, 1969), where anticlines become tighter and synclines become broader at depth. Concentric folding is seen as deep as 5 seconds of 2-way travel time data on the seismic lines across the Sui and Loti structures (Figure 5). Low dips also infer that at depth below Jurassic, the space in the cores of these anticlines is occupied by the ductile flow of fine carbonates and pelitic strata at the decollement along brittle/ductile transition.

The surface expression of Pirkoh anticline (third fold from the deformation front) is a foreland-dipping monocline with dips between 35°-75°. Banks and Warburton (1986) suggested that the surface expression of duplex structures may be a foreland-dipping monocline. The Pirkoh anticline has almost flat strata (nodular Eocene limestone) along its hinge area for about 15 km. The northern limb, over a buried ramp, is concealed below an anticline, and gives the entire structure a box-like form. Seismic reflection data (Figure 9) show a zone of 4 km uplifted Cretaceous and younger strata under the hinge zone of the Pirkoh fold. This zone consists logically of a duplex horse of thick massive Jurassic (Chiltan) limestone and older rocks. This interpretation suggests that the Pirkoh structure is a duplex related, fault-bend fold. The near horizontal dips along the hinge zone of Pirkoh anticline are due to the juxtaposition of the hanging-wall flat of the Pirkoh duplex horse over the footwall flat. The steep foreland dipping limb of a monocline, like the Pirkoh structure, may represent a culmination wall over the foreland propagating duplexes. Structural relief of about 4 km below the Pirkoh structure increases to about 8 km below Tadri (Figure 9). Stratigraphy is not disrupted by major faults above the Jurassic. This structural uplift is interpreted to be due to a thin-skinned, passive-roof duplex style of deformation (Figures 9 and 10). The duplex sequence consists of Jurassic and older rocks, bounded between a floor thrust at the base of the wedge and a roof thrust (Dahlstrom, 1970) or upper detachment (Jones, 1982) in Cretaceous shales. The roof sequence is interpreted to remain passive during the foreland propagation of the underlying duplex horses and is regarded as a passive-roof sequence with a decollement in thick Cretaceous (Sembar) shales.

The composite seismic reflection profile and balanced cross section show a continuous passive-roof sequence in the foreland that is discussed with more detail by Jadoon (1991). The structures in it are fault-related folds of variable tightness, symmetry, and extent as a result of variable ramp spacing and relative displacement in the foreland (Jadoon et al, 1991). These broad folds at the surface reflect the shape of deep structures associated with faults in the duplex sequence which never break the surface in this zone of blind faults. However, the duplex structures, are exposed (Figure 11) in the western Sulaiman fold belt (Banks and Warburton, 1986).

The duplex style of deformation is consistent with that reported from northern Kirthar Range and western (Banks and Warburton, 1986) and eastern (Humayon et al, 1991) Sulaiman Range. However, it is contrary to the imbricate style of deformation proposed by Bannert et al (1989). Jadoon (1991) based on surface geology and seismic reflection data disagrees imbricate style of deformation in the Sulaiman lobe because of: (1) absence of major thrust faults duplicating deeper level of stratigraphic section; and (2) only minor offset (1-2 km) of the Cretaceous and younger strata along the emergent reverse faults in the central part of the Sulaiman fold-and-thrust belt.

The interpreted chronology of structures along the transect A-A′ is: (1) growth of broad, concentric fault tip folds in the foreland: (2) development of a duplex horse bounded between basal decollement and a passive-backthrust; (3) propagation of the duplex as critical taper is achieved; and (4) tear and extensional normal faults (flexural faults) within the overthickened wedge. The chronological order in this section suggesting folding prior to faulting, is similar to the Canadian Rockies (Dahlstrom, 1970) and the experimental modelling (Liu and Dixon, 1990).

Jadoon et al (1991) show that the deformed section (A-A′, Figure 10) is about 129 km long and restores to an undeformed length of about 205 km which gives 76 km shortening with duplex sequence. This shortening is very unevenly divided between the duplexes (120 km shortening), and broad Sui and Loti anticlines (<1 km shortening). The shortening in the roof sequence is suggested to be taken up by a passive-backthrust in the hinterland (Jadoon, 1991).

B-B′: Uch, Zin, Pirkoh, Danda (Southwest Sulaiman)

The cross section B-B′ (Figure 2) extends 86 km into the foreland. The frontal Uch anticline along this cross section is relatively a small doubly plunging anticline. This frontal fold located farther to the south in the foredeep, has an en-echelon relationship with the frontal Sui fold in A-A′ (Figures 2 and 10). Seismic reflection data show that the Uch fold unlike broad Sui anticline (Figure 10) is a small, half wavelength (about 3.5 km) and amplitude (1 km), incipient fault-propagation fold (Figure 12) at the tip of the decollement. The decollement is deep in the Paleozoic section consistent with the structural cross section A-A′ (Figures 9 and 10). The ramp from the tip of the decollement does not offset the competent Jurassic limestone (Figure 12b). The resultant narrow Uch fold at the tip of the decollement is presently growing as an incipient fault- propagation fold. The active deformation is evidenced by the growth strata (Figures 12b and c) and unconformity between Holocene and recent deposits (Tainish et al, 1959). Similar folds from the eastern Sulaiman front (Ahmad and Khan, 1990) are less than 50,000 year.

Towards the hinterland, seismic reflection data was not available across strike of the broad Zin anticline (Figures 2 and 3). However, along strike, depth to the top of the major stratigraphic units is constrained by the seismic data (Figures 2 and 3). The extrapolated structural cross section (Figure 13) suggests that the Zin anticline, north of the frontal Uch fault-propagation fold, is a broad (half wavelength about 25 km), concentric anticline with excess strata in its core similar to the Loti anticline along its axis (Figures 2 and 10). Farther north is the Nighari duplex appears (Figure 13). It is a westward extension of the the duplex structures in A-A′ (Figures 2 and 10). However, the Nighari duplex in B-B′ (Figure 13) has a smaller (~9 km) displacement than 20.5 km (Jadoon et al, 1991) along cross section A-A′ (Figure 10). This suggests limited lateral extent of the individual duplex structures that are expressed by doubly-plunging anticlines at the surface (Figure 2). The duplexes may die out at depth along lateral ramps. Thus, maximum displacement along the duplex could logically be across the centre of the axis of the fault-related doubly-plunging anticline. The relatively tight folds north of the Bugti syncline along this cross section may be interpreted as detachment folds (Wallace and Hanks, 1990) in the passive-roof sequence.

Interpreted chronology of structures from foreland towards hinterland along this cross section is: (1) a small wavelength (~3.5 km) fault-propagation Uch fold; (2) development of a broad concentric fold (Zin/Loti); (3) development and propagation of duplex as critical taper is achieved along with some detachment folds in the roof-sequences.

The 86 km long deformed cross section B-B′ in Figure 12 could be restored to an original length of about 108 km. The shortening is partitioned between the duplex (20 km) and the frontal folds (<2 km).

C-C′: Giandari fold (Southeast Sulaiman)

The cross section C-C′ (Figures 2 and 14) is across the Giandari anticline at the deformation front. This anticline with half- wavelength of about 15 km has surface expression of a monocline with moderate dips (~40°) towards the foredeep. This is in contrast to the gentle, concentric folding at the tip of the decollement in A-A′ (Figure 10). Notice that cross section C-C′ is oblique to plate convergence vector (Figure 2). However, strike of the surface structures (NE-SW) is similar to the crystalline basement (Figure 2).

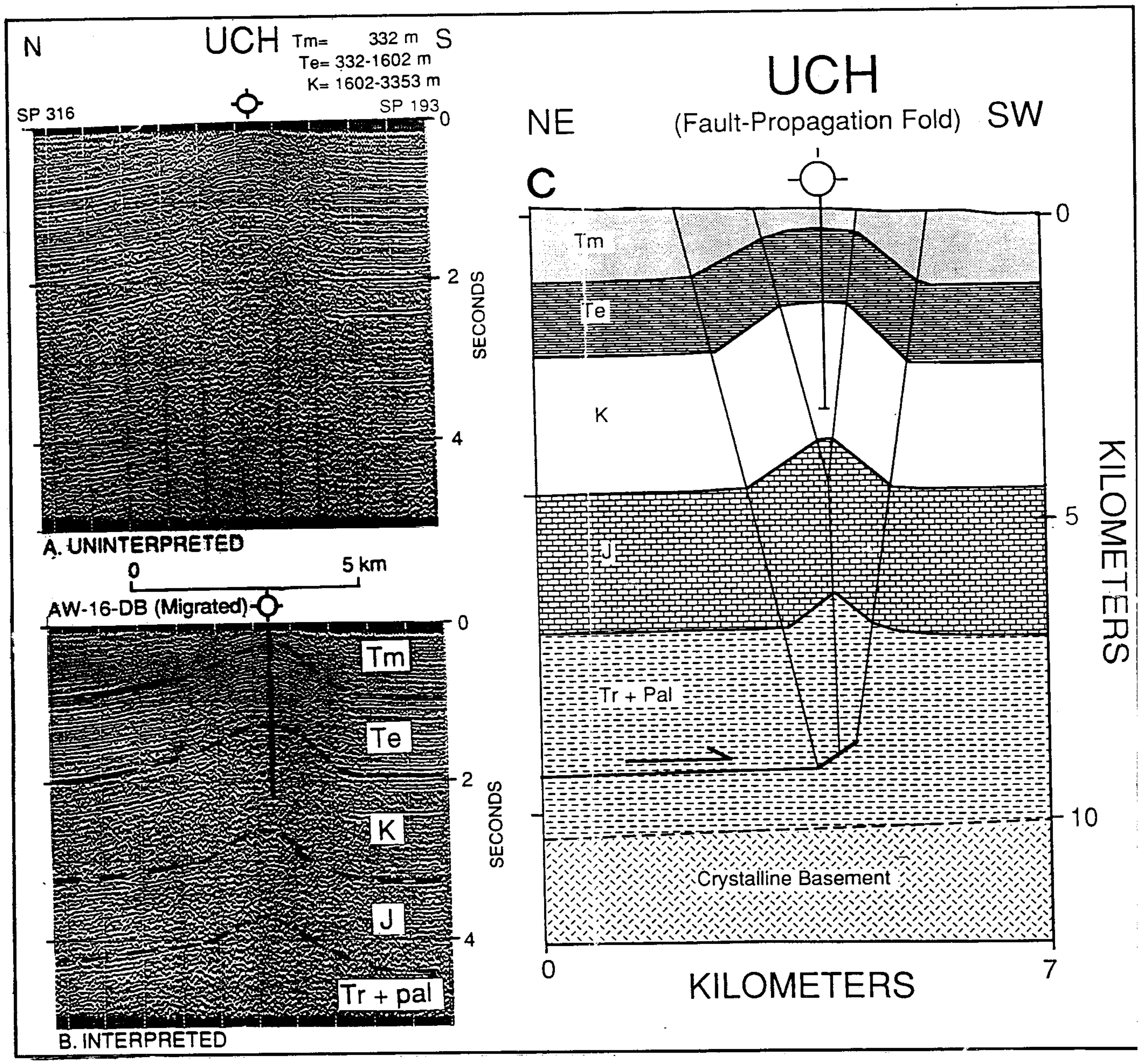


Figure 12— Uninterpreted (A) and interpreted (B) seismic reflection line AW-16-DB between VP193-316 over the Uch frontal anticline (Figures 2, and 3). C is a depth section of A and B that interprets the Uch fold as a fault-propagation fold. Notice the decollement in the Paleozoic section consistent with A-A′ (Figures 9 and 10). Compare the narrow wavelength of the Uch anticline with the broad folds (Sui and Loti) in Figure 10. Patterns are the same as in Figure 10. Line AW-16-DB is 8-32 Hz, migrated vibroseis source, recorded and processed by Western Geophysical Company of America in 1973.

Seismic data is not available across this fold. The crystalline basement is extrapolated as it descends northwestwards from a depth of about 8 km along the axis of the Indus river (Figure 2). Two wells, Kotrum in the foredeep and the Giandari in the fold belt along the cross section C-C′(Figure 3) provide subsurface constrains. The Kotrum well in the foredeep drilled to a depth of 4798 metres (Figure 8). This well drilled to the Cretaceous, penetrated through 2780 m of Neogene molasse strata (Kamran and Ranke, 1987). In the adjacent fold belt Paleogene rocks are exposed in the hinge zone of the Giandari anticline (Figure 2). Giandari well drilled along the axis of the Giandari anticline penetrated through a normal section to a depth of 3659 metres. Top Pab (Cretaceous) sandstone in Giandari well in the fold belt was hit at a depth of 30m (Figure 8). The same sandstone in the

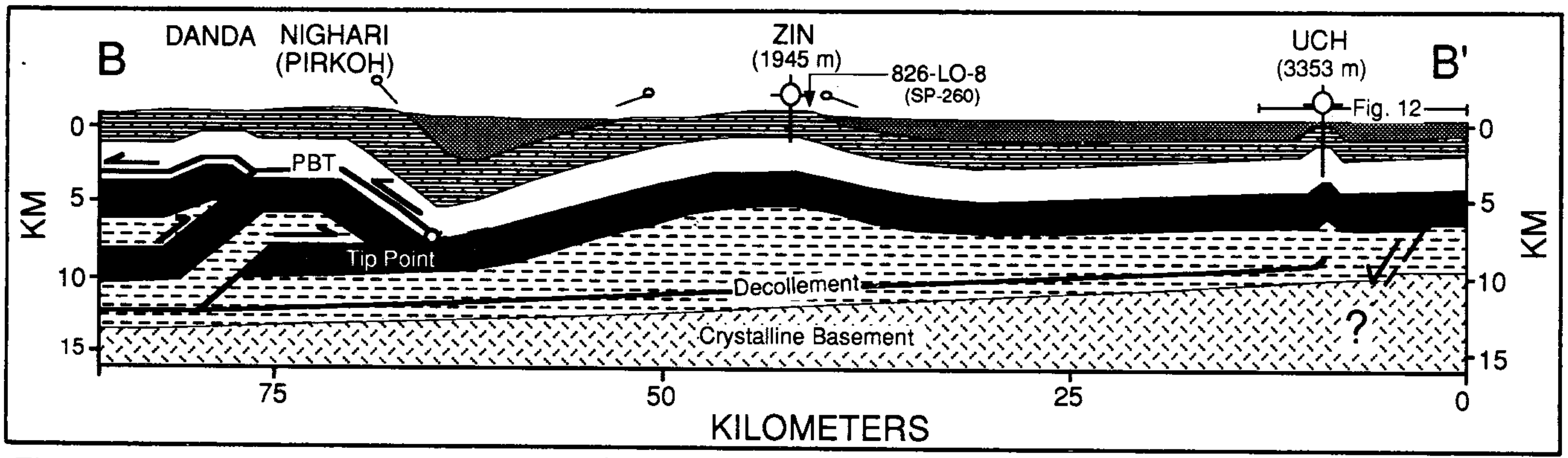


Figure 13— The structural cross section (B-B′) of the southwestern Sulaiman foreland. See Figures 2 and 3 for location. Notice the fault-propagation fold at the tip of the decollement and a broad concentric fold to duplex structures. Patterns are the same as in Figure 10. PBT = Passive-backthrust.

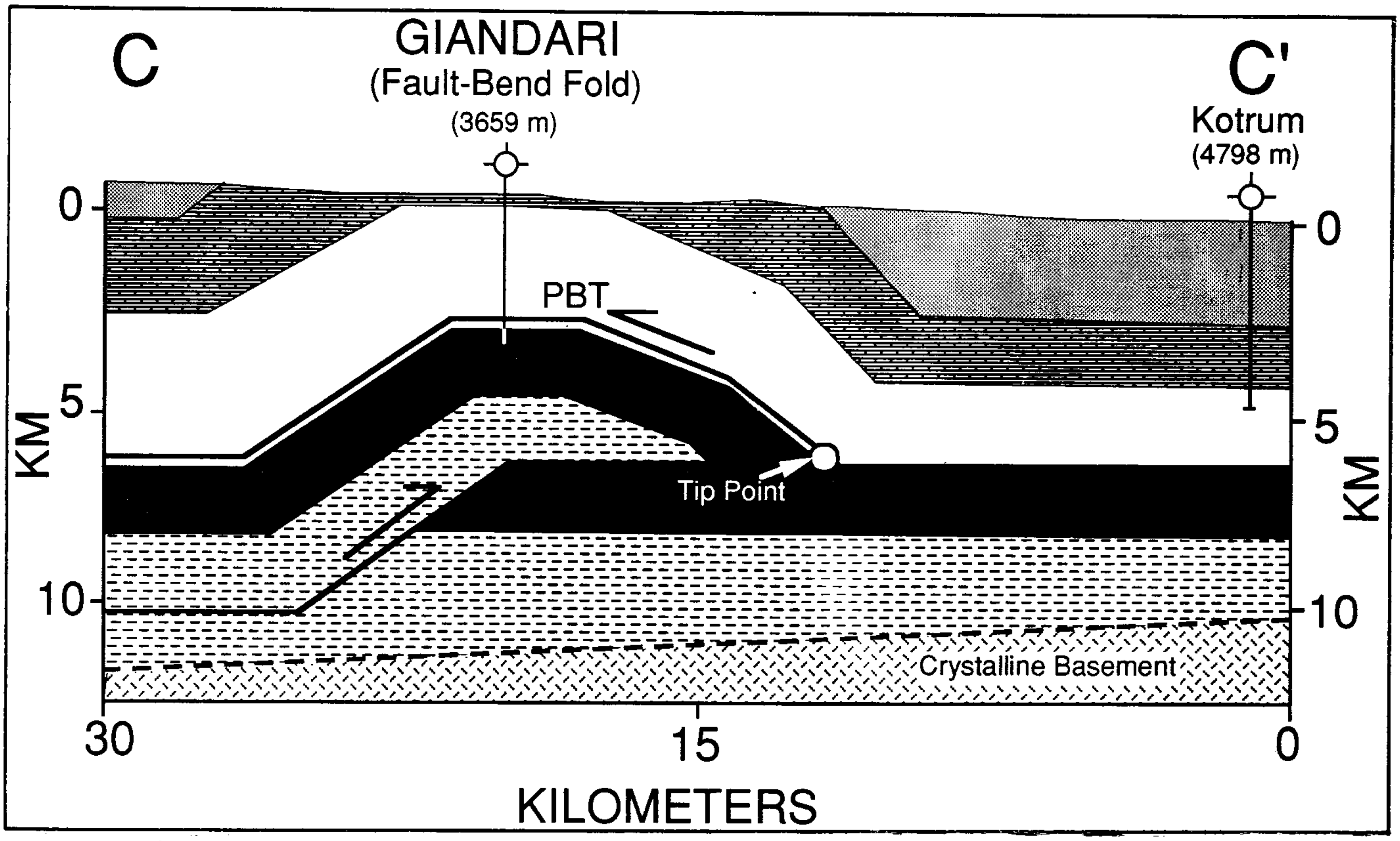


Figure 14— The structural cross section (C-C′) of the southeastern Sulaiman foreland. See Figures 2 and 3 for location. This interpretation suggests the Giandari anticline, a duplex related fault-bend fold at the deformation front. Patterns are the same as in Figure 10. PBT = Passive-backthrust.

Kotrum well in the adjacent foredeep was penetrated at a depth of 4425 m. This observation shows an uplift of more than 4 km of Cretaceous and younger rocks. In the absence of a fault in the Cretaceous and younger rocks, this structural relief is interpreted with duplication of Jurassic and older strata, along a blind fault (Figure 14). This structural duplication is consistent with that observed in the former section and in the eastern (Humayon et al, 1991) Sulaiman Range. Thus, the Giandari anticline is interpreted to be a fault-bend fold at the deformation front (Figure 14). As in A-A′ (Figure 10) and B-B′ (Figure 13), the style of deformation is interpreted to be a passive-roof duplex. Notice that about 1700 m of Sembar (Cretaceous) shale has been drilled in the Giandari well. The upper detachment (passive-backthrust) is proposed to be in this strata of dominantly pelitic rocks.

Shortening between cutoff points along the Giandari duplex horse is about 8 km compared to about 20.5 km with the 1st duplex horse along cross section A-A′ (Figure 10) and 9 km along B-B′ (Figure 13).

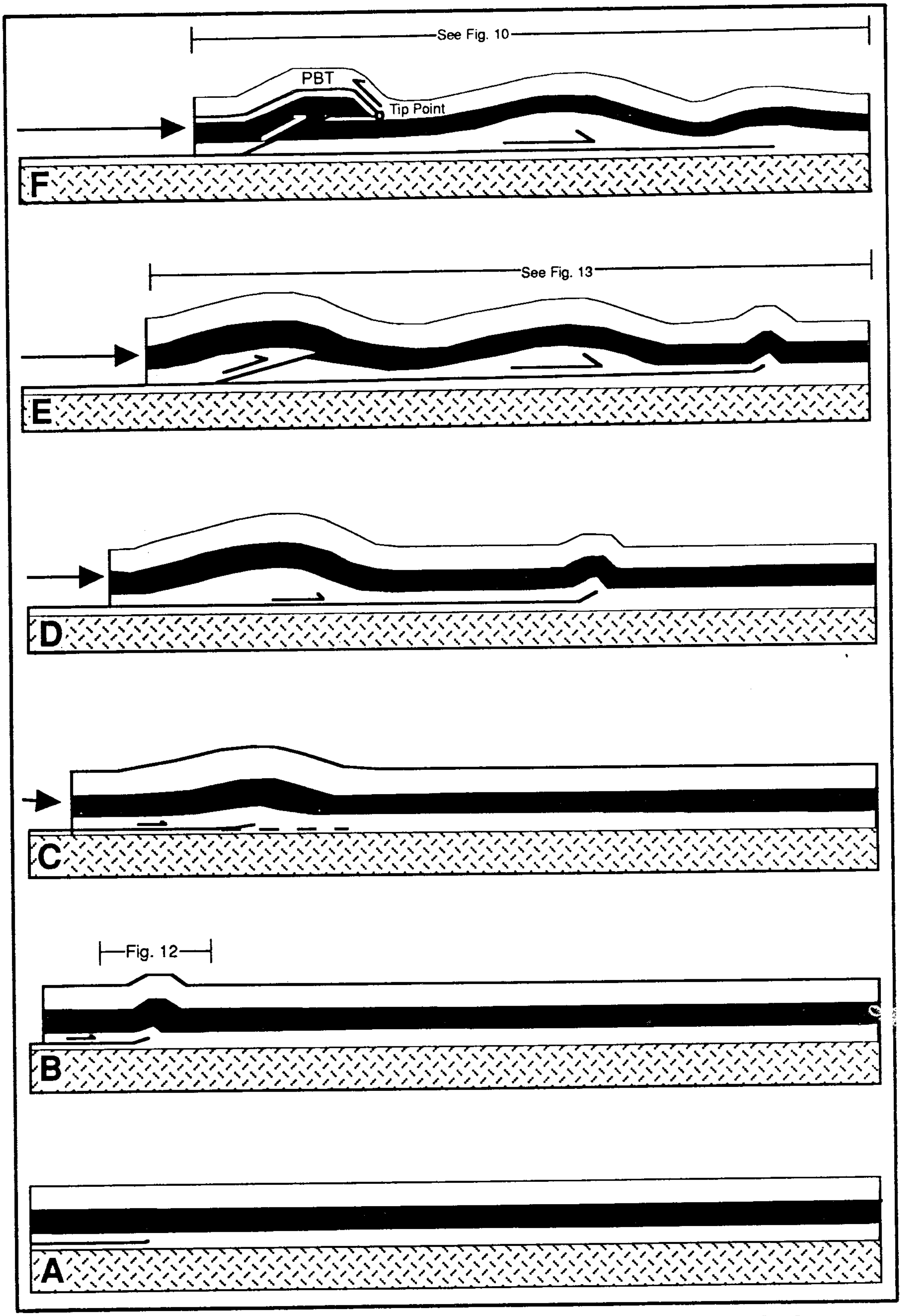


Figure 15— Schematic cross sections A-F to demonstrate progressive evolution of foreland structures from a fault-propagation fold at the tip of the decollement to a broad concentric fold and duplex structures. See text for discussion. PBT = Passive-backthrust.

DISCUSSION

Initiation of foreland structures

Surface and subsurface observations (Figures 9, 10, 12 and 13) from the foreland of the Sulaiman allow a detailed analysis of southward propagation of the active Sulaiman fold belt. The Sui and Loti anticlines are broad, concentric folds which are south of a duplex, the Pirkoh. I interpret these concentric folds as buckle folds that develop above the ductile material of the detachment horizon. Liu and Dixon (1990) have experimentally modelled similar broad folds preceding faulting. Cooper and Trayner (1986) discuss the propagation of thrust sheets in terms of a ductile bead of deformation ahead of the propagating thrust tip. The southern folds of the Sulaiman belt appear to be a place where this process is now occurring. The small half-wavelength (about 3.5 km) Uch frontal fold in the south-western Sulaiman (Figures 12 and 13) is actively forming in front of the broad (half-wavelength about 25 km) concentric Zin (= Loti) fold over the tip of the basal decollement, as an incipient fault-propagation fold. I suggest that the broader folds (Figure 10), Sui and Loti/Zin, were initiated by such a structural perturbation which then developed into a long wavelength buckle fold as ductile material flowed from under the synclines into the cores of the anticlines. This shows that broad folding is initiated by a fault-propagation fold due to ductility of material at the decollement horizon. Thus, the Sui and Loti concentric folds were initiated as fault tip line folds. It seems apparent that the future evolution of these structures will involve the propagation of a ramp through the core/forelimb of the folds to develop the flat and ramp structures currently seen farther to the north (Figures 10 and 13).

Mitra (1990) described translation of a fault-propagation fold to a fault-bend fold with examples from the Appalachians and the Cordilleran, Absaroka thrust sheet. The geometry of the foreland structure in the Sulaiman lobe suggests the translation of a fault-propagation fold to a concentric buckle fold and then to a duplex-related fault-bend fold. Thus the Sulaiman provides a clear example of one way that a thrust system propagates into the foreland.

Sequential Evolution of the Foreland Structures

Figure 15 illustrates the sequential evolution of the foreland structures in the Sulaiman lobe. Figure 15A-B shows a decollement and the development of a fault-propagation fold at the tip of the decollement. The decollement is weak with ductility of material at the detachment horizon. The tip of the decollement is the site of the maximum differential stress. This stress is released by the ductile flow of material at the decollement horizon into the core zone of the small wavelength fault-propagation fold. Figure 15B-C illustrates the translation of fault-propagation fold to a broad concentric, buckle fold. As the decollement propagated towards the foreland, a new incipient fault propagation fold developed at the tip of the decollement at a time when concentric buckle fold is growing in amplitude (Figure 15D). This situation is similar to Zin concentric fold to the hinterland of the Uch fault-propagation fold (Figure 13). The Figure 15E shows a new increment of deformation with increasing shortening. It illustrates an incipient ramp, similar to as suggested by Liu and Dixon (1990), Dixon and Tirrul (1991) in the forelimb of a buckle fold, compatible with increasing differential stress in the competent unit. Increasing deformation and shortening initiated the development of 1st passive-roof duplex (Figures 15E and 10).

CONCLUSION

The broad (~300 km) and gentle (<1°), Sulaiman fold-and-thrust belt, is an active thin-skinned feature. The general structural style is of passive-roof duplex geometry with a duplex sequence that consists of Jurassic and older rocks. The duplexes are bounded between a deep decollement at the base of the wedge probably along the brittle/ductile transition and a roof thrust in the Cretaceous Sembar shales. The roof thrust, with a backthrust sense of vergence, remains passive relative to the foreland underthrusting of the duplex rocks (Banks and Warburton, 1986).

Detailed analysis of the structural geometries suggest one way for the evolution of the foreland structures from: 1) a fault- propagation fold at the tip of the decollement; 2) to a broad and gentle concentric folding; and 3) the development and propagation of a duplex related fault-bend folds as thrust flattens along the upper detachment.

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