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Mari-Bugti pop-up zone in the central Sulaiman fold belt, Pakistan

ISHTIAQ A. K. JADOON* and ROBERT D. LAWRENCE

Department of Geosciences, Oregon State University, Corvallis, OR 97331-5506, U.S.A.

and

SHAHID HASSAN KHAN

Geological Survey of Pakistan, Quetta, Pakistan

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Abstract—The Sulaiman fold-and-thrust belt is an active tectonic feature of the Himalayan mountain system in Pakistan. Seismic reflection profiles, borehole, surface geology data and Bouguer gravity modeling suggested a 'passive-roof duplex' geometry over a transitional crust related to the former passive margin of the Indian subcontinent. In the frontal part of the Sulaiman fold belt, a passive-roof sequence of Cretaceous and younger rocks is structurally uplifted. At the surface, the roof sequence displays a coherent stratigraphy over the underlying duplex sequence of Jurassic and older strata. The folds in the roof sequence reflect blind faults in the duplex sequence. The duplex style of deformation persists throughout the central Sulaiman fold belt. However, unlike the frontal Sulaiman fold belt, stratigraphy at the surface in the central Sulaiman is disrupted by E–W- and NE-trending faults, with apparent map lengths of tens of kilometers. These foreland- and hinterland-verging high-angle faults juxtapose Cretaceous rocks in the cores of tight, symmetrical anticlines against Eocene Ghazij Shale and Kirthar Limestone. According to seismic reflection data, they have only minor vertical offsets of 1–2 km and are mostly restricted to the roof sequence. As a result Cretaceous rocks bounded between reverse faults are exposed at the surface in the cores of tight anticlines as pop-up structures. This implies that: (1) the exposed faults in the central Sulaiman fold belt are not primary structures with major shortening; and (2) recognition of these faults in the roof sequence may reflect an early stage of development of overstep back thrusts from the upper décollement (passive-roof thrust).

INTRODUCTION

THE broad, presently active, Sulaiman fold belt is located along the western transpressional boundary of the Indian subcontinent in Pakistan. In the central part of the Sulaiman fold belt, various workers (Hunting Survey Corporation 1961, Kazmi & Rana 1982) recognize an extensive system of thrust faults. Kazmi (1979) considers this fault system, termed the Mekhtar–Kohlu fault system (box in Fig. 1), to be active based on the high level of local seismic activity (Quittmeyer *et al.* 1979). The lateral extent, nature and direction of vergence of these faults are not clear from prior work. Do these faults extend at depth to the base of the sedimentary wedge? Do they extend laterally for several tens and even hundreds of kilometers as shown by Bannert *et al.* (1989, 1992) and accommodate major shortening in the broad (>300 km) Sulaiman fold belt or, alternatively, are they secondary structures?

A correct understanding of these structures is critical to developing an overall model of Sulaiman structure. One model, based on surface reconnaissance mapping and Landsat data, interprets the range in terms of a series of imbricate, forward-verging thrust sheets which break the surface as these faults (Bannert *et al.* 1989, 1992). An alternate model suggests that the fold belt is dominated by an extensive passive-roof back thrust system (Banks & Warburton 1986, Izatt 1990). Recent studies on the tectonic evolution of the Sulaiman fold belt that integrate surface geology with seismic reflection profiles and borehole data (Humayon *et al.* 1991, Jadoon *et al.* 1992) provide a chance to evaluate these models, particularly in the Mekhtar–Kohlu fault system (here called the central Sulaiman fold belt). The purposes of this paper are: (1) to determine the nature of these faults; and (2) to establish the relationship between the surface structures (mostly tight anticlines) and deep structure in the central Sulaiman fold belt.

TECTONIC FRAMEWORK

The lobate Sulaiman fold belt is the broadest (>300 km) foreland fold-and-thrust belt of the Himalayan mountain system. Abdul-Gawad (1971), Sarwar & DeJong (1979) and Lawrence *et al.* (1981) and others have linked the lobate geometry of the Sulaiman Lobe to oblique convergence along the western left-lateral strike-slip boundary of the Indian subcontinent. The rocks exposed in the Sulaiman fold belt are generally younger toward the foreland. The thick (>7 km) Triassic to Paleogene stratigraphic platform sequence (Jadoon *et al.* 1992) is bordered by Neogene molasse toward the foreland and lower Eocene–Miocene flysch in the hinterland of the Sulaiman fold belt (Fig. 1).

*Present address: Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan.

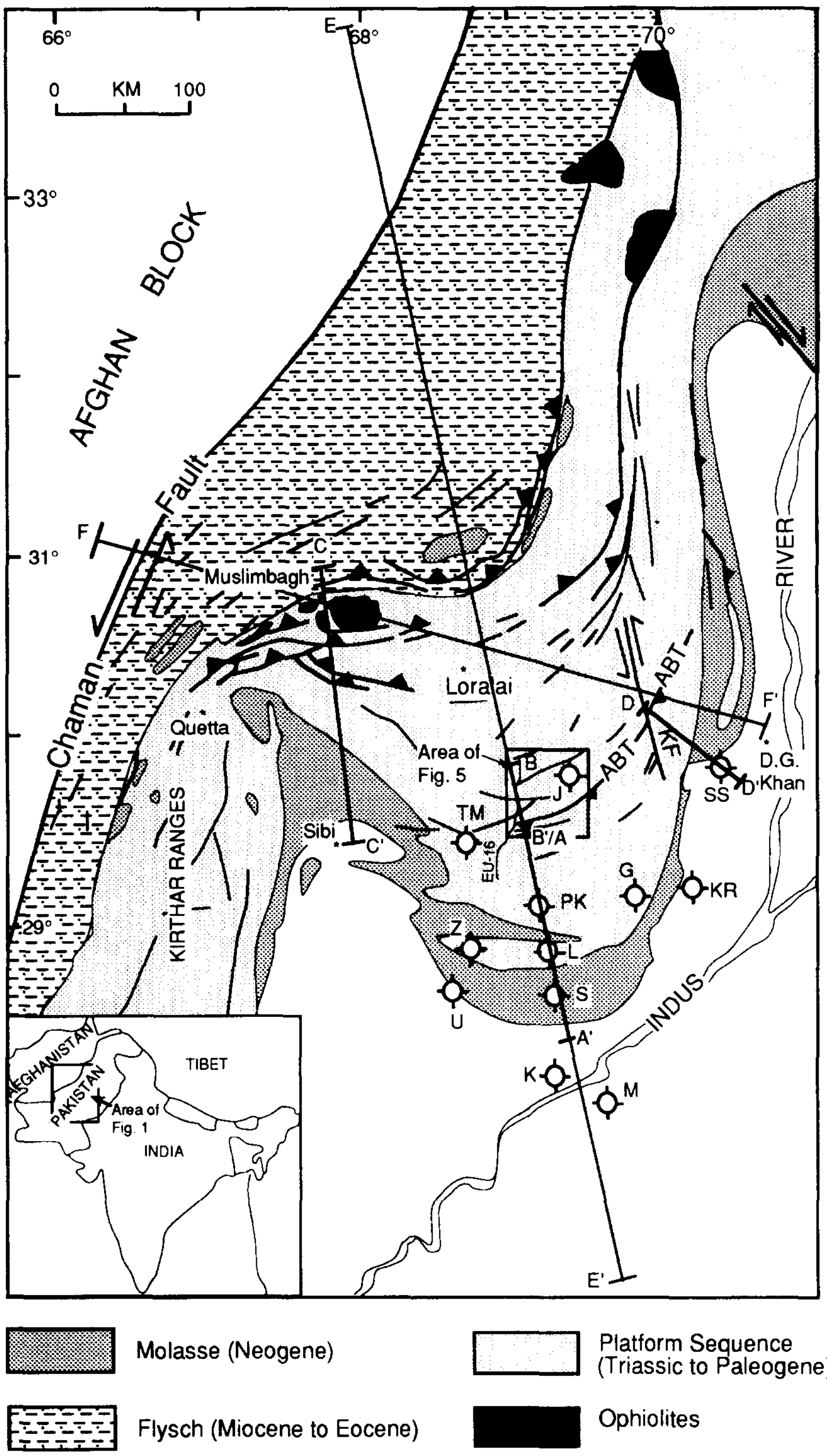

Fig. 1. The Sulaiman fold-and-thrust belt in Pakistan (modified from Kazmi & Rana 1982). A–A′ and B–B′ show the locations of the structural cross-sections in Figs. 4 and 8. C–C′ and D–D′ show the locations of the structural cross-sections (Fig. 2) constructed by Banks & Warburton (1986) and Humayon *et al.* (1991), respectively. E–E′ and F–F′ show the locations of crustal sections by Jadoon (1991c, 1992) and Khurshid (1991), respectively. ABT = Andari back thrust; KF = Kingri fault. Well abbreviations: G = Giandari-1; J = Jandran; K = Kandkot-2; KR = Kotrum; L = Loti-2; M = Mari-2; PK = Pirkoh-2; S = Sui-1; SS = Sakhi Sarwar, TM = Tadri Main; U = Uch; Z = Zin.

Kazmi & Rana (1982) mapped folds in the frontal part and southward-verging thrust faults in the hinterland of the broad Sulaiman fold belt. Bannert *et al.* (1989, 1992) inferred from Landsat data that the Sulaiman fold belt consists of a series of nappes exposed at the surface. Each major thrust is shown to extend as a single fault of great lateral extent. Banks & Warburton (1986) (C–C′ in Figs. 1 and 2a) suggested a passive-roof duplex geometry for the western Sulaiman and the northern Kirthar Ranges. Humayon *et al.* (1991), Jadoon (1991a) and Jadoon *et al.* (1992, in press a) integrated seismic reflection profiles and borehole, Landsat and surface geology data from eastern and frontal part of the Sulaiman fold belt. On this basis, they drew structural cross-sections

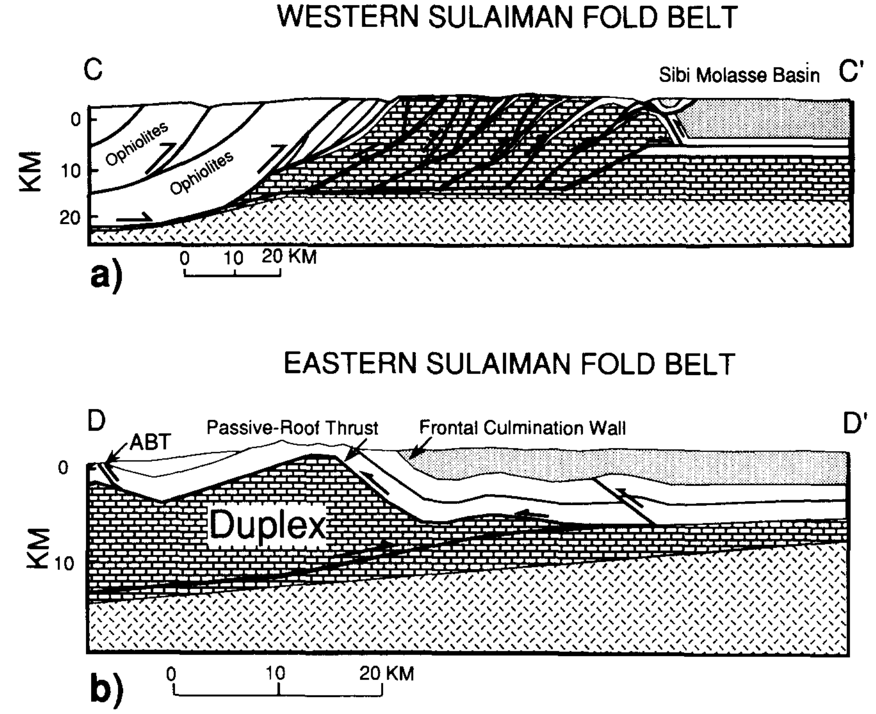

Fig. 2. Structural cross-sections from the western (C–C') and eastern (D–D') Sulaiman fold belt. (a) Passive-roof duplex geometry from the western Sulaiman fold belt in an advanced stage of deformation where roof sequence is removed by erosion along passive-back thrusts (modified from Banks & Warburton 1986). (b) Passive-roof duplex geometry from the eastern Sulaiman fold belt (modified from Humayon *et al.* 1991) in an early stage of deformation where a roof sequence over an anticlinal stack is preserved. Notice the minor displacement along the Andari back thrust (ABT) that is shown to have a long map trace (Figs. 1 and 5).

that favor a thin-skinned model with a duplex style of deformation (A–A' and D–D' in Figs. 1, 2b, 3 and 4). In these cross-sections, a Paleozoic to Jurassic duplex sequence is separated from the roof sequence by a passive-roof thrust in thick Cretaceous shales (see Humayon *et al.* 1991, Jadoon *et al.* 1992, in press a, for details of seismic and well data). The passive-roof thrust has hinterland vergence and remains stationary relative to the foreland propagating duplex (Banks & Warburton 1986). The passive roof-sequence over the hinterland dipping duplex is not disrupted by faults in the eastern (Fig. 2b) and frontal (Figs. 3 and 4) Sulaiman Range. Tear faults, such as the Kingri fault (Fig. 1), manifest neotectonic activity by offsetting fold axes and faults and by uplifting and tilting Holocene gravel beds along the margin of the Sulaiman fold belt (Rowlands 1978). Such faults also may function as lateral ramps.

Gravity modeling along crustal transects E–E' and F–F' in Fig. 1 (Jadoon *et al.* 1990, Khurshid 1991, Jadoon 1992) suggests a transitional crust averaging about 20 km thick underneath the Sulaiman fold belt. This is unlike the full thickness of continental crust of the Salt Range–Potwar Plateau of northern Pakistan (Lillie *et al.* 1987, Duroy *et al.* 1989). This implies an early stage of collision of the Indian subcontinent in the Sulaiman fold belt in comparison to a more advanced stage of collision in northern Pakistan.

The initial collision event in the Sulaiman fold belt is the emplacement of the Muslimbagh ophiolite between the late Cretaceous and early Eocene (Allemann 1979). Renewed southward thrusting since late Oligocene–early Miocene has constantly reworked the molasse strata as the deformation front migrated farther south and east (Banks & Warburton 1986, Ahmad & Khan 1990, Waheed & Wells 1990). Southward thrusting of the cover sediments is currently in progress. It is manifested by a pronounced topographic front, linear seismicity over the topographic front in the foreland, and various degrees of tilt in the Quaternary to Holocene molasse sediments in the frontal part of the Sulaiman fold belt. This is similar to the southward migration of the active foredeep basins of the Ganges plain in India and the Jhelum plain in Pakistan (Acharyya & Ray 1982, Raivermann *et al.* 1983, Johnson *et al.* 1985).

FRONTAL SULAIMAN FOLD BELT

The frontal portion of the Sulaiman fold belt is constrained by good quality seismic reflection and borehole data (Jadoon 1991a, Jadoon *et al.* 1992, in press a) provided by Amoco, the Oil and Gas Development Corporation of Pakistan and Texaco. It consists of broad E–W-trending, doubly plunging folds (Fig. 3). The rocks structurally uplifted to the surface of the cores of anticlines become progressively older toward the hinterland. However, these exposed rocks everywhere show a coherent stratigraphy that is not disrupted by thrust faults.

A structural cross-section (A–A' in Fig. 4) constrained by the seismic reflection and well data (Jadoon 1991a, Jadoon *et al.* 1992) shows the progressive structural development of the foreland features. At the tip of the décollement (Fig. 4) are two large concentric folds

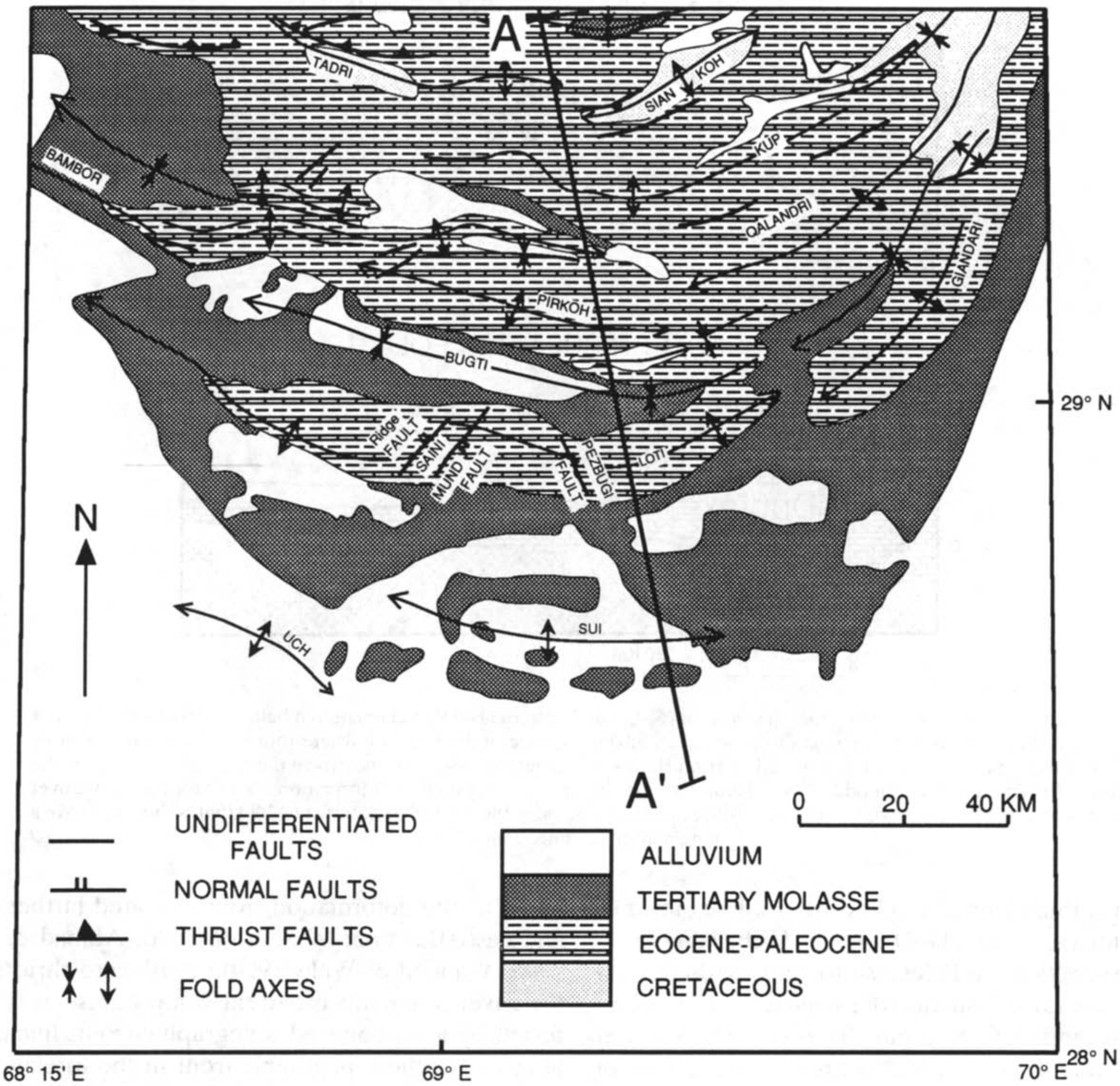

Fig. 3. Generalized geological map of the frontal Sulaiman fold belt (modified from Jadoon *et al.* 1992). A–A′ shows the location of structural cross-section in Fig. 4. Notice the folds as dominant foreland structures.

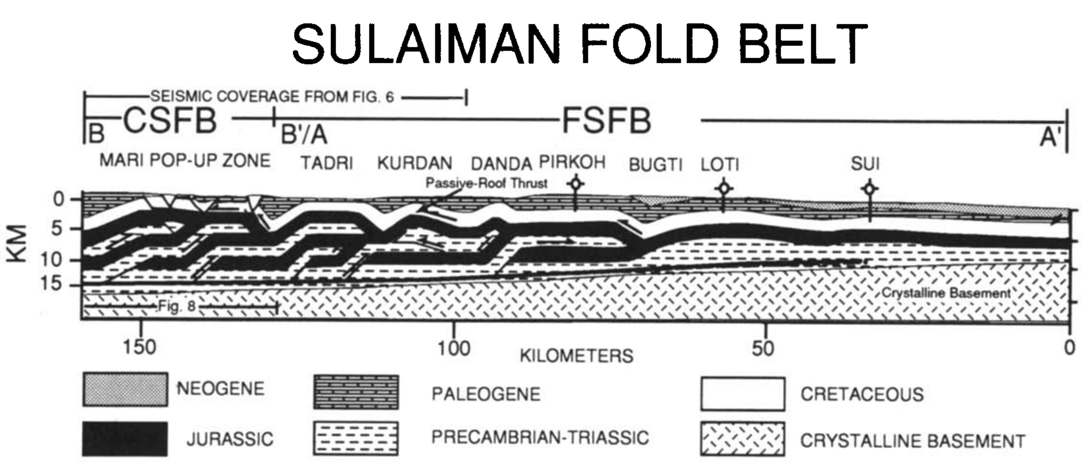

Fig. 4. Structural cross-section from the frontal (A–A′ in Figs. 1 and 3) and central (B–B′ in Figs. 1, 5 and 8) Sulaiman fold belt. A–A′ constrained by seismic data is modified from Jadoon *et al.* (1991). Seismic coverage over B–B′ is shown in Figs. 6 and 7. Notice the duplex style of deformation with a passive-roof thrust in Cretaceous shales, broad duplex related folds in the roof sequence at the surface in the frontal Sulaiman fold belt (FSFB), and secondary structures in the central Sulaiman fold belt (CSFB). See Figs. 5–9(b) for structures of CSFB.

with about 25 km half wavelength in a structural member about 8 km thick. The Sui anticline has an amplitude of about 1 km, and the Loti anticline has an amplitude of 1.5 km. Limb dips do not exceed 4° on Sui and 15° on Loti. These appear to be buckle folds that developed due to ductility of strata within the regional décollement, that is cores of folds are filled by ductile flow of carbonate and pelitic strata within the detachment layer. Nearly 10 km of a stratigraphic sequence are detached at the deformation front. This stack of sedimentary rocks thickens tectonically to about 15 km in the central Sulaiman fold belt.

These folds give way to duplex structures above a deep décollement north of the Loti anticline (Jadoon *et al.* 1992). Duplexing dominates between a floor thrust just above crystalline basement and a passive-roof thrust in Cretaceous shale (Fig. 4). Duplexing appears to be initiated when the buckle folds reach a limiting amplitude (Jadoon 1991b, Jadoon *et al.* in press a). The Pirkoh, Danda and Kurdan anticlines are cored by a single horse. The Tadri anticline and the Mari anticlinal zones are cored by two horses. Tadri is fundamentally an anticlinal stack.

The entire portion of the section underlain by duplexes is topped by a hindward-vergent passive-roof sequence. At and south of Tadri, overstep back thrusts do not cut the section above Cretaceous rocks, and fault-related folds predominate in the exposed Paleogene rocks (Figs. 3 and 4). The folds in the passive-roof sequence at the surface reflect the shape of the fault-bend folds in the duplex sequence (for example, Pirkoh anticline). The great length of the passive-roof structure across strike in the frontal Sulaiman fold belts is inconsistent with the duplex model of Banks & Warburton (1986) such that the roof sequence is not breached by multiple back thrusts.

CENTRAL SULAIMAN FOLD BELT

Surface geology

In the central part of the Sulaiman fold-and-thrust belt (Fig. 5), the mostly Eocene to Cretaceous exposed rocks are first cut by closely spaced faults of significant lateral extent. These faults generally parallel the traces of major fold axes. These foreland- and hinterland-verging faults mostly juxtapose Cretaceous rocks against Eocene rocks. The largest of these is the Andari back thrust. This fault may consist of smaller faults in comparable structural positions, similar to faults in the southern Appalachians (Diegel & Wojtal 1985). 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 belts (Figs. 1 and 5). The Andari back thrust partially shown in Fig. 5 is mapped by Humayon *et al.* (1991) as a single fault from the eastern Sulaiman Range. The Jandran and Ismail faults are oblique to the main structural trend (Fig. 5).

The geological map in Fig. 5 is modified from unpublished maps of the Geological Survey of Pakistan (GSP), which are primarily based on Landsat data with some field checking by the third author. In the politically unstable area of Mari (Baluchistan), a new field check of the map along the location of the Amoco seismic reflection line (EU-16) was crucial due to: (1) complex structures (tight fault-bounded anticlines) at the surface; and (2) poor seismic resolution along the cross-section B–B′ (Fig. 6). A new traverse by the first author from Kohlu southwards to Tadri in the central Sulaiman fold belt confirms the surface geology interpretation. Important attitudes that were used in interpreting the seismic reflection data are shown in Figs. 5–7.

Seismic observations

Seismic reflection line EU-16 (Figs. 1 and 6), which extents about 85 km across strike in the central Sulaiman fold belt, may be divided into two segments. The southern half of the seismic line, south of Tadri syncline, exhibits good seismic resolution with two relatively simple broad anticlines (Tadri and Kurdan on Fig. 6). This segment of EU-16 was interpreted earlier as part of a composite seismic reflection line (174 km long) from the foreland of the Sulaiman fold belt (Jadoon *et al.* 1992). A well drilled to a depth of 1935 m (6000 feet) by Amoco at the Tadri structure (TM on Fig. 1) penetrated a normal stratigraphic sequence from Cretaceous (Fort Munro) through Jurassic (Chiltan). The entire 5 s of two-way travel time data shown in this seismic line are layered sedimentary rocks; basement and the décollement level are deeper than this section. Jadoon (1991c) and Jadoon *et al.* (1992) infer a depth of about 14 km (7 s) for the projected top of the crystalline basement below Tadri. The absence of faults at the surface and the documented thickness of the stratigraphic section together suggest that the Cretaceous and younger rocks at Tadri are uplifted about 8 km above their regional stratigraphic level (Fig. 4). Jadoon *et al.* (1992) interpreted this relief as produced by two duplex horses of Jurassic and older rocks, implying that the Tadri structure is an anticlinal stack. Seismic reflection data (Fig. 6) suggest that the folds above the passive-roof thrust reflect the shape of the duplex structures below. This implies that the passive-roof sequence is not deforming independently south of the Tadri syncline.

The northern half of the seismic line, north of the Tadri syncline, loses good seismic resolution due to complex structures (closely spaced faults and tight anticlines; see Figs. 5 and 6). The reflections from the base of the Cretaceous, which are located at about 1.4–1.8 s on two-way travel time data (2.5–3 km below the surface), are subhorizontal (Figs. 6 and 7). These rocks are about 7–8 km above their regional stratigraphic level on forward propagating duplexes in a manner similar to the Tadri structure. In the synclinal areas, mostly subhorizontal Eocene rocks are exposed at the surface, except in the Tadri syncline where attitudes are steep (Figs. 5 and 6). Horizontal to subhorizontal reflections from the top of the Cretaceous 0.2–1 km below synclines

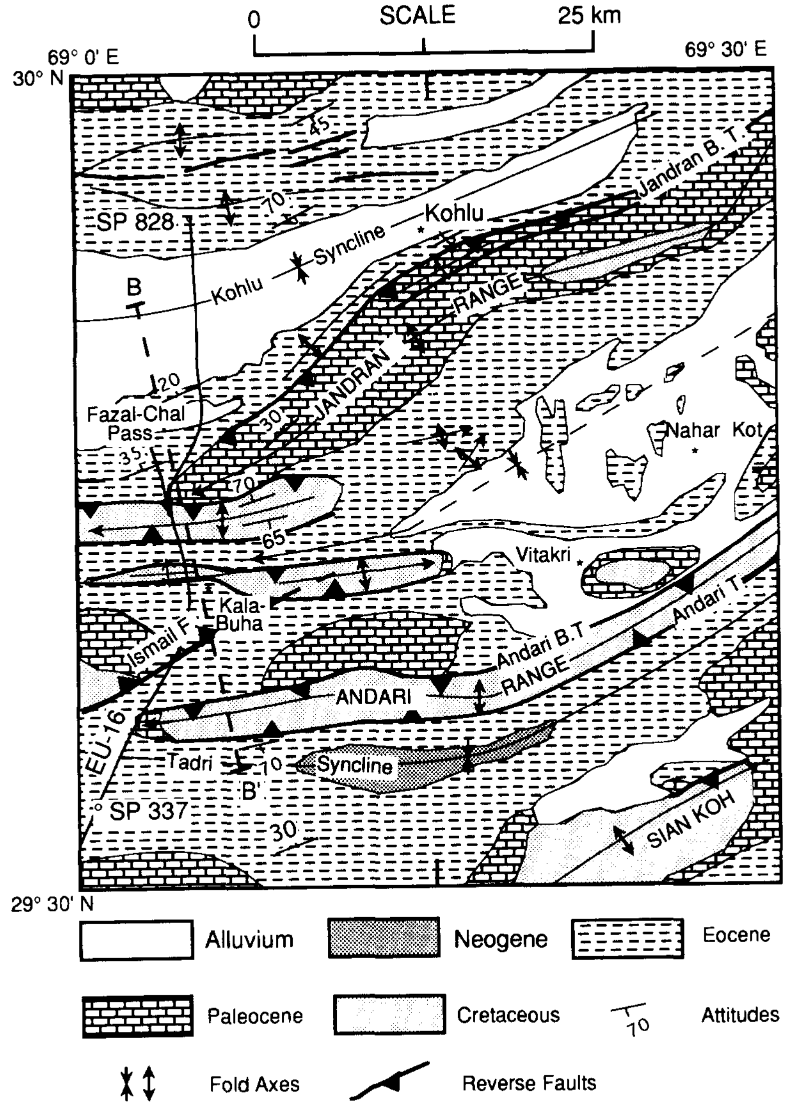

Fig. 5. Geological map of the central Sulaiman fold-and-thrust belt. EU-16 shows the location of the seismic reflection line (Fig. 6). T = foreland-verging thrust; BT = hinterland-verging back thrust.

are consistent with the surface geology (Figs. 6–8). Anticlinal areas are narrow (about 1–3 km) with steeply-dipping Cretaceous strata juxtaposed against sub-horizontal Eocene strata along foreland- and hinterland-verging faults in the central Sulaiman fold belt (Fig. 5). These faults with long map traces (Fig. 5) are recognized as reverse faults that emerge from a passive back (roof) thrust. In each case, these reverse faults emerge from the passive-roof thrust and generate 1–2 km offsets of cut-off points in the seismic line (Figs. 6 and 7). The Ismail fault (Fig. 5) shows up at the surface as a very prominent ridge of NW-dipping massive Paleocene Dungan limestone against valley fills over synclinal Eocene shale. In the seismic data excellent reflections from this massive limestone show a displacement of about 1 km between the cut-off points along the Ismail fault (Figs. 7 and 8). Apparent map length of the Ismail fault is about 45 km (Figs. 1 and 5). Another intriguing feature is the greater thickness (about 2 km) of the Cretaceous in the seismic and depth section (Figs. 4 and 6) compared to the narrow (1–3 km) areas of tight anticlines occupied by the Cretaceous rocks between these faults. In most cases, the major fault of the paired high-angle faults (Jandran, Fazal Chal, Kala Buha and Andari) emerges from the roof thrust (upper décollement) and has a back thrust sense of vergence (Fig. 8). This suggests that the faults at the surface in the central Sulaiman fold belt are shallow structures rooted in the roof thrust.

Recognition of the reverse fault system with apparent long map length (Humayon *et al.* 1991, Bannert *et al.* 1992, Bannert & Raza 1992) and minor offset (this study) in the central Sulaiman fold belt is inconsistent with the fault propagation theory of Elliott (1976) (P. Geiser written communication 1991). Elliott (1976) suggested a linear relationship between thrust displacement (d) and map length (l) as $d=kl$, with most faults having k values of about 1/14. In the central Sulaiman fold belt, reverse faults have k values of about 1/22. We suggest that relatively small k values may be due to: (1) close proximity of seismic and depth section to the tip points of the Andari and Jandran thrusts; and (2) an apparent single trace of more than one fault, similar to the southern Appalachians (Diegel & Wojtal 1985). The

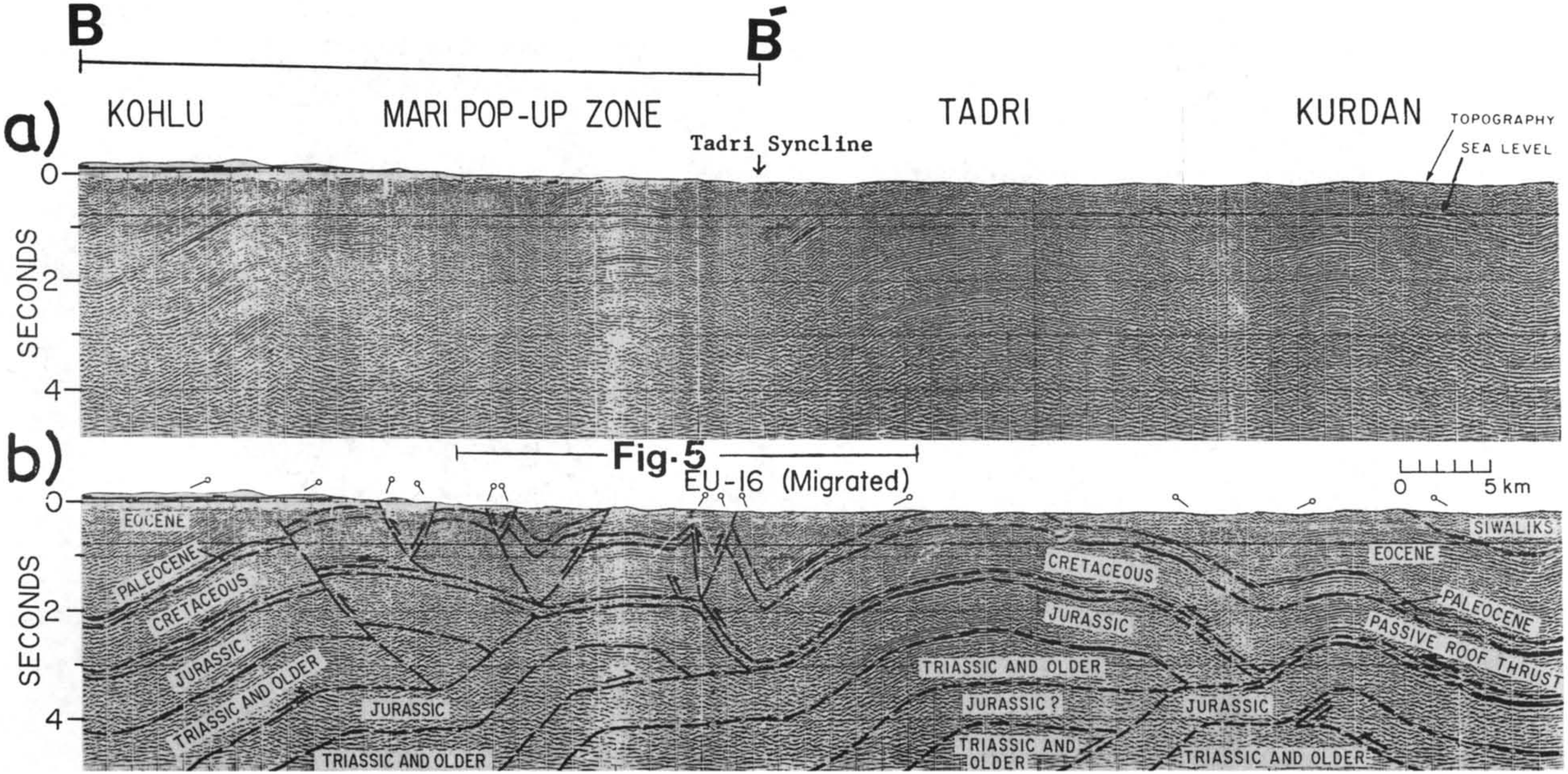

Fig. 6. (a) Uninterpreted and (b) interpreted seismic reflection line, EU-16 shown in Figs. 1 and 5. Seismic line shows that the simple folds in the passive-roof sequence south of Tadri syncline mimic the shapes of the duplex horses below them. In contrast north of the Tadri syncline pop-ups are interpreted. These complex secondary structures are restricted to the roof sequence where it is deforming independently from the duplex sequence below. Seismic reflection line EU-16 is 10–40 Hz, migrated vibroseis source, recorded and processed by Western Geophysical Company of U.S.A. in 1975.

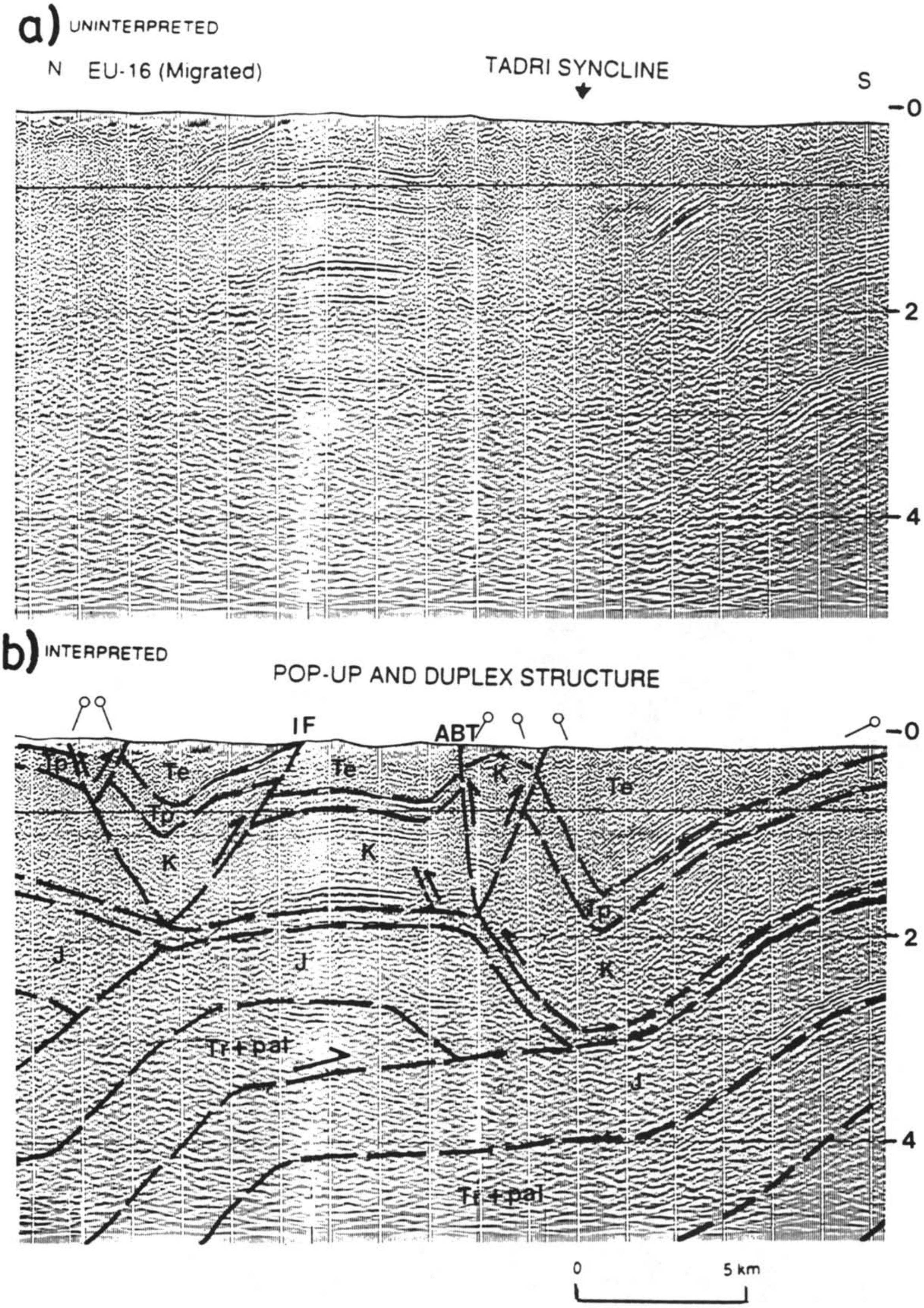

Fig. 7. Part of seismic reflection line EU-16 (Fig. 6) across Kala Buha, Andari Range pop-ups and Ismail fault to emphasize the minor displacement between cut off points along top Cretaceous and Paleocene. These secondary faults extend tens of kilometers laterally on the surface in the Sulaiman fold belt. ABT = Andari back thrust; IF = Ismail fault; Te = Eocene; Tp = Paleocene; K = Cretaceous; J = Jurassic; Tr + Pal = Triassic and older.

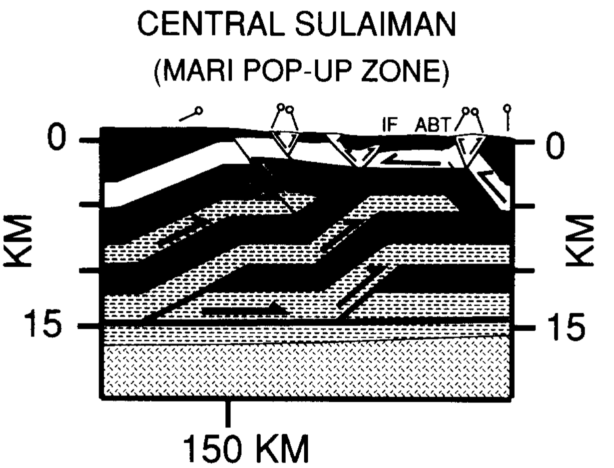

Fig. 8. Depth section along B–B′ (Figs. 5 and 6) from the central Sulaiman fold belt. Pop-ups between secondary reverse faults mostly restricted to the roof sequence, may represent an early stage of development of overstep back thrusts. Symbols above section represent dips measured in the field. See Fig. 4 for the legend to the patterns. ABT = Andari back thrust; IF = Ismail fault; JBT = Jandran back thrust.

latter is supported by a relatively much smaller map length of the faults in the Mari-Bugti (Figs. 1 and 5) than shown by Bannert *et al.* (1992) and Bannert & Raza (1992). The thrusts with major displacement related to the duplex are concealed by the roof sequence. The apparent long map trace of the reverse fault may be a result of the linkage of two or more faults. Thus, fault propagation theory is probably not violated by these reverse faults. We intend to conduct more thorough investigation by multiple stratigraphic separation diagrams to examine the problem in the Sulaiman fold belt.

Tectonic models

Alternate models have been presented for the general structural style of the Sulaiman–Kirthar fold belt (Banks & Warburton 1986, Bannert & Raza 1992). Banks & Warburton (1986) first suggested a passive-roof duplex geometry for the western Sulaiman fold belt (Fig. 2a). Izatt (1990) drew very general sections across the foreland of the entire range as an elaboration of Banks & Warburton's (1986) ideas. Humayon *et al.* (1991) and Jadoon *et al.* (1992) drew balanced cross-sections from the eastern and frontal Sulaiman Range (Figs. 2b and 4, respectively). These sections constrained by extensive seismic and well data support a thin-skinned, duplex geometry. In contrast, Bannert & Raza (1992) and Bannert *et al.* (1992) infer, based on Landsat data and reconnaissance mapping, that the broad Sulaiman fold belt consists of a series of foreland-verging continuous imbricate thrusts, piggyback style, without major back thrusts. A similar interpretation is implied by the maps of the Hunting Survey Corporation (1961) and Kazmi & Rana (1982), but not presented in detail by these workers. Bannert *et al.* (1989) proposed that Eocene shale, widely distributed in the frontal and the central part of the Sulaiman fold belt, provides a favorable décollement horizon for the movement of the thrust sheets over the footwall. Both interpretations require major shortening along foreland-verging thrust faults. In the latter cases foreland-verging faults must be exposed at the surface, and hinterland-verging faults are only minor antithetic features (Fig. 9a). This interpretation is not favored by surface geology and newly available seismic reflection data (Figs. 5 and 6) because: (1) the strata in the Bugti syncline in the frontal Sulaiman fold belt are not disrupted by a thrust fault (Fig. 3) as suggested by Bannert & Raza (1992) and Bannert *et al.* (1992); (2) the prominent surface faults in the central Sulaiman fold belt are back thrusts (Andari and Jandran back thrusts in Figs. 1 and 5), not the foreland-vergent nappe of Bannert *et al.* (1992); (3) seismic reflection data show minor dip-slip displacements of 1–2 km on all the exposed faults in the central Sulaiman fold belt including the Andari back thrust (Figs. 2b and 8); and (4) seismic reflection data show all imbricate features to be concealed beneath a roof layer.

Our structural cross-section B–B′ in Figs. 4 and 8 shows that duplex-style deformation persists in the central Sulaiman fold belt. Regardless of vergence, exposed faults are restricted to the roof sequence and do not extend deeper than 3–4 km. Of these reverse faults, each has a minor displacement of about 1–2 km, offsetting only Cretaceous and younger rocks. The Andari back thrust (Fig. 1) is inferred to extend laterally at least 170 km. It may consist of more than one faults in comparable structural positions, like some thrusts in the southern Appalachians (Diegel & Wojtal 1985). However, at present it is mapped as a single fault about 85 km long in

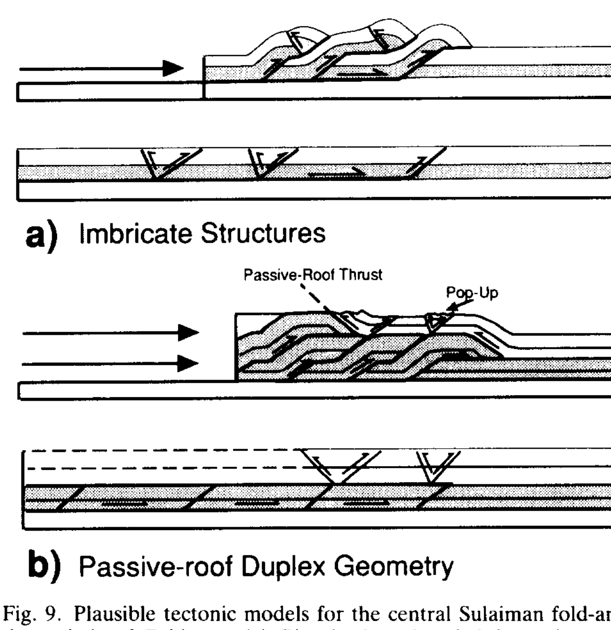

Fig. 9. Plausible tectonic models for the central Sulaiman fold-and-thrust belt of Pakistan. (a) Piggyback style of deformation with secondary hinterland-verging minor thrust faults. (b) Passive-roof duplex style of deformation with a preserved roof-sequence, pop-ups and a passive-roof thrust. Presently, shortening in the roof sequence occurs along the emergent tip of the passive-roof thrust. Pop-ups in the roof sequence may reflect an early stage of development of multiple back thrusts.

the eastern (Humayon *et al.* 1991) and about 45 km long in the central Sulaiman fold belt (Fig. 5). In the eastern Sulaiman fold belt, it is encountered by Humayon *et al.* (1991) along their balanced cross-section (Fig. 2b). Humayon *et al.* (1991) interpret the Andari back thrust to emerge from a passive-roof thrust (Fig. 2b). In both cases (eastern and central Sulaiman), it emerges from a depth of 4–6 km out of a syncline in front of a duplex and exhibits less than 2 km of displacement (Figs. 2b and 8). Thus most of the complex structures exposed at the surface in the central Sulaiman fold belt are secondary structures, pop-ups (terminology from Butler 1982) between paired back- and forward-thrusts (Fazal-Chal Pass, Kala-Buha and Andari Range) that are restricted to the roof sequence (Figs. 5–9b). Perry (1978), Mitra (1987) and Ahmed & McElroy (1991) have shown pop-up structures in roof sequences in cross-sections from the Appalachian foreland in west Virginia and the Himalayan foreland in Kohat Plateau. In the central Sulaiman fold belt, the roof sequence is not fully emergent due to minor offset along reverse faults. However, a passive-roof thrust is fully emergent in hinterland to take-up the relative shortening in the roof sequence (Fig. 9b) (see Jadoon in press a, b for details).

The presence of extraordinary reverse faults with apparent long map traces but minor dip-slip offset is inferred to reflect their mechanical origin. They are produced when laterally prolonged folds (Andari Range–Jandran Range in Fig. 5) over persistent blind thrusts lock the passive-roof duplex and initiate accommodating faults within it. The Jandran back thrust is an exception that cuts through the upper duplex horse to a depth of about 8 km (Figs. 5, 6 and 8). The Jandran Range anticline is a fault-propagation fold at the tip of the hinterland-verging Jandran fault (Figs. 5 and 8). Both the Ismail fault and Jandran back thrust are oblique to the trend of the main surface structures.

DISCUSSION

Passive-roof duplex geometry

Our model for the structural style of the Sulaiman has three layers: a passive-roof layer, a main duplex layer and a basement layer (Fig. 9b), and has a much thicker deformed section than was recognized previously (Izatt 1990). In our preferred model for the structural style in the central Sulaiman fold belt (Fig. 9b), the roof sequence is presently actively deforming by faulting over the duplex sequence. The larger faults extend into the uppermost duplex and merge with the faults at the base of this structure. This model may be supported by high level of shallow (<5 km) seismic activity in the central Sulaiman fold belt (Quittmeyer *et al.* 1979, 1984). Thus, many of the faults exposed at the surface may be active. Lack of ground rupture may be related to distributed seismicity over multiple faults (T. Nakata personal communication 1991). The lower duplex sequence is inferred to slide stably towards the foreland as a coherent slab above a basal décollement.

The structural cross-section (Fig. 4) showing a passive-roof duplex geometry is consistent with the western (Banks & Warburton 1986) and eastern (Humayon *et al.* 1991) Sulaiman fold belt. However, contrary to the western Sulaiman where overstep back thrusts develop from the tip of each duplex to accommodate shortening strain in the roof sequence, a continuous roof sequence is present in the frontal and eastern Sulaiman fold belt. The passive-roof sequence is breached in the central Sulaiman fold belt. However, it is not fully emergent due to minor throw of about 2 km along forward- and hindward-verging reverse faults. The seismically active central Sulaiman structure may represent out-of-sequence thrusting and associated folding, herein interpreted as pop-ups. Thus, secondary thrusting may represent an incipient stage in the evolution of overstep back thrusts, mostly emerging from the passive-roof thrust.

The descriptive situation in our model (Fig. 9b) is a very long roof sequence similar to the Appalachians (Boyer & Elliott 1982, Geiser 1988a), and the Papua New Guinea fold belts (Hobson 1986). The proposed model (Fig. 9b) for the long roof sequence is similar to a model by Boyer & Elliott (1982) in that both have an intact roof sequence for great distances. However, in our model the emergent fault is a passive-roof thrust with hinterland vergence in the Sulaiman fold belt instead of foreland-vergent faults in the foredeep basin. The pop-up structures confined to the roof sequence (out-of-sequence of Morley 1988) may show an early stage of development as passive-back thrusts. This implies that passive-back thrusts (Banks & Warburton 1986) may not necessarily be present in the early stages of development of a passive-roof duplex geometry. The proposed model (Fig. 9b) for the long roof sequence is based on a balanced cross-section across strike from the foreland to the hinterland of the Sulaiman fold belt (see Jadoon 1991c, Jadoon *et al.* in press a, b for details). The Cretaceous (Sembar) shale with abundant calcite veins and detachment folds in an overlying limestone (Parh) are extensively distributed along the detachment horizon. More than 1700 m of the Sembar shale has been drilled in the Giandari well (Fig. 1). In the absence of multiple back thrusts, a majority of shortening in the roof sequence is accommodated by erosion along the emergent passive-back thrust in the Loralai valley (Fig. 1). To some extent shortening is accommodated by secondary thrusting (incipient back thrusting) and detachment folding, similar to the Canadian Rockies (Dahlstrom 1970, Wallace & Hanks 1990). All other mechanisms in a hindward translated roof sequence, i.e. layer parallel shortening (Geiser 1988a, 1988b), are yet to be determined to overcome the problem of the shortening mechanism in the current stage of evolution of the active Sulaiman fold belt. Other examples of duplex geometry with long roof sequences are reported from the Appalachians (Roeder *et al.* 1978, Berg *et al.*

1980, Herman 1984), the Papua New Guinea (Hobson 1986) and the Brooks Range, Alaska (Wallace & Hanks 1990).

Duplex vs imbricate model

The structural cross-section (Fig. 4) showing a passive-roof duplex geometry is inconsistent with an imbricate (nappe) model for the evolution of the Sulaiman fold belt. Bannert *et al.* (1989, 1992) inferred from Landsat data that the Sulaiman fold belt consists of a series of foreland-vergent continuous thrusts exposed at the surface. This interpretation is not favored by stratigraphic separation along faults and seismic reflection data. For example, see the map view of the oblique Ismail fault that juxtaposes the Paleocene and Cretaceous strata against the Eocene (Fig. 5). The massive Paleocene (Dungan) limestone is a marker horizon in the seismic profiles (Figs. 6 and 7). The seismic trace of Paleocene limestone in the hangingwall (inclined reflections) and footwall (flat reflections) blocks of the emergent Ismail fault clearly displays the hangingwall and footwall cutoff points. The dip-slip displacement between cutoff points is about 1 km (Fig. 8). Similarly, all other emergent faults show minor throw and are rooted in the upper detachment (Sembar shale) at shallow depth. This suggests the presence of duplex and pop-up structures, unlike nappe structures in the central Sulaiman fold belt.

CONCLUSIONS

Passive-roof duplex geometry exists in the Sulaiman fold belt. A roof sequence of Cretaceous and younger rocks structurally uplifted about 8 km is deforming with hinterland vergence over anticlinal stack horses in forward-verging duplexes in the central Sulaiman fold belt. Complicating structures at the surface are foreland- and hinterland-verging reverse faults, associated pop-up structures (Fazal-Chal Pass, Kala-Buha and Andari Range tight anticlines), and oblique faults (Ismail and Jandran thrusts), most of which are restricted to the roof sequence. They extend laterally for tens of kilometers, but do not extend deep in the wedge and have minor displacements of 1–2 km. These reverse faults emerge from the passive-roof thrust at the base of the passive-roof sequence and are recognized as secondary (out-of-sequence) structures. Their recognition may reflect an early stage in the evolution of overstep back thrusts in the passive-roof sequence of the central Sulaiman fold belt. Overstep back thrusts are passive faults which accommodate internal shortening of the passive-roof layer. The foreland-vergent décollement (floor thrust) and the hinterland-vergent passive-roof thrust bounding a duplex may be visualized as a conjugate fault set of fold-and-thrust belts.

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