Pakistan Journal of Hydrocarbon Research
Vol.4, No.2(July 1992), P.33-44, 6 Figs., 1 Table

Ocean/Continental Transitional Crust Underneath the Sulaiman Thrust Lobe and an Evolutionary Tectonic Model for the Indian/Afghan Collision Zone

Ishtiaq Ahmad Khan Jadoon[1]

ABSTRACT

Gravity data along a NNW-SSE profile from western Pakistan and eastern Afghanistan has been incorporated with recent structural interpretations based on seismic reflection, borehole and surface geological data from the Sulaiman fold belt to infer the gross crustal structure across the Indian/Afghan collision zone. Seismic reflection profiles reveal that the stratigraphic thickness of the rocks at the deformation front of the Sulaiman fold belt is about10 km. The wedge thickens northward and may have a thickness of 20 km in the hinterland. Gravity modeling depicts the depth to the Moho at about 35 km at the deformation front of the southern Sulaiman fold belt. The Moho depth decreases northward with a gentle gradient of 1.1° (20 m/km) below the Sulaiman fold belt, and then deepens abruptly with a gradient of about 7.8° (136 m/km) across the Chaman fault zone, attaining a depth of about 57 km in eastern Afghanistan. Interpretation of the model suggests that the Sulaiman fold belt is underlain by transitional crust, in contrast to the full thickness of crystalline crust underneath the fold-and-thrust belt of the Himalayan collision zone in northern Pakistan.

INTRODUCTION

The collision of two plates begins with destruction of a constructive plate margin. The orogeny may stop in a stage, where rift related features and a thinner crust could still be intact underneath the mountain belts, as in the Paleozoic Ouachitas of the Kansas and Oklahoma of the south central United States (Lillie, 1985; Kellers et al., 1989). In other cases, ongoing collision may have progressed to an advanced stage such that all the oceanic crust and features related to a thinner passive margin are destroyed leading towards head-on continental collision, as in the main Himalayas (Searle, 1986; Duroy et al., 1989; Malinconico, 1989).

The Himalayan mountain system that is presently active due to ongoing continent-continent collision between Eurasian and Indian plate extends in NW-SE direction for about 2500 km through Burma, Nepal, India, and Pakistan (Molnar and Tapponnier, 1975; Gansser, 1981; Molnar, 1984). Studies based on the analyses of surface-wave dispersion suggests a crust of nearly twice normal continental thickness in the main Himalayan collision zone (Gupta and Narain, 1967; Chun and Yoshii, 1977). Physically, the crustal doubling is manifested along the length of the Himalayas by the emplacement of the crystalline basement rocks of the Indian plate over its own cover strata along the Main Central Thrust (LeFort, 1975). The NW-SE trending Himalayas change their trend to NE-SW, east of Nanga Parbat-Haramosh massif (NPHM) and Hazara-Kashmir syntaxis (HKSA) in Pakistan (Figure 1). This change of trend occurs prior to the termination of the Himalayan mountain system in a zone of transpression along the western left-lateral strike-slip boundary of the Indian plate (Lawrence et al., 1981a). Crustal modelling along a Bouguer gravity profile across a zone of direct collision in northern Pakistan shows a full thickness of continental crust that extends from the Himalayan foredeep to the suture zone, Main Mantle Thrust (Lillie et al., 1987; Duroy et al., 1989; Figure 2). North of the suture, crust thickens to about 65 km along the main zone of collision. The Sulaiman lobe, is a broad (300 km) fold-and-thrust belt (Kazmi and Rana, 1982) southwest of the main Himalayas in Pakistan (Figure 1). In the Sulaiman thrust lobe Eocene to Permian platform strata are overlain by ophiolites and flysch (Abbas and Ahmad, 1979; Kazmi and Rana, 1982), at the western boundary of the Indian plate (Figure 1). Interpretation of seismic reflection data (Jadoon et al., 1991a; Jadoon, 1991b; Humayon et al., 1991) shows a thick carbonates dominant (~7 km) sequence at the deformation front of the Sulaiman lobe (Figure 3). This is related to the deposition over a transitional crust (Malik et al., 1988; Jadoon et al., 1989; Humayon et al., 1991). In this paper a Bouguer gravity profile (A-A′ in Figure 1) is modelled from the Sulaiman foredeep across western boundary of the Indian subcontinent to: (1) determine the nature of the crust (oceanic/transitional or continental) underneath the Sulaiman lobe; (2) evaluate crustal variation across the Indian/Afghan collision zone; and (3) to present a kinematic model of crustal structures. These results may further allow to compare the degree of continental convergence in the Sulaiman with that of the main Himalayas and to understand the kinematics of a transpressional system.

---

[1] Department of Earth Sciences, Quaid-I-Azam University, Islamabad, Pakistan.

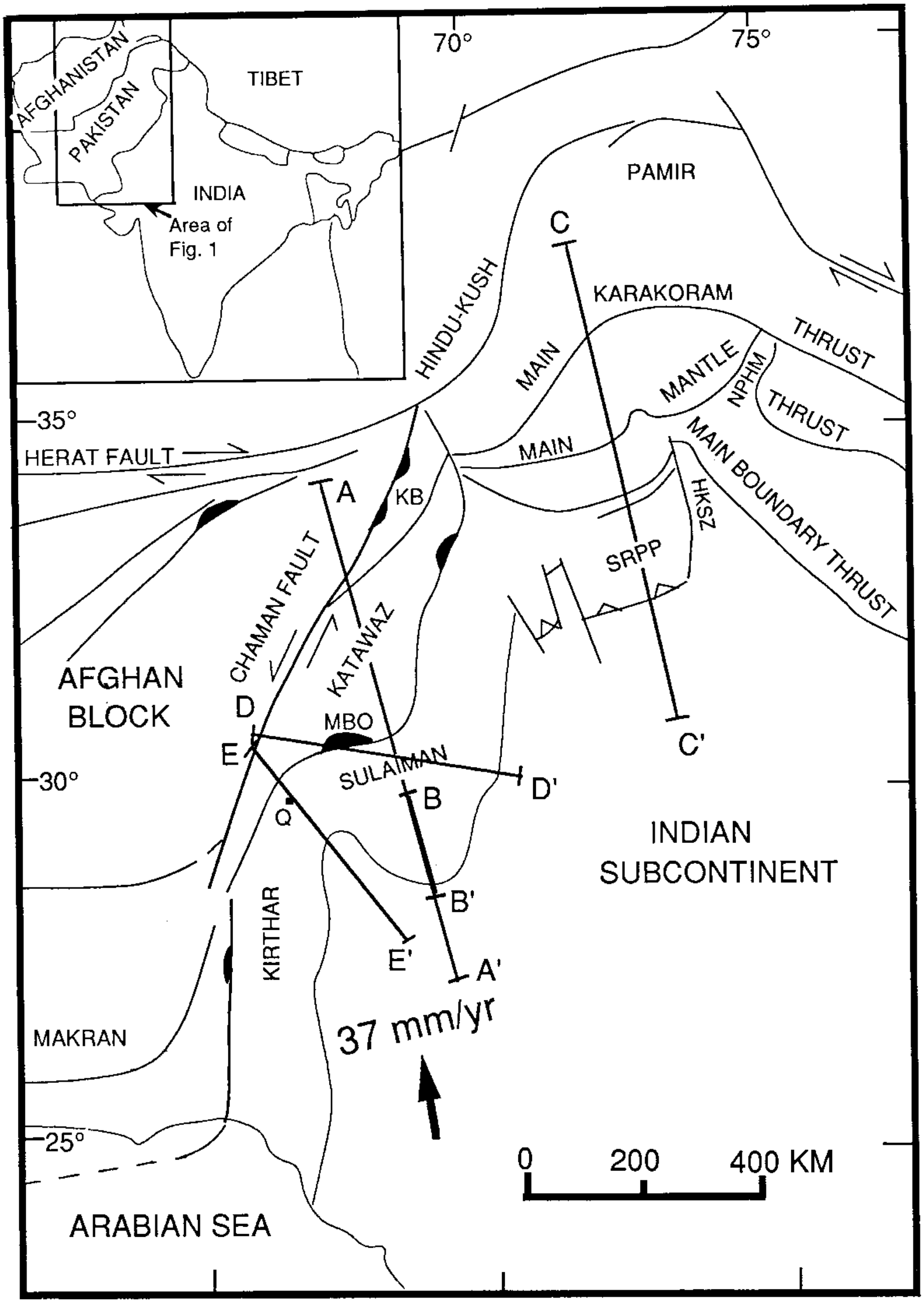

Figure 1— Simplified tectonic map of Indian/Eurasian collision zone, along western transpressional boundary of the Indian subcontinent. Arrow indicates relative drift of Indian plate with respect to Afghan block ((Minster & others, 1974; Minster & Jordan, 1978)). $A-A'$ is a Bouguer gravity transit modelled in figure 5. $B-B'$ represents a structural cross-section constrained by seismic reflection data (Jadoon & others, 1991; Jadoon, 1991a & b), $C-C'$ by Duroy & others (1989) integrates gravity modelling from Malinconico (1982 and 1986), Farah et al., (1977) and Duroy (1986). $D-D'$ and $E-E'$ show gravity profiles modelled by Khurshid (1991) and Rahman (1969). HKSA = Hazara-Kashmir Syntaxis; KB = Kabul Block; MBO = Muslimbagh Ophiolites; NPHM = Nanga-Parbat Haramosh Massif, Q = Quetta, SRPP = Salt Range/Potwar Plateau.

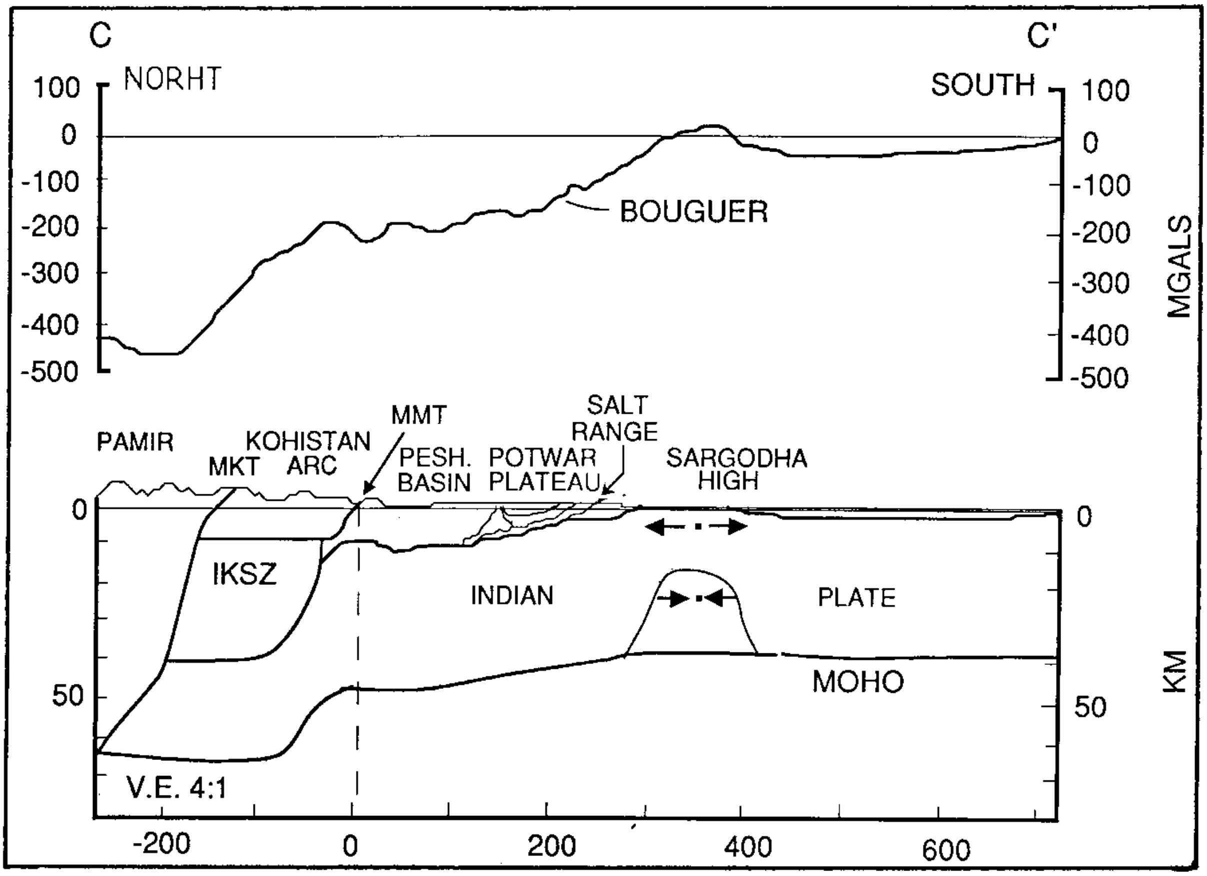

Figure 2— Generalized cross-section C-C′ of the lithosphere from the stable Indian craton, across the Himalayas of Pakistan (from Duroy et al., 1989; see Fig. 1 for location). Bouguer gravity data is compiled from Farah et al. (1977), Duroy (1986), Marussi (1976), and Malinconico (1982 and 1986). Gross upper crustal geometry of MMT and MKT are from Malinconico, 1982 and 1986.

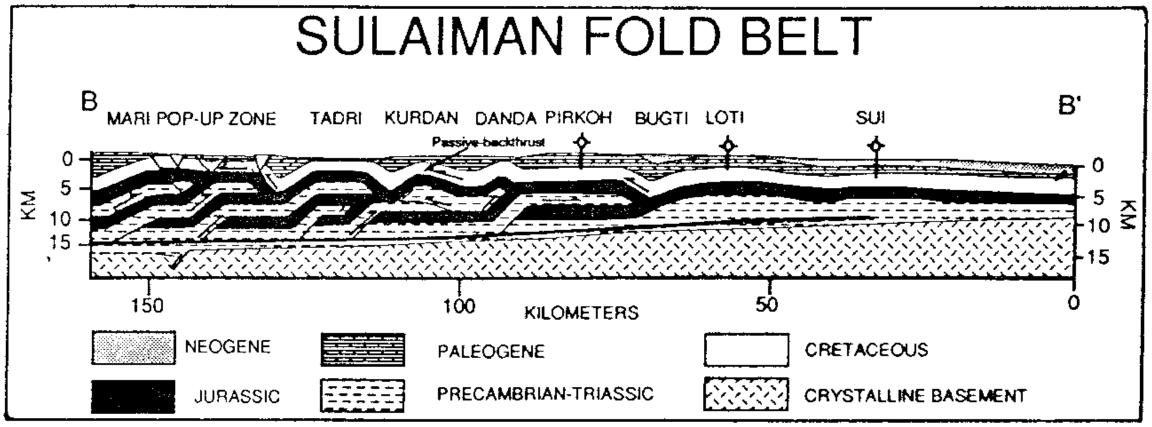

Figure 3— Structural cross-section (B-B′ in Figure 1) constrained by seismic reflection data from the Sulaiman fold belt of the active Himalayan mountain system in Pakistan (modified from Jadoon, 1991a and b). Important feature of the section are a passive-roof duplex geometry, an extremely deep decollement, and about 10 km depth to the top of the crystalline basement with about 7 km of carbonates at the deformation front.

TECTONIC SETTING AND PREVIOUS WORK

The gross crustal structures of southwest Asia are a result of accretion of island arcs and fragments of Gondwana to the Eurasian landmass, and later closing of the Tethys during collision between the Indian subcontinent and the Eurasia at about 55 Ma (Powell, 1979). Paleomagnetic data show that since collision, the Indian subcontinent has moved northwards about 2000 km into Asia (Klootwijk et al., 1985). This ongoing collision has produced the active Himalayan mountain system. Direct collision in northern Pakistan gives way to transpression along the Chaman transform zone (Lawrence et al., 1981a; Farah et al., 1984; Lawrence and Khan, 1991a). This oblique convergence (Figure 1) produced the festoon-shaped Sulaiman fold belt along the western edge of the Indian subcontinent (Sarwar and DeJong, 1979; Klootwijk et al., 1981).

The broad Sulaiman fold belt to the south-east of the Chaman fault manifests prograding of deformation toward the foreland. It involves Neogene continental molasse strata in the foreland part and a Permian to Paleogene platform sequence in the hinterland (Kazmi and Rana, 1982). In the extreme north, ophiolites encased in flysch may represent pieces of oceanic lithosphere thrust over the platform sequence (Allemann, 1979). Seismic data reveal stratigraphic thickness of about 7 km of shelf and platform sequence at the deformation front in the southern Sulaiman fold belt (Jadoon et al., 1991a; Jadoon, 1991b), in contrast to the 1 km thickness of age-equivalent strata in the Salt Range/Potwar plateau of Pakistan (Lillie et al., 1987). Structural cross- sections from western, central, and eastern Sulaiman ranges suggest an extremely thick pile of sediments (about 20 km in the rear) and a passive-roof duplex style of deformation (Banks and Warburton, 1986; Jadoon et al., 1991a; Jadoon, 1991c; Humayon et al., 1991).

The left-lateral strike-slip Chaman fault separates the Indian subcontinent to the east from the Eurasian plate to the west (Lawrence et al., 1981a; Farah et al., 1984). The 860 km long, Chaman transform fault shows a displacement of about 450±10 km (Lawrence and Khan, 1991b). However, the nature of the Chaman fault as a crustal shear or a feature restricted to the upper crust is not known. Quittmeyer et al. (1979 and 1984) show distribution of seismicity at shallow depths (<15 km) in the Sulaiman lobe and the Chaman fault. Izatt (1990) drew a generalized crustal section to infer that distal end of the Indian plate may extend to the west of the Chaman fault. The Afghan block between the Chaman and Herat faults is considered to consist of microfragments, which were detached and drifted from Gondwana, and accreted to the Eurasian landmass from late Paleozoic through the Cenozoic (Bordet, 1978; Boulin, 1981; Tapponnier et al., 1981). Gravity modelling across the Himalayan collision zone in northern Pakistan (Lillie et al., 1987; Duroy et al., 1989) shows a full thickness of continental crust (38 km) extending from the Jhelum plain beneath the Salt Range/Potwar Plateau and Peshawar Basin to the Main Mantle Thrust (MMT), and a crust of about 65 km below the Kohistan Arc (C-C$'$ in Figure 1 and Figure 2). In contrast, about 7 km thick dominantly carbonate sequence coupled with relatively high Bouguer gravity from the Sulaiman fold belt, suggest a thinner crust at the west end of the Indian plate (Jadoon et al., 1989; Lillie et al., 1989). This is consistent with S-wave studies of earthquake data (Chun, 1986) that suggests crystalline oceanic/transitional crust underneath the Sulaiman fold belt. Gravity modelling along the profile D-D$'$ in Figure 1 (Khurshid, 1991) supports a transitional crust below the Sulaiman fold belt. Rahman (1969), however, produced a very simplified Bouguer gravity model along the western margin of the Indian plate (Line E-E$'$ in Figure 1). His model depicts the crustal thickening from about 30 km in the western Sulaiman foredeep to about 55 km along the Chaman fault. This suggests a westward thickening of the crust of the Indian plate that is inconsistent with the model proposed by Khurshid (1991). Rahman (1969) could not account the enormous pile of sedimentary rocks from the Sibi trough and Sulaiman/Kirthar ranges (Banks and Warburton, 1986) in his model. These results are tested in this study by Bouguer gravity modelling along crustal transect A-A$'$ in Figure 1.

GRAVITY MODELLING

Gravity Data and Constraints

Gravity modelling was done for an 800 km long profile extending from the Sulaiman foredeep to eastern Afghanistan (A-A$'$ in Figures 1 and 4). Regional Bouguer gravity data along this profile from kilometer marks 0 to 250 are from an OGDC partially published map at a contour interval of 2 mgals (published in part for the southern Indus basin by Quadri and Shuaib, 1986). The values from kilometer marks 250 to 800 (Figure 4) are from the Marussi (1976) map which has a 50 mgal contour interval. Observed Bouguer gravity values obtained from Marussi (1976) were compared with values given by McGinnis (1971) in Afghanistan and with recently collected data by the Geological Survey of Pakistan (GSP) at an interval of 5 km between kilometer marks 250 to 350 in the Loralai, Muslimbagh, and Duki areas of the central Sulaiman fold belt (Khurshid, 1991). The regional gravity values from Marussi (1976) are too coarse to reveal any anomalies related to shallow structures. As a result most of the gravity profile is smooth with anomalies near zero in the southern Sulaiman foredeep, then continually decreasing northward to about -190 mgals along the Chaman fault and -265 mgals farther north in Afghanistan (Figure 4).

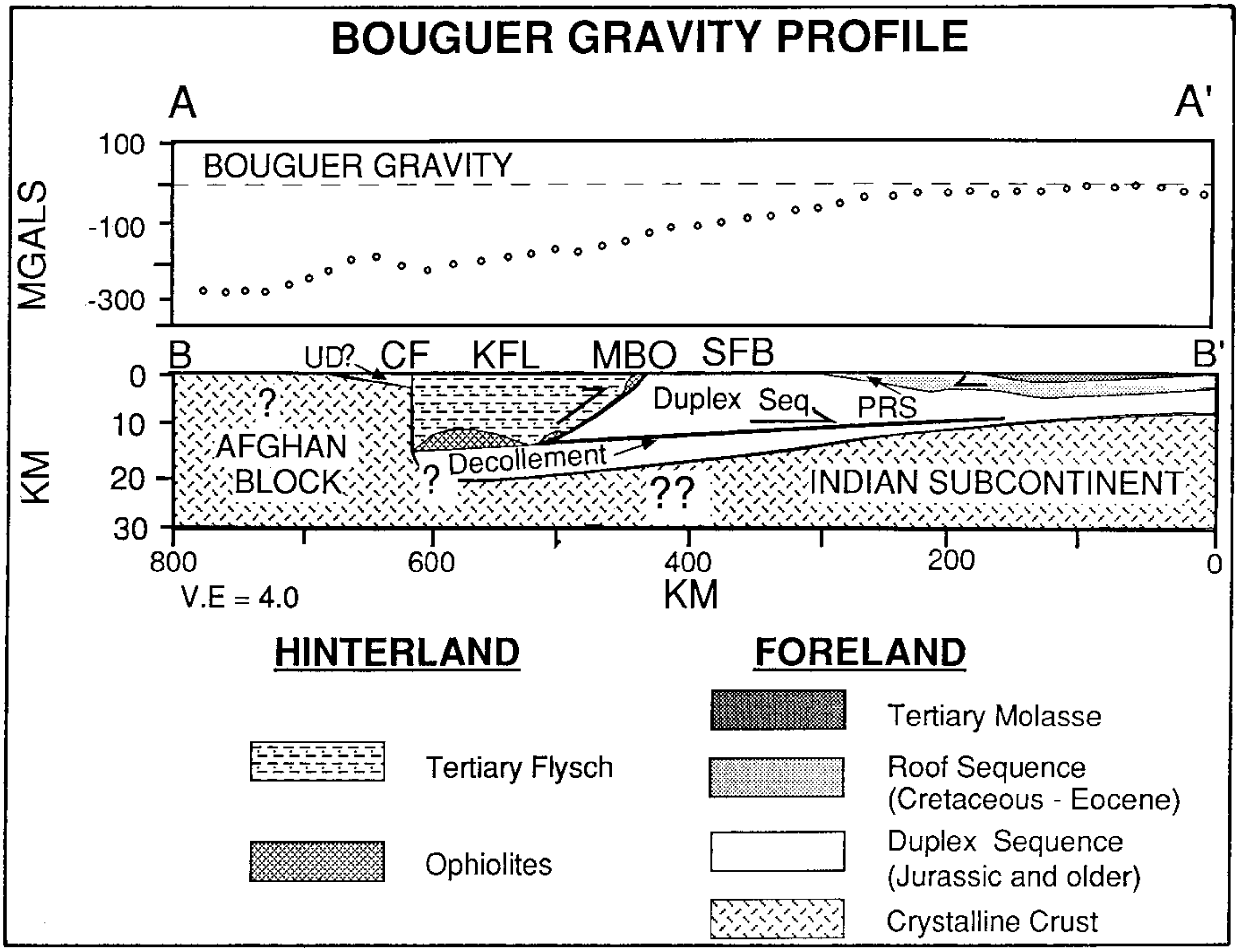

Figure 4— Bouguer gravity anomaly profile and two dimensional geologic sketch along line A-A′ in Figure 1. Observed Bouguer gravity data between mark 0-250 km are from a Bouguer gravity map by the Oil and Gas Development Corporation of Pakistan (OGDC), partially published for southern Indus Basin by Quadri and Shuaib (1986). Gravity data from mark 250 to 800 km are from the map of Marussi (1976). These data are consistent with observations reported by McGinnis (1971) for Afghanistan, and Khurshid (1991) for the zone between the 350-450 km marks. Depth to the basement and structural interpretation in the cover strata are based on the seismic reflection interpretation from the Sulaiman Ranges (line B-B′ in Figure 1 and 3; Jadoon et al., 1991; Jadoon, 1991a and b). CF = Chaman Fault, KFL = Katawaz Flysch Basin (Neogene), MBO = Muslimbagh Ophiolite, PRS = Passive-roof sequence, SFB = Sulaiman Fold Belt, and UD = Undifferentiated.

The effective modelling of Bouguer gravity data requires a constrained depth to the top of the crystalline basement. Estimates of the depth to the top of crystalline basement and the structural interpretation (duplex geometry) in the cover strata in Figure 3 is from Jadoon et al. (1991a) and Jadoon (1991b and c). Seismic reflection data shows the crystalline basement at depth of about 6 km in the Sulaiman foredeep that approaches to about 10 km at the deformation front. Jadoon (1991a and b) suggests an average dip of about 3° to the northwest at the top of the crystalline basement. The extrapolated depth to the top of the crystalline basement in the hinterland of the Sulaiman fold belt is about 20 km (Jadoon, 1991c). These observations and interpretations provided the basic layers for gravity modelling, south of the Muslimbagh ophiolite. This data set is combined with the geological maps (Hunting Survey Corporation, 1961; Kazmi and Rana, 1982) in Pakistan and published work and maps (Wittekindt and Weippert, 1973; Bordet, 1978; Boulin, 1981; Tapponnier et al., 1981) in Afghanistan to construct the

Table 1. Estimated Average Densities of Geologic and Structural Units.

Geologic and Structural Units	Approximate Velocity (km/sec)	Approximate Density (gm/cm^3)
Molasse (Tertiary)	2.5-3.0	2.3
Flysch (Tertiary)	No Seismic Available	2.55-2.65
Roof Sequence (Eocene-Cretaceous)	2.8-4.5	2.55
Duplex Sequence (Jurassic and older)	4.5-5.2	2.65

Note: The P-wave velocities are from seismic reflection interpretations from the southern (Jadoon et al., 1991a) and eastern (Humayon et al., 1991) Sulaiman Range. The approximate densities are estimated from Nafe and Drake curve by Sheriff (1984).

simplified geologic cross-section (A-A′ in Figure 4) to model the observed Bouguer gravity profile from the Sulaiman foredeep to the Chaman fault in eastern Afghanistan (Figure 1). The cross-section (Figure 4) is simplified by showing the basement at the surface north of the Chaman fault because of shallow exposures of crystalline rocks north of the Chaman fault (Wittekindt and Weippert, 1973).The densities for the sediments are obtained by converting seismic reflection velocities from the eastern (Humayon et al., 1991) and southern (Jadoon et al., 1991) Sulaiman Range. Table 1 shows estimates of average P-wave velocities and appropriate densities used for the sedimentary package above the crystalline basement. In the Khojak flysch zone, zone of incipient metamorphism below decollement, and undifferentiated crystalline rocks shown in the Afghan block (Figure 5A). Densities are approximated based on the known densities for the roof and duplex sequences in Table 1. The density for the crystalline crust was assumed to be 2.8 gm/cm^3. This is based on about 6 to 7 km/sec of P-wave velocities from earthquakes (Menke and Jacob, 1976; Kaila, 1981). Standard density contrast of $+0.4\ gm/cm^3$ is used for upper mantle across the Moho. The density model in Figure 5 shows relative density contrasts with an assumed density of 2.8 gm/cm^3 for the crystalline crust.

Bouguer Gravity Modelling and Results

Bouguer gravity anomalies consistently decrease northward from near zero milligals in the Sulaiman foredeep, to about -190 milligals along the Chaman fault and -265 milligals in central Afghanistan (Figure 4). As a first approximation, low values of Bouguer gravity anomalies in the Sulaiman fold belt can be compared with: (1) those of the Salt Range/Potwar plateau and the Main Himalaya in northern Pakistan (Figure 2); and (2) Bouguer gravity modelling along cross-sections of the Kirthar and Sulaiman Ranges respectively (Rahman, 1969; Khurshid, 1991). In the northern Potwar Plateau Bouguer gravity anomalies of -160 mgals are modelled to suggest a full thickness of crystalline crust (Figure 2). The thickness of the sediments in the seismic reflection lines is about 9 km there (Lillie et al., 1987; Jaswal, 1990). In the Kirthar Ranges Bouguer gravity anomalies of about -250 mgals are modelled to suggest a crystalline crust of about 55 km (Rahman, 1969). Alternatively, these large anomalies may be compensated by a shallower mantle underneath the Sulaiman Range (Khurshid, 1991). This second preferred hypothesis, suggesting a transitional crust underneath the Sulaiman Range, is consistent with the presence of a thick (about 7 km) platform sequence beneath the southern Sulaiman front (Jadoon et al., 1989). This supports the interpretation that the Sulaiman fold belt is at an earlier stage of continental collision compared to northern Pakistan. If the Sulaiman fold belt is going through a very early stage of continental convergence, then the Bouguer gravity values should become less negative across the Chaman fault in eastern Afghanistan (The response of Bouguer gravity anomaly values to successive stages of convergence is discussed in Lillie, 1991). Instead, the northward gradient of Bouguer gravity anomaly values continues to decrease in Afghanistan, which suggests thickening of crystalline crust across the plate boundary. The Bouguer gravity profile has a general gradient of -0.35 mgal/km towards the north. This can in general be interpreted as a combined result of the sediment thickness and Moho depth variations (Figure 4). Figures 5A and 5B separate the effect of these contributions on the observed Bouguer gravity profile. Figure 5A (sediment contribution) shows the superimposed gravity lows and highs due to low density molasse sediments in the Sulaiman foredeep, high density Muslimbagh ophiolites, and the crystalline crust of the Afghan block against the Khojak flysch north of the Chaman fault. Figure 5B (mantle contribution) shows the negative northwards gradient due to the northwards dipping Moho with a gentle inclination of about 1^{o}. This overall gradient is modified by a slight upwards convexity of the Moho in the Sulaiman foredeep region and a steeper Moho gradient at the margin of the Afghan block. These effects are interpreted as a result of flexural bending in the Sulaiman foredeep and thickening of the crust of the Afghan block. The slight upward convexity in the foreland is consistent with the distribution of Airy isostatic anomalies from the Sulaiman Range (Khurshid, 1991). Near zero Airy isostatic anomalies (McGinnis, 1971; Marussi, 1976) from eastern Afghanistan could mean that the region north of the Chaman fault is near a state of Airy isostatic equilibrium. The region just south of the Chaman

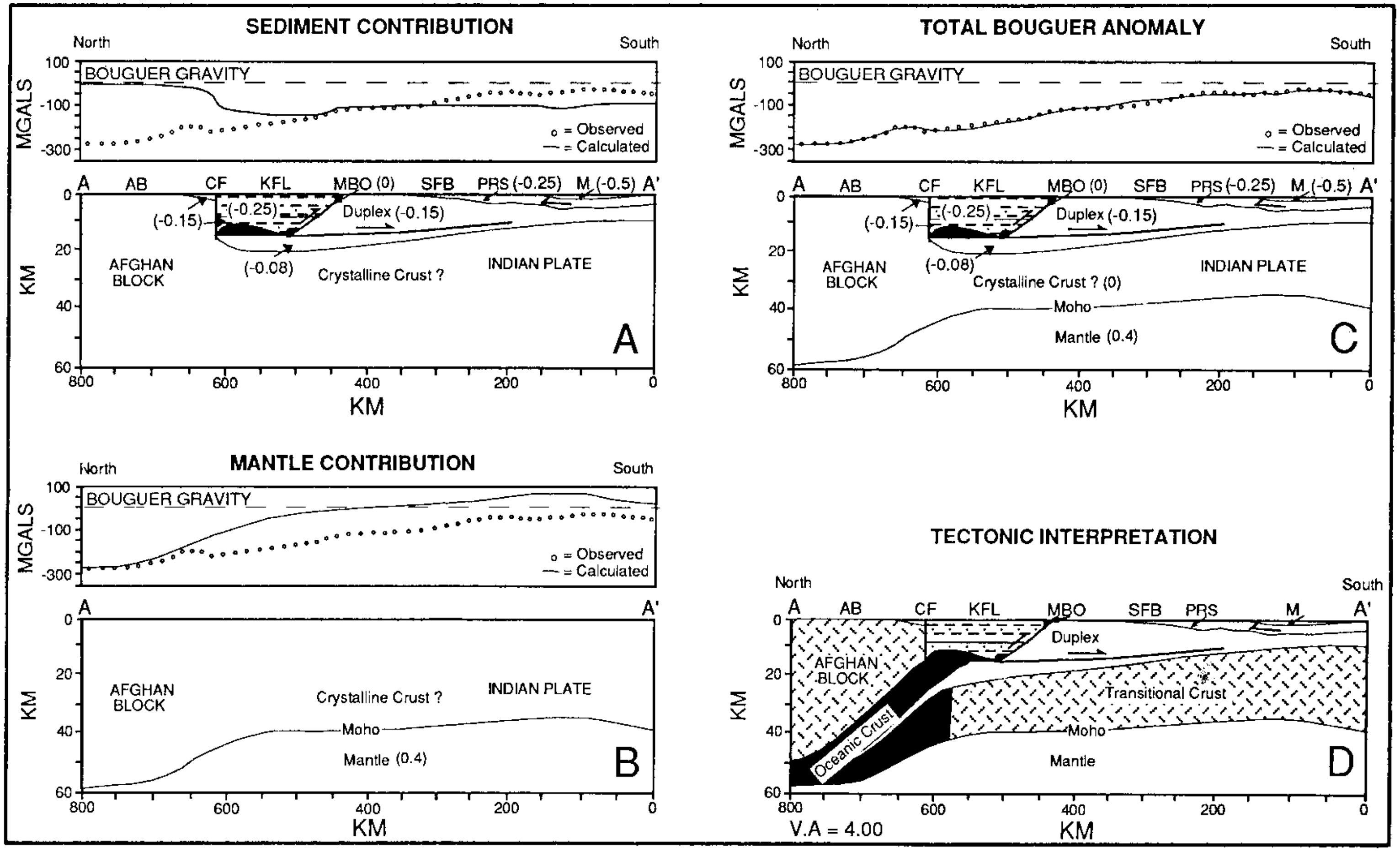

Figure 5— Two dimensional density and tectonic model for observed Bouguer gravity anomaly across the Sulaiman fold belt and the Chaman fault zone. Density contrasts are in gm/cm^3 relative to the crystalline crust. See Figure 4 for details about the source of observed Bouguer gravity data. Depths to the basement, structural interpretation in the cover strata, and approximate densities are controlled by well logs, and seismic reflection profiles from the southern (Jadoon et al., 1991; see Table 1 for density model) and eastern Sulaiman Ranges (Humayon et al., 1991). Abbreviations are the same as in Figure 4. Figures 5A and B show the contribution to the Bouguer gravity anomaly from the sedimentary strata and mantle, respectively. Figure 5C shows the close fit between observed and calculated. Figure 5D represents a two dimensional tectonic model across the Indian/Afghan collision zone based on the density model in Figure 5C.

fault in the Khojak flysch belt is overcompensated (mass deficiency). In contrast, the frontal Sulaiman and adjacent foredeep region is undercompensated (mass excess). Khurshid (1991) suggests that the mass excess in the foreland is shallow mantle material from the Mesozoic rifted continental margin of India, while the deficiency beneath the interior is due to flexural bending associated with Cenozoic collision. Flexure models proposed for the northern Pakistan (Duroy et al., 1989) and central Himalayas (Karner and Watts, 1983; Lyon-Caen and Molnar, 1983 and 1985) effectively explain the anomalous distribution of mass under the active mountain ranges. Figure 5C shows the best match between observed and calculated anomalies. This is obtained by combining the effect due to sediment and mantle contributions (Figures 5A and 5B). The gravity model depicts the depth to the Moho as about 35 km at the deformation front of the Sulaiman fold belt. The Moho is flexed upward in the foredeep. North of the foredeep it has a gentle northward dip of about 1.1° (20 m/km) until it approaches the Chaman fault zone. The depth to the Moho below the Chaman fault zone is about 42 km along the transect. It deepens abruptly across the Chaman fault zone from about 42 km south of the Chaman fault to about 57 km north of the fault. A steep northward dip of 7.8° (136 m/km) to the Moho below the Chaman fault zone results from this model. The Moho regains its gentler northwards dip north of the Chaman fault system. About 57 km depth in eastern Afghanistan is consistent with previously interpreted crustal thicknesses of 53 km in central Afghanistan (McGinnis, 1971). Figure 5D suggests my preferred tectonic interpretation of the density model in Figure 5C.

DISCUSSION

Tectonic Implications

The crustal model developed above (Figure 5D) from the Sulaiman foredeep across eastern Afghanistan (A-A′ in Figure 1) as several important tectonic implications. These are as follows:

1) The model (Figure 5D) shows that crystalline crust is about 27 km thick in the Sulaiman foredeep. It thins to about 20 km in the hinterland of the Sulaiman fold belt. This suggests Sulaiman fold belt to overlie a broad (300 km) transitional crust related to the western pre-collisional passive margin of the Indian subcontinent. This interpretation is consistent with S-wave studies of earthquakes (Chun, 1986) and recent Bouguer gravity modelling along an east-west profile from the Sulaiman Range (D- D' in Figure 1; Khurshid, 1991). Crust closer to oceanic thickness is apparently underthrusting the Afghan block beneath the Chaman fault zone (Figure 5D) as the distal end of the Indian plate crust.

2) Across the Chaman fault, crystalline crust thickens dramatically to about 57 km in eastern Afghanistan. The model (Figure 5D) suggests that this change in the crustal variation across the Indian- Afghan collision zone may be due to: (a) structural thickening within the Afghan block; or (b) underplating by oceanic crust of the Indian subcontinent.

3) The intact transitional crust (20 km) and lack of basement involvement under the Sulaiman fold belt contrast with the full thickness crystalline crust (about 38 km) underneath the Salt Range/Potwar Plateau (Duroy et al., 1989) and hinterland basement involvement (Baig, 1990) in northern Pakistan. This suggests an early stage of convergence along the western margin of the Indian subcontinent.

4) Bouguer gravity modelling along A-A′ (herein) and D-D′ (Khurshid, 1991) in Figure 1 constrains the attitude of the Moho underneath the Sulaiman fold belt. Crustal variation along these sections suggests a dip of 1° toward N57°W to the Moho underneath the Sulaiman fold belt. Seismic and well data resolves nearly the same dip direction, but a larger dip of about 3° at the top of the crystalline basement (Jadoon, 1991b). Thus the strikes (N33°E) at the top and the base of the north-westwards thinning crystalline basement are about the same. This northeast basement strike underneath the Sulaiman Range suggests that the former passive margin on the western edge of the Indian subcontinent was oriented at almost right angles to the northwest-southeast- trending passive margin involved in the main Himalayan orogeny (Seeber et al., 1981).

5) Precollisional (Cretaceous) western passive margin of the Indian subcontinent may resemble to the Blake Plateau Basin of the US Atlantic continental margin (Grow and Sheridan, 1981; Klitgord et al., 1988) in that both margins have a post-rift platform sequence more than 7 km thick, and a broad (about 350 km) transitional crust with an average thickness of 20 km.

Kinematic Model of Crustal Development

An evolutionary diagram beginning in the Jurassic (precollision) models the crustal structures, timing, and rate of deformation across the Indian/Afghan collision zone (Figure 6). In the Jurassic, the Neotethys ocean separated the Afghan block from the Indian subcontinent (Figure 6A). Deformation of the northern Tethys margin started along a northwards subducting slab of Tethys oceanic lithosphere along the south margin of paleo-Asia (Figure 6B). This produced the mid-Cretaceous Kandahar andesitic arc (Lawrence et al., 1981b; Farah et al., 1984; Debon et al., 1986). Deformation of the northwestern

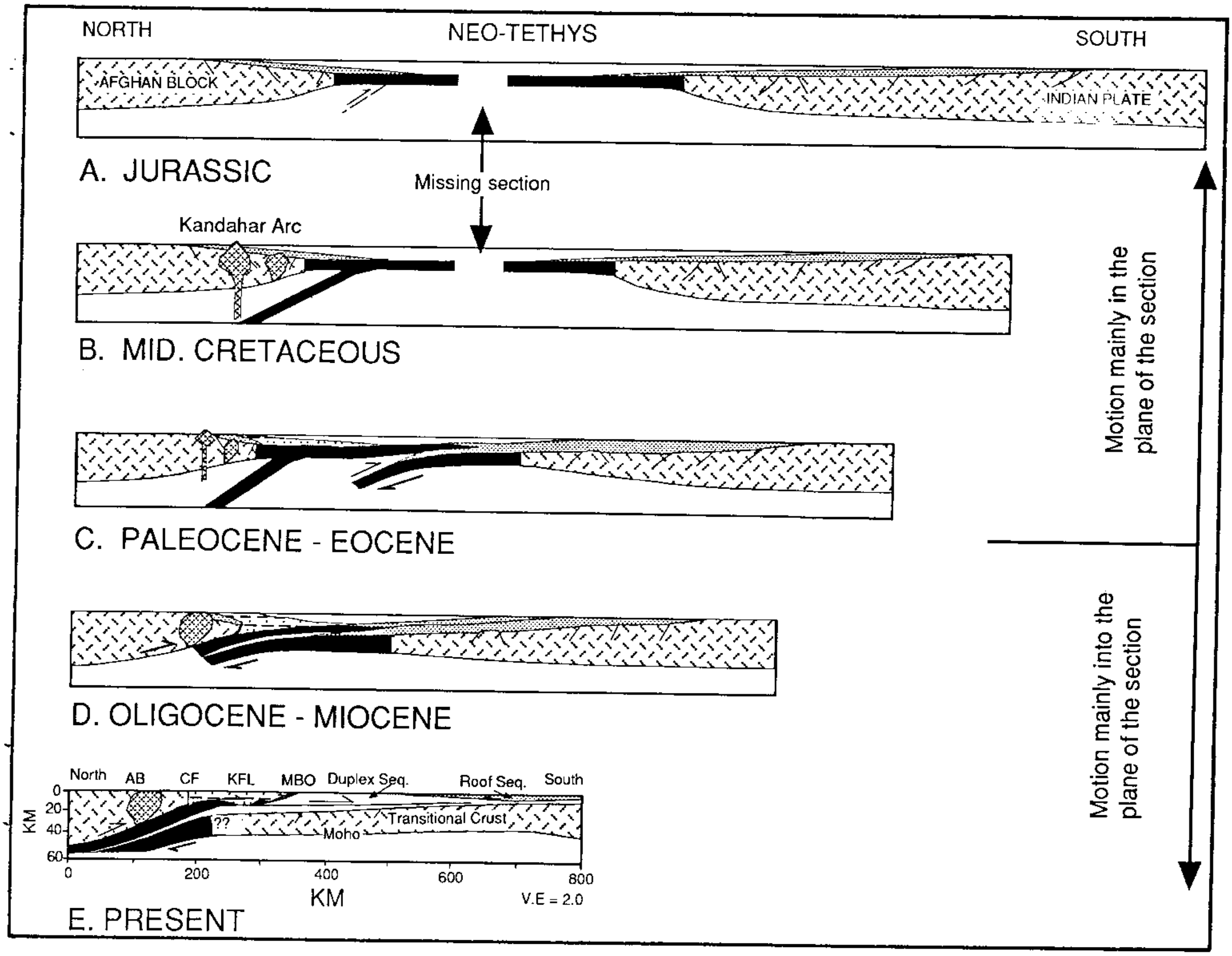

Figure 6— Kinematic model inferring the tectonic development across the Indian/Afghan collision zone. A) In Jurassic the Neotethys Ocean separated the Afghan Block from the Indian subcontinent; B) Subduction of the Neotethys and Cretaceous Kandahar andesitic arc volcanism at the leading edge of the Indian subcontinent (Lawrence et al., 1981b; Debon et al., 1986); C) Paleocene to early Eocene records the emplacement of Muslimbagh Ophiolites (MBO) over the Cretaceous shelf sediments, onlapped by Eocene limestone (Allemann, 1979; Otsuki et al., 1989); D) Deposition and deformation of Eocene-Miocene Khojak flysch and closure of the ocean basin (Lawrence et al., 1981a; Lawrence and Khan, 1991a). Subsequent initiation of sinistral motion along the earlier thrust that now becomes the Chaman fault. After initiation of the Chaman fault todate, 353±25 km of shortening has occured in the shelf and slope facies of the Indian subcontinent (present day Sulaiman fold belt); E) Present situation.

margin of the Indian subcontinent, the future Sulaiman area, started by the Paleocene to early Eocene emplacement of the Muslimbagh ophiolites (Allemann, 1979; Otsuki et al., 1989). This event is constrained by the emplacement of ophiolites over Maastrichtian shelf sediments and onlap of Eocene platform rocks (Figure 6C; Allemann, 1979; Otsuki et al., 1989). During the emplacement of the ophiolites, distal, deep-marine facies of Triassic rocks were scraped from the downgoing plate and were transported south eastwards beneath the translating oceanic lithosphere (Otsuki et al., 1989). Otsuki et al. (1989) suggest that these exotic facies which include some basalt flows were deposited near a mid-ocean ridge in relatively shallow water. They may have travelled 200-300 km during the emplacement of the Muslimbagh ophiolite (Otsuki et al., 1989). Deposition of the Khojak flysch occurred on remaining oceanic lithosphere between the Eocene and late Oligocene with the early Himalayan uplift as the most likely sediment source (Lawrence and Khan, 1991a). Continued oblique convergence in the late

Oligocene to early Miocene (2515 Ma?) resulted in the final closure of the ocean, the initiation of the left-lateral strike-slip Chaman fault system, and deformation of the Khojak flysch (Figure 6D; Lawrence and Khan, 1991b). Since then 353±25 km of shortening has occurred in the cover sediments of the Indian subcontinent (Jadoon, 1991c). Figure 6E represents the present crustal model. Present model shows that the structures at the surface (including the sinistral Chaman fault and the Sulaiman thrust system) are restricted to a brittle flake above a decollement at brittle/ductile transition. Below the decollement oceanic/transitional crust related to the former Mesozoic passive margin of the Indian plate is preserved and is underthrusting the Afghan block. This suggests deformation partitioning with transpression in the thin-skinned brittle wedge above and pure translation of the distal end of the rigid Indian plate below the decollement. This model is similar to the flake tectonic hypothesis (Oxburg, 1972) proposed for the transverse ranges (Yeats, 1981), central California margin (Crouch et al., 1984), and northern Pakistan (Seeber, 1983). Crouch et al. (1984) have proposed that the shortening along the strike-slip and thrust faults in the upper crust is separated from a lower, possibly oceanic crustal layer, along an aseismic zone of decollement. The Pacific/North American plate boundary is located to the east of the San Andreas fault in their model similar to the presence of rigid Indian plate to the west of the Chaman fault in my model (Figure 6E).

CONCLUSIONS

Gravity modelling along a north-south transect from the southern Sulaiman foredeep in Pakistan across the Chaman fault zone in eastern Afghanistan suggests that the Sulaiman fold belt is a northward thickening wedge of sediments thrust over transitional crust of the western passive margin of the Indian subcontinent. Crystalline crust of about 27 km thickness in the southern Sulaiman foredeep thins northward to become 20 km thick underneath the hinterland of the Sulaiman fold belt. Moho that dips gently to the NNW, steepens abruptly along the Chaman fault system. As a result crystalline crust thickens to about 57 km in eastern Afghanistan. This thick crystalline crust may be due to: (1) structural thickening within the Afghan block; and (2) underplating by crust of the Indian subcontinent. A geological model suggests that the western Mesozoic passive margin of the Indian subcontinent, trending NNE and dipping to the NW is underthrusting the Afghan block along a decollement at about 15 km depth in the hinterland of the Sulaiman fold belt. Deformation partitioning is occurring along the Indian/Afghan collision zone by pure translation of the rigid Indian plate below the decollement transpression with internal deformation (including the sinistral Chaman fault and the Sulaiman thrust system) in the thin-skinned brittle wedge above, and buttressing by the relatively rigid Afghan block.

ACKNOWLEDGEMENT

This work in the Sulaiman fold belt is part of a cooperative project between Oregon State University (OSU), Oil and Gas Development Corporation of Pakistan (OGDC), and the Hydrocarbon Development Institute of Pakistan (HDIP). Ishtiaq at Oregon State University was supported by a scholarship from the United States Agency for International Development (USAID) to the Government of Pakistan. Northwest Geophysical Associates of Corvallis are acknowledged for donating the GM-SYS program to Oregon State University for gravity modelling. I gratefully acknowledge L. Seeber, K. DeJong, Bob Yeats, Alan Niem, and Jon Kimerling for critical review of a preliminary manuscript and Khurshid Akbar for discussions. Bob Lillie and Bob Lawrence are duly acknowledged for their constant enthusiastic guidance, critical comments, and review of many manuscripts. Special thanks are due to Arif Kemal, Azam Malik from OGDC and Hilal Raza, Riaz Ahmed, Manshoor Ali, from HDIP for their cooperation.

REFERENCES

Abbas, G., and Z. Ahmad, 1979, The Muslimbagh Ophiolites, in A. Farah, and K.A. DeJong, eds., Geodynamics of Pakistan, Geol. Surv. of Pakistan, Quetta, p.243-250.

Allemann, F., 1979, Time of emplacement of the Zhob valley ophiolites and Bela ophiolites, in A. Farah and K.A. DeJong, eds., Geodynamics of Pakistan, Geol. Surv. of Pakistan, Quetta, p.215-242.

Baig, M.S., 1990, Structure and geochronology of pre-Himalayan and Himalayan orogenic events in the northwest Himalaya, Pakistan, with special reference of the Besham area: Ph.D thesis, Oregon State University, Corvallis, Oregon, 397p.

Banks, C.J., and J. Warburton, 1986, 'Passive-roof' duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belt, Pakistan: Journal of Structural Geology, v.8, p.229-237.

Bordet, P., 1978, The western border of the Indian plate: implications for Himalayan geology: Tectonophysics, v.51, p.171-176.

Boulin, J., 1981, Afghanistan structure, greater India concept, and eastern Tethys evolution: Tectonophysics, v.72, p.261-287.

Chun, Kin-Yip., and Yoshii, 1977, Crustal structure of the Tibet Plateau: a surface wave study by moving window analysis: Bull. Seis. Soc. of Amer. v.67, p.735-750.

Chun, Kin-Yip., 1986, Crustal block of the western Ganga Basin: A fragment of oceanic affinity: Bull. Seis. Soc. of Amer., v.76, p.1687-1698.

Crouch, J.K., S.B. Bachman, and J.T. Shay, 1984, Post-Miocene compressional tectonics along the central California margin, in J.K. Crouch, and S.B. Bachman, eds., Tectonics and Sedimentation Along the California Margin: Pacific Section, v.38, p.37-54.

Debon, F., H. Afzali, P. LeFort, and J. Sonet, 1986, Plutonic belts in Afghanistan: Typology, Age, and Geodynamic setting: Sciences de la Terre, Memoire 47, p.129-153.

Duroy, Y., 1986, Subsurface densities and lithospheric flexure of the Himalayan foreland in Pakistan, interpreted from gravity data: M.Sc. thesis, Oregon State University, Corvallis, Oregon, 77p.

Duroy, Y., A. Farah, and R.J. Lillie, 1989, Subsurface densities and lithospheric flexure of the Himalayan foreland in Pakistan, in L.L. Malinconico and R.J. Lillie, eds., Tectonics of the western Himalayas: Geol. Soc. of Amer., Special Paper 232, p.217-236.

Farah, A., M.A. Mirza, and M.H. Butt, 1977, Gravity field of the buried shield in the Punjab Plain, Pakistan: Geol. Soc. of Amer. Bull., v.88, p.1147-1155.

Farah, A., G. Abbas, K.A. DeJong, and R.D. Lawrence, 1984, Evolution of the lithosphere in Pakistan: Tectonophysics, v.105, p.207-227.

Gansser, A., 1981, The geodynamic history of the Himalaya, in H.K. Gupta, and F. Delany, eds., Zagros, Hindu Kush, Himalaya: Geodynamic evolution, Amer. Geophy. Union, Geodynamic Series, v.3, p.111-121.

Grow, J.A., and R.E. Sheridan, 1981, Deep structure and evolution of the continental margin off the United States: Oceanologica Acta, Geology of continental margins symposium, Paris, July 7-17, p.11-19.

Gupta, H.K., and H. Narain, 1967, Crustal structure of the Himalayan and the Tibet Plateau regions from surface wave dispersion: Bull. Seis. Soc. of Amer., v.57, p.235-248.

Humayon, M., R.J. Lillie, and R.D. Lawrence, 1991, Structural interpretation of eastern Sulaiman fold belt and foredeep, Pakistan: Tectonics, v.10, p.299-324.

Hunting Survey Corp., 1961, Reconnaissance geology of part of West Pakistan: A Columbo Plan Cooperative Project, Government of Canada, Toronto, Canada, 550p.

Izatt, C.N., 1990, Variation in thrust front geometry across the Potwar Plateau and Hazara/Kalachitta Hill Ranges, northern Pakistan: Ph.D thesis, Imperial College of Science, Technology, and Medicine, University of London, 353p.

Jadoon, I.A.K., R.J. Lillie, M. Humayon, R.D. Lawrence, S.M. Ali, and A. Cheema, 1989, Mechanism of deformation and the nature of the crust underneath the Himalayan foreland fold-and-thrust belts in Pakistan: EOS, Transaction, Amer. Geophy. Union, v.70, p.1372-1373.

Jadoon, I.A.K., R.D. Lawrence, and R.J. Lillie, 1991a, Balanced and retrodeformed geological cross-section from the frontal Sulaiman Lobe, Pakistan: Duplex development in thick strata along the western margin of the Indian plate, in K. McClay, ed., Thrust Tectonics, Chapman and Hall, London, p.343- 356.

Jadoon, I.A.K., 1991b, The style and evolution of foreland structures: An example from the Sulaiman lobe, Pakistan: Pak. Jour. of Hydrocarbon Res., v.3, n.2, p.1-17.

Jadoon, I.A.K., 1991c, Thin-skinned tectonics on continent/ocean transitional crust, Sulaiman Range, Pakistan: Ph.D thesis, Oregon State University, Corvallis, Oregon, 154p.

Jaswal, T., 1990, Structure and evolution of the Dhurnal oil field, Northern Potwar Deformed Zone, Pakistan: M.Sc. thesis, Oregon State University, Corvallis, Oregon, 62p.

Kaila, K.L., 1981, Structure and seismotectonics of the Himalaya-Pamir-Hindukush Region and the Indian plate boundary, in H.K. Gupta and F. Delany, eds., Zagros, Hindu Kush, Himalaya, Geodynamic evolution: Amer. Geophy. Union, Geodynamic Series, v.3, p.272-293.

Karner, G.D., and A.B. Watts, 1983, Gravity anomalies and flexure of the lithosphere at mountain ranges: Journ. of Geophy. Res., v.88, p.10449-10477.

Kazmi, A.H., and R.A. Rana, 1982, Tectonic map of Pakistan, 1:2,000,000: Geol. Surv. of Pakistan, Quetta.

Keller, G.R., L.W. Braile, G.A. McMechan, W.A. Thomas, W. Chang, and W.G. Jardine, 1989, Paleozoic continent-ocean transition in the Ouachita Mountains imaged from PASSCAL wide-angle seismic reflection-refraction data: Geology, v.17, p.119-122.

Khurshid, A., 1991, Crustal structure of the Sulaiman Range, Pakistan from gravity data: M.Sc. thesis, Oregon State University, Corvallis, Oregon, 56p.

Klitgord, K.D., D.R. Hutchinson, and H. Schouten, 1988, U.S. Atlantic continental margin; Structural and tectonic framework, in R.E. Sheridan and J.A. Grow, eds., Atlantic continental margin, U.S.: Geological Society of America, The Geology of North America, v.I-2, p, 19-53.

Klootwijk, C.T., R. Nazirullah, K.A. DeJong, and A. Ahmad, 1981, A paleomagnetic reconnaissance of northern Balochistan, Pakistan: Journ. of Geophy. Res., v.86, p.289-305.

----------, P.J. Conaghan, and C.M. Powell, 1985, The Himalayan Arc: large-scale continental subduction, oroclinal bending, and back-arc spreading: Geologische Rundschan, v.67, p.37-48.

Lawrence, R.D., S.H. Khan, K.A. DeJong, A. Farah, and R.S. Yeats, 1981a, Thrust and strike-slip fault interaction along the Chaman fault zone, Pakistan, in K.R. McClay and N.J. Price, eds., Thrust and Nappe Tectonics, Geol. Soc. of London, Special Publication 9, p.363-370.

----------, R.S. Yeats, S.H. Khan, A.M. Subhani, and D. Bonelli, 1981b, Crystalline rocks of the Spinatizha area, Pakistan: Journ. of Struc. Geol., v.3, p.449- 457.

----------, and S.H. Khan, 1991a, Structural reconnaissance of Khojak flysch, Pakistan and Afghanistan (in prep.).

----------, ----------, 1991b, Chaman fault, Pakistan, Afghanistan (in prep.).

LeFort, P., 1975, Himalayas: the collided Range, Present knowledge of the continental arc: Amer. Journ. of Sc., v.275, p.1-44.

Lillie, R.J., 1985, Tectonically buried continent/ocean boundary, Ouachitas Mountains, Arkansas: Geology, v.13, p.18-21.

----------, G.D. Johnson, M. Yousaf, A.S.H. Zaman, and R.S. Yeats, 1987, Structural development within the Himalayan foreland fold-and-thrust belt of Pakistan, in C. Beaumont and A.J. Tankand, eds., Sedimentary basins and basin-forming mechanisms: Canadian Soc. of Pet. Geol. Mem. 12, p.379-392.

----------, R.D. Lawrence, M. Humayon, and I.A.K. Jadoon, 1989, The Sulaiman thrust Lobe of Pakistan: Early stage underthrusting of the Mesozoic rifted margin of the Indian subcontinent: Geol. Soc. of Amer., Abstract with Program, v.21, p.A318.

----------, 1991, Evolution of gravity anomalies across collisional mountain belts: clues to the amount of continental convergence and underthrusting: Tectonics (in press).

Lyon-Caen, H., and P. Molnar, 1983, Constraints on the structure of the Himalaya from an analysis of gravity anomalies and a flexure model of the lithosphere: Journ. of Geophy. Res., v.88, p.8171-8191.

----------, ----------, 1985, Gravity anomalies, flexure of the Indian plate, and the structure, support and evolution of the Himalaya and Ganga Basin: Tectonics, v.4, p.513-538.

Malik, Z., A. Kemal, and J.W. Boudenhausen, 1988, Petroleum potential and prospects in Pakistan, in H.A. Raza and A.M. Sheikh, eds., Proc. International symposium on Petroleum for the Future, Jan. 28-30, Islamabad, Pakistan.

Malinconico, L.L., 1982, Structure of the Himalayan suture zone in Pakistan interpreted from gravity and magnetic data: Ph.D thesis, Dartmouth College, Hanover, New Hampshire, U.S.A., 128p.

-----------, 1986, The structure of the Kohistan Island-Arc inferred from gravity data: Tectonophysics, v.124, p.297-307.

----------, 1989, Crustal thickness estimates for western Himalayas, in L.L. Malinconico and R.J. Lillie, eds., Tectonics of the western Himalayas: Geol. Soc. of Amer., Special paper 232, p.237-242.

Marussi, A., 1976, Introductory report of geophysics, in Geotectonica Delle Zone Orogeniche Del Kashmir Himalaya, Karakoram-Hindukush-Pamir: Accademia Dei Lincei, v.21, p.15-25.

McGinnis, L.D., 1971, Gravity field and tectonics in the Hindukush: Journ. of Geophy. Res., v.76, p.1894-1904.

Menke, W.H., and K.H. Jacob, 1976, Seismicity pattern in Pakistan and northwestern India associated with continental collision: Seis. Soc. of Amer. Bull., v.66, p.1695-1711.

Molnar, P., and P. Tapponnier., 1975, Cenozoic tectonics of Asia: effects of a continental collision: Science, v.189, p.419-426.

Molnar, P., 1984, Structure and tectonics of the Himalaya: Constraints and implications of Geophysical data: Annual review of the Earth and Planetary Science, v.12, p.489-518.

Otsuki, K., M. Anwar, J.M. Mengal, I.A. Brohi, K. Hohino, A.N. Fatmi, and Y. Okimura, 1989, Muslimbagh area of Balochistan: Geol. Bull., University of Peshawar, v.22, p.103- 126.

Oxburg, E.R., 1972, Flake tectonics and continental collision: Nature, v.239, p.202-204.

Powell, C.M.A., 1979, A speculative tectonic history of Pakistan and surroundings: Some constraints from Indian Ocean, in A. Farah and K.A. DeJong, eds., Geodynamics of Pakistan, Geol. Surv. of Pakistan, Quetta, p.5-24.

Quadri, V.N., and M. Shuaib, 1986, Hydrocarbon prospects of southern Indus basin: AAPG Bull., v.70, p.730-747.

Quittmeyer, R.C., A. Farah, and K.H. Jacob, 1979, The seismicity of Pakistan and its relation to surface faults, in A. Farah and K.A. DeJong, eds., Geodynamics of Pakistan, Geol. Surv. of Pakistan, Quetta, p.271-284.

----------, A.A. Kaffa, and J.G. Armbruster, 1984, Focal mechanism and depths of earthquakes in central Pakistan: A tectonic interpretation: Journ. of Geophy. Res., v.89, p.2459- 2470.

Rahman, A., 1969, Crustal section across the Sibi- Syntaxial Bend, West Pakistan, Based on gravity measurements: Journ. of Geophy. Res., v.74, p.4367-4370.

Sarwar, G., and K.A. DeJong, 1979, Arcs, oroclines, syntaxes: The curvature of mountain belts in Pakistan, in A. Farah and K.A. DeJong, eds., Geodynamics of Pakistan, Geol. Surv. of Pakistan, Quetta, p.341-349.

Searle, M.P., 1986, Structural evolution and sequence of thrusting in the High Himalayan, Tibetan-Tethys and Indus suture zones of Zanskar and Ladakh, western Himalaya: Journ. of Struc. Geol., v.8, p.923-936.

Seeber, L., J.G. Armbruster, and R.C. Quittmeyer, 1981, Seismicity and continental subduction in the Himalayan Arc, in H.K. Gupta and F.M. Delany, eds., Zagros, Hindukush, Himalaya; geodynamic evolution: Amer. Geophy. Union Geodynamic Series, v.3, p.215-242.

Seeber, L., 1983, Large scale thin-skinned tectonics: Review of Geophysics and Space Physics, v.21, p.1528- 1538.

Sheriff, R.E., 1984, Encyclopedic dictionary of exploration geophysics, 2nd ed: Society of exploration geophysicists, 323p.

Tapponnier, P., M. Mattauer, F. Proust, and C. Cassaigneau, 1981, Mesozoic ophiolites, sutures, and large-scale movements in Afghanistan: Earth and Planetary Science Letters, v.52, p.355- 371.

Wittekindt, H., and D. Weippert, 1973, Geological map, central southern Afghanistan: Geol. Surv., Fed. Repub. of Germany, Hannover and Kabul.

Yeats, R.S., 1981, Quaternary flake tectonics of the California Transverse Ranges: Geology, v.9, p.16-20.