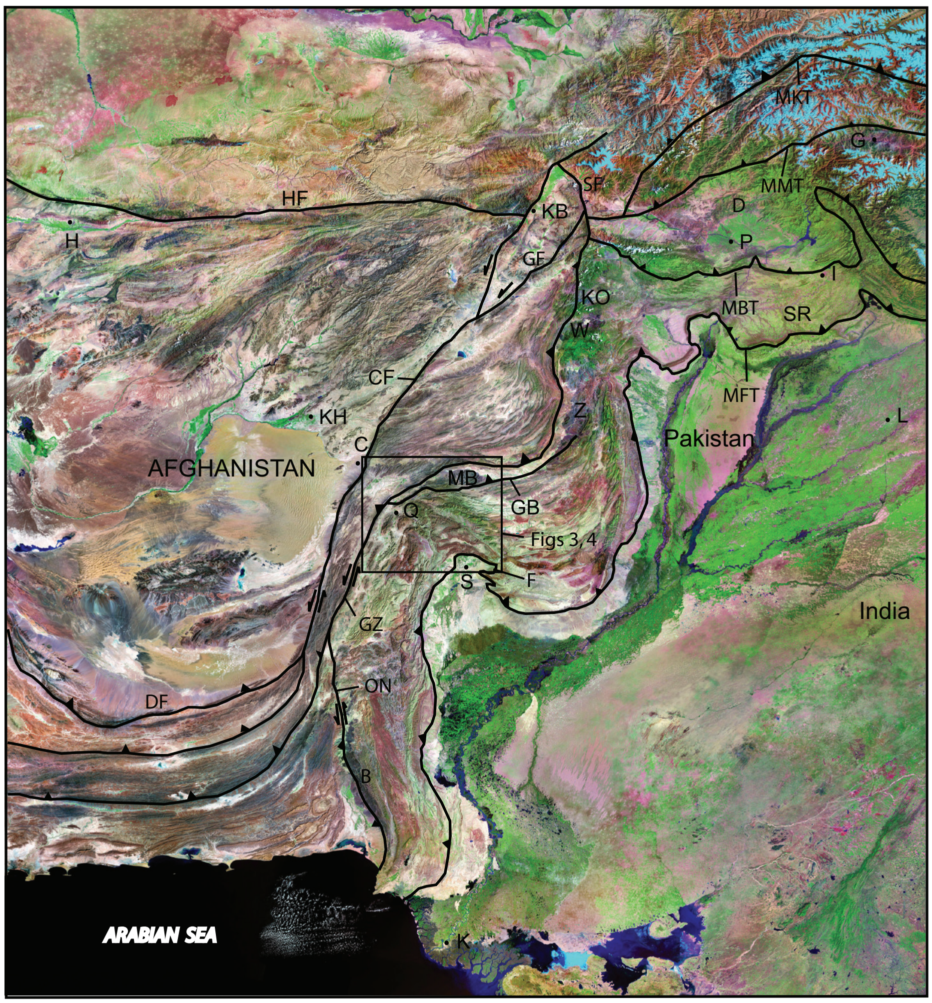
# Summary of the Stratigraphy and Structural Elements Related to Plate Convergence of the Quetta-Muslim Bagh-Sibi Region, Balochistan, West-Central Pakistan

By Florian Maldonado, Jan M. Mengal, Shahid H. Khan, and Peter D. Warwick

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**Cover:** Landsat imagery showing study area in West-Central Pakistan.

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## Figure

# Summary of the Stratigraphy and Structural Elements Related to Plate Convergence of the Quetta-Muslim Bagh-Sibi Region, Balochistan, West-Central Pakistan

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## Abstract

Obduction of an ophiolite complex onto the northwestern continental margin of the India plate occurred during the Late Cretaceous to early Paleocene, followed by collision of the ophiolitic complex of the India plate with the Eurasia plate in the Eocene. Lower Eocene marine strata overlie the ophiolitic complex suggesting that suturing was completed by early Eocene time.

The Quetta-Muslim Bagh-Sibi region is a structurally complex area within west-central Pakistan characterized by broad and tight folds, and reverse, thrust, and strike-slip faults. In order to understand this complex deformation, we have divided this region into five structural domains which are separated by four major boundary faults formed during four major periods of deformation related to oblique convergence of the India and Eurasia plates.

The five structural domains are (1) a foredeep, (2) a foreland fold-and-thrust belt, (3) a major deep trough that formed within the foreland fold-and-thrust belt and filled with collision molasse, (4) a thick flysch deposit, and (5) a subduction-obduction and related igneous rock terrane on the margin of the Eurasia plate (Afghan block).

The four major faults that bound the structural terrane are the Frontal (F), Ghazaband-Zhob (GZ), Gwal-Bagh (GB), and Chaman (C) faults. Four major periods of deformation are recognized: (1) emplacement of ophiolitic rocks onto the continental margin of the India plate; (2) convergence of the India-Eurasia plates; (3) deposition of Tertiary–Quaternary molasse units followed by major folding and thrusting, and formation of strike-slip faults; and (4) deposition of Pleistocene molasse units with subsequent folding, thrusting, and strike-slip motion that continues to the present.


## Introduction

The purpose of this paper is to summarize the stratigraphy of the area and to discuss the individual structural elements within this complex area in the context of current collision structural models to further the understanding of collision zones.

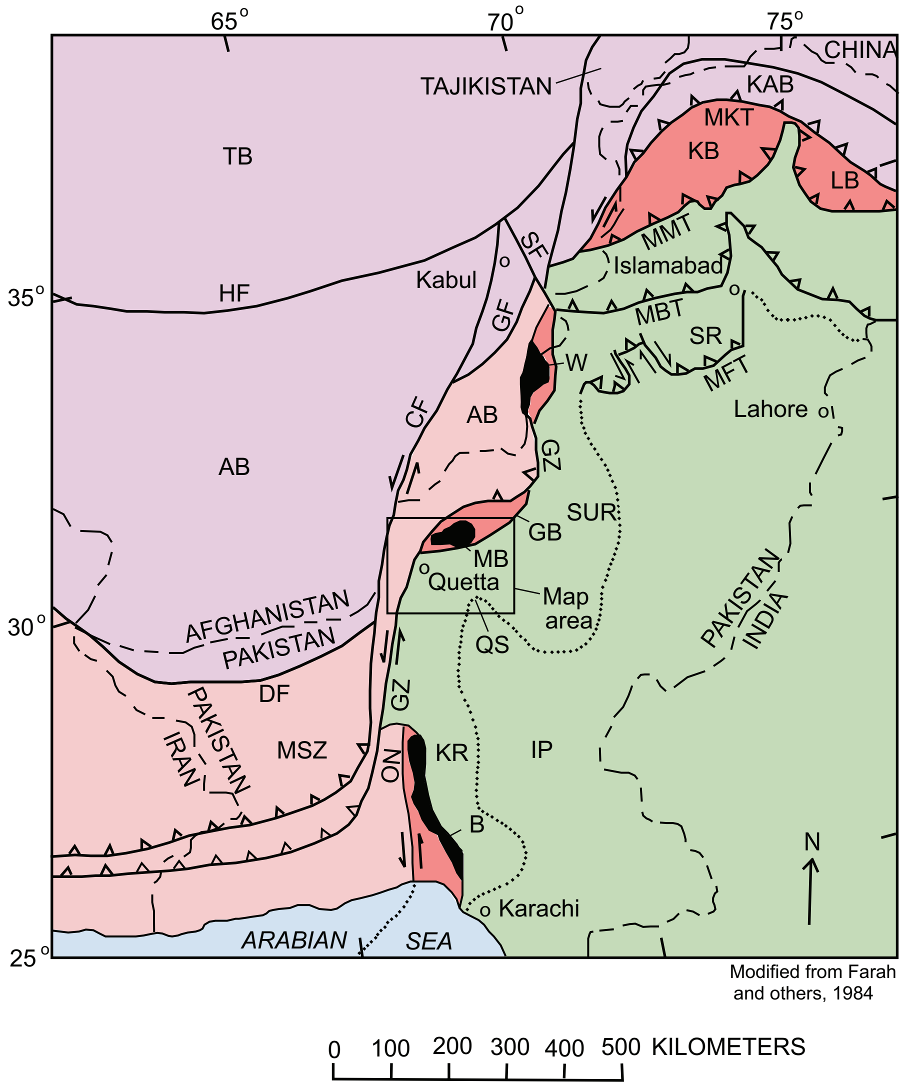
The closing of the Neotethys ocean, the result of collision of the India plate with the Eurasia plate, is documented in rocks of the Quetta-Muslim Bagh-Sibi region, a structurally complex area within the Sulaiman-Kirthar foldbelt (Quetta syntaxis) in west-central Pakistan (figs. 1, 2, 3). The region is characterized structurally by broad and tight folds, and reverse, thrust, and strike-slip faults. The region contains five structural domains as a consequence of deformation related to oblique convergence of the India and Eurasia plates. Four major faults that bound the structural domains are identified, and four major periods of deformation are recognized.

The sources of geologic map data are primarily 1:253,440-scale geologic maps prepared by the Hunting Survey Corporation, Limited (1960), the geologic map of the Muslim Bagh Ophiolite Complex and Bagh Ophiolite Complex area (Mengal and others, 1993), and the 1:50,000-scale geologic map of the Quetta-Muslim Bagh-Sibi region (fig. 4) (Maldonado and others, 1998, 2011). Additional references are provided following the references cited.

## Geologic Setting

### General Review of Stratigraphy

The pre-Eocene depositional setting of the exposed rocks in the study area was that of a stable marine shelf derived from the Indian subcontinent (Shah, 1977). These deposits are represented by more than 5,000 m of carbonate rocks and subordinate amounts of sandstone and mudstone. Overlying the shelf rocks, the Eocene Ghazij Formation (>1,600 m thick) is predominately a siliciclastic marine shelf sequence that has a very different depositional history than that of the underlying carbonate sequence (Warwick and others, 1998; Johnson and others, 1999). The Ghazij Formation is conformably overlain by middle Eocene and




EXPLANATION

Eurasia plate

Makran-Khojak-Pishin flysch belt

Bela-Muslim Bagh-Waziristan-Ophiolite belt and Kohistan-Ladakh block

India plate

| | |
|---|---|
| AB | Afghanistan block |
| B | Bela Ophiolite |
| CF | Chaman fault |
| DF | Dalbandin fault |
| GB | Gwal-Bagh fault |
| GF | Gardez fault |
| GZ | Ghazaband-Zhob fault |
| HF | Herat fault |
| IP | India plate |
| KAB | Karakoram block |
| KB | Kohistan block |
| KR | Kirthar Range |
| LB | Ladakh block |
| MB | Muslim Bagh Ophiolite and Bagh Complexes |
| MBT | Main boundary thrust |
| MFT | Main frontal thrust |
| MKT | Main Karakoram thrust |
| MMT | Main mantle thrust |
| MSZ | Makran subduction zone |
| ON | Ornach-Nal fault |
| QS | Quetta syntaxis |
| SF | Sarobi fault |
| SR | Salt Range |
| SUR | Sulaiman Range |
| TB | Turan block |
| W | Waziristan Ophiolite |

Ophiolite

Fault

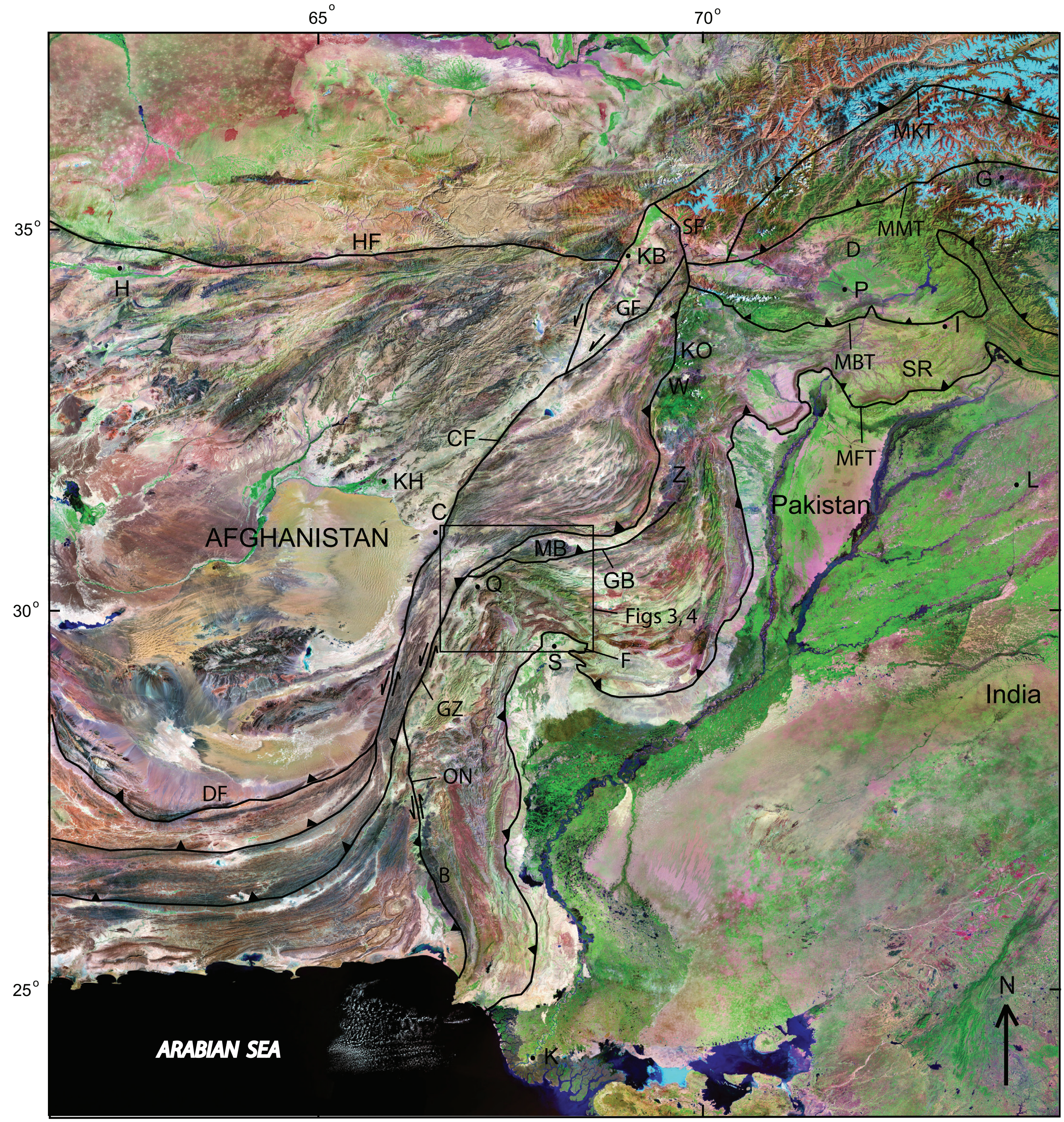
Thrust fault

Strike-slip fault

Concealed tectonic boundaries

Approximate international boundary

**Figure 1.** Tectonic map showing study area.




Longitude and latitude approximately located.

**Figure 2.** Landsat imagery showing study area. Geology modified from Farah and others, (1984) and Maldonado and others, (1998). C, Chaman; G, Gilgit; H, Herat; I, Islamabad; K, Karachi; KB, Kabul; KD, Kandahar; L, Lahore; P, Peshawar; Q, Quetta; S, Sibi; SR, Salt Range; B, Bela Ophiolite Complex; D, Dargai Ophiolite complex; KO, Khost Ophiolite Complex; MB, Muslim Bagh-Bagh Ophiolite Complex; WO, Waziristan Ophiolite Complex; Z, Zohob Ophiolite Complex; CF, Chaman fault; DF, Dalbandin fault; GF, Gardez fault; GB, Gwal-Bagh fault; GZ, Ghazaband-Zhob fault; F, Frontal fault; HF, Herat fault; MBT, Main boundary thrust; MFT, Main frontal thrust; MKT, Main Karakoram thrust; MMT, Main mantle thrust; ON, Ornach-Nal fault; SF, Sarobi fault.

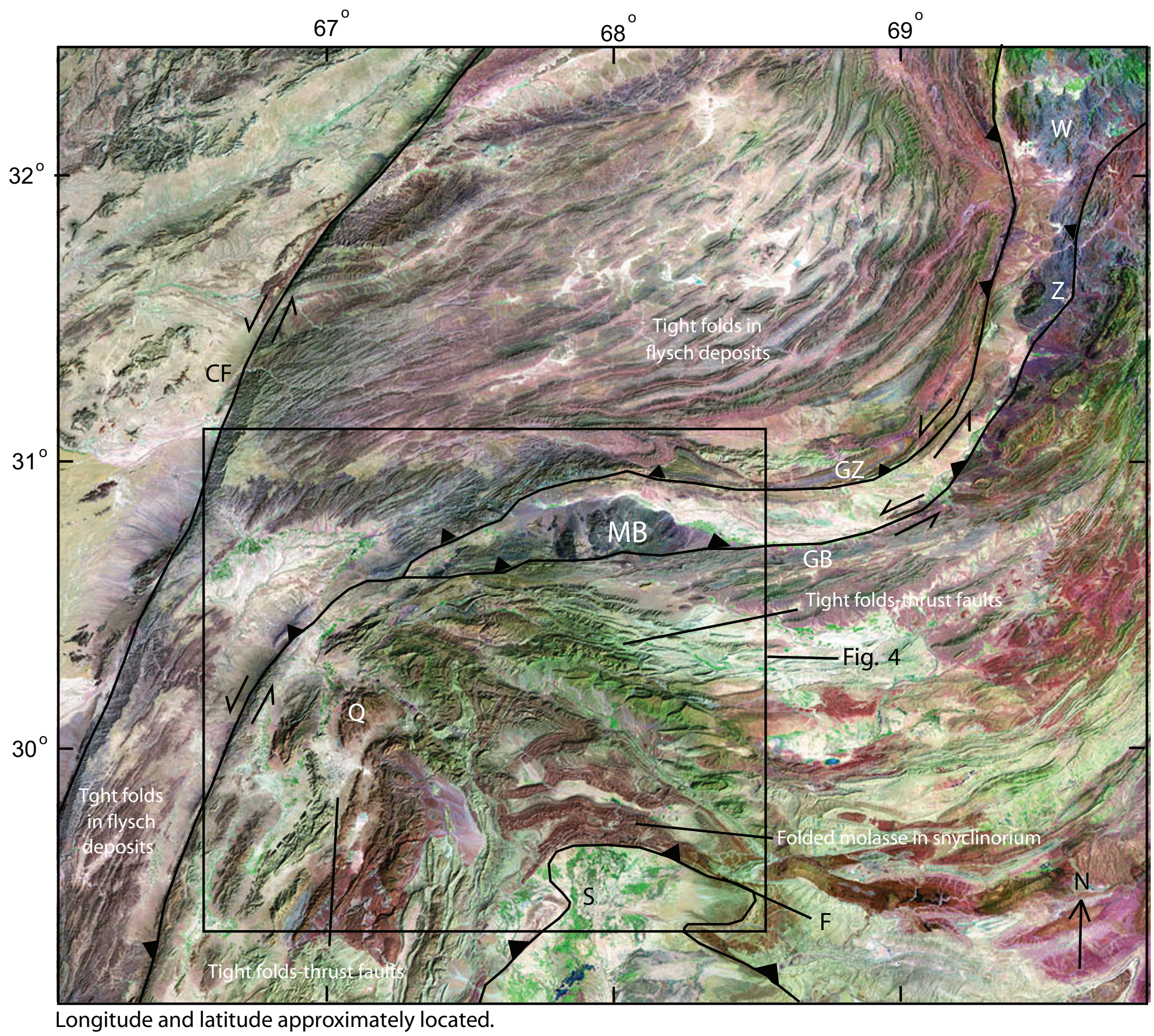
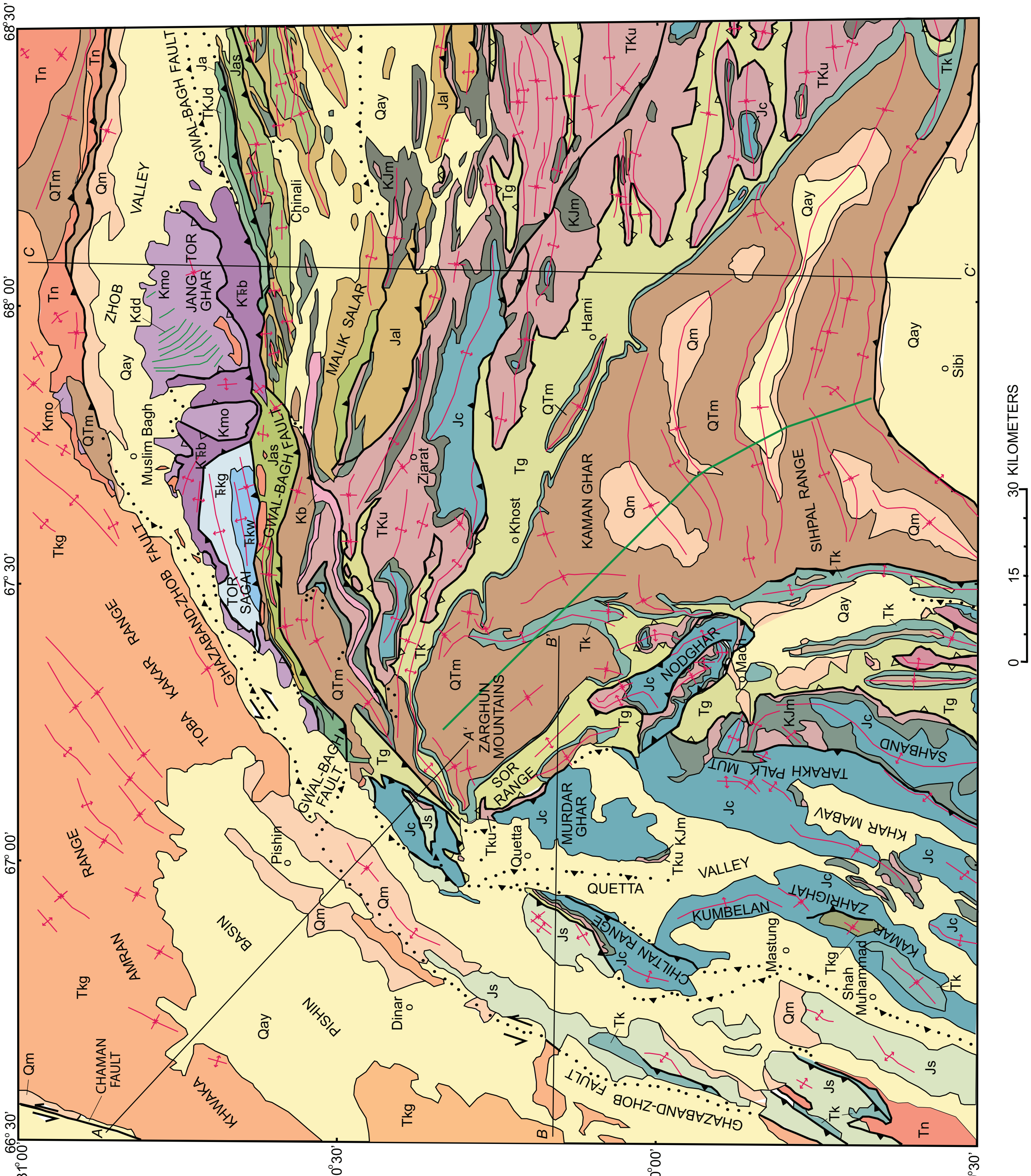



**Figure 3.** Landsat imagery showing study area and contiguous areas. M, Muslim Bagh; Q, Quetta; S, Sibi; CF, Chaman Fault; GB, Gwal-Bagh fault; GZ, Ghazaband-Zhob fault; F, Frontal fault; MB, Muslim Bagh-Bagh Ophiolite Complex; W, Waziristan Ophiolite Complex; Z, Zohob Ophiolite Complex.

lower Eocene carbonate and siliciclastic rocks of the Kirthar Formation. The Hunting Survey Corporation, Limited (1960) reported that the contact is disconformable in at least a few places. The carbonate rocks composing the Kirthar Formation indicate that a major marine transgression followed deposition of the Ghazij Formation, and the area returned to marine shelf conditions. Overlying the Kirthar Formation are Miocene to Pleistocene marginal-marine rocks (Nari and Dhok Pathan Formations, about 1,500 m thick) and continental rocks that comprise the post-collisional molasse (Soan-Lei Conglomerate, several thousand meters thick) (Shah, 1977).

## Basement Rocks

The basement rocks are composed of Neoproterozoic metasediments and meta-igneous rocks (Zr) that are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30 KILOMETERS
C
C'
A
A'
B
B'
CHAMAN FAULT
GHAZABAND-ZHOB FAULT
GWAL-BAGH FAULT
ZHOB VALLEY
TOBA KAKAR RANGE
AMRAN RANGE
KHWAKA
PISHIN BASIN
QUETTA VALLEY
JANG TOR GHAR
TOR SAGAI
MALIK SALAR
ZARGHUN MOUNTAINS
SOR RANGE
MURDAR GHAR
NODGHAR
KAMAN GHAR
SIHPAL RANGE
CHILTAN RANGE
KUMBELAN
ZAHRIGHAT
KAMAR
TARAKH PALK MUT
SAHBAND
KHAR MABAV
Muslim Bagh
Chinali
Ziarat
Khost
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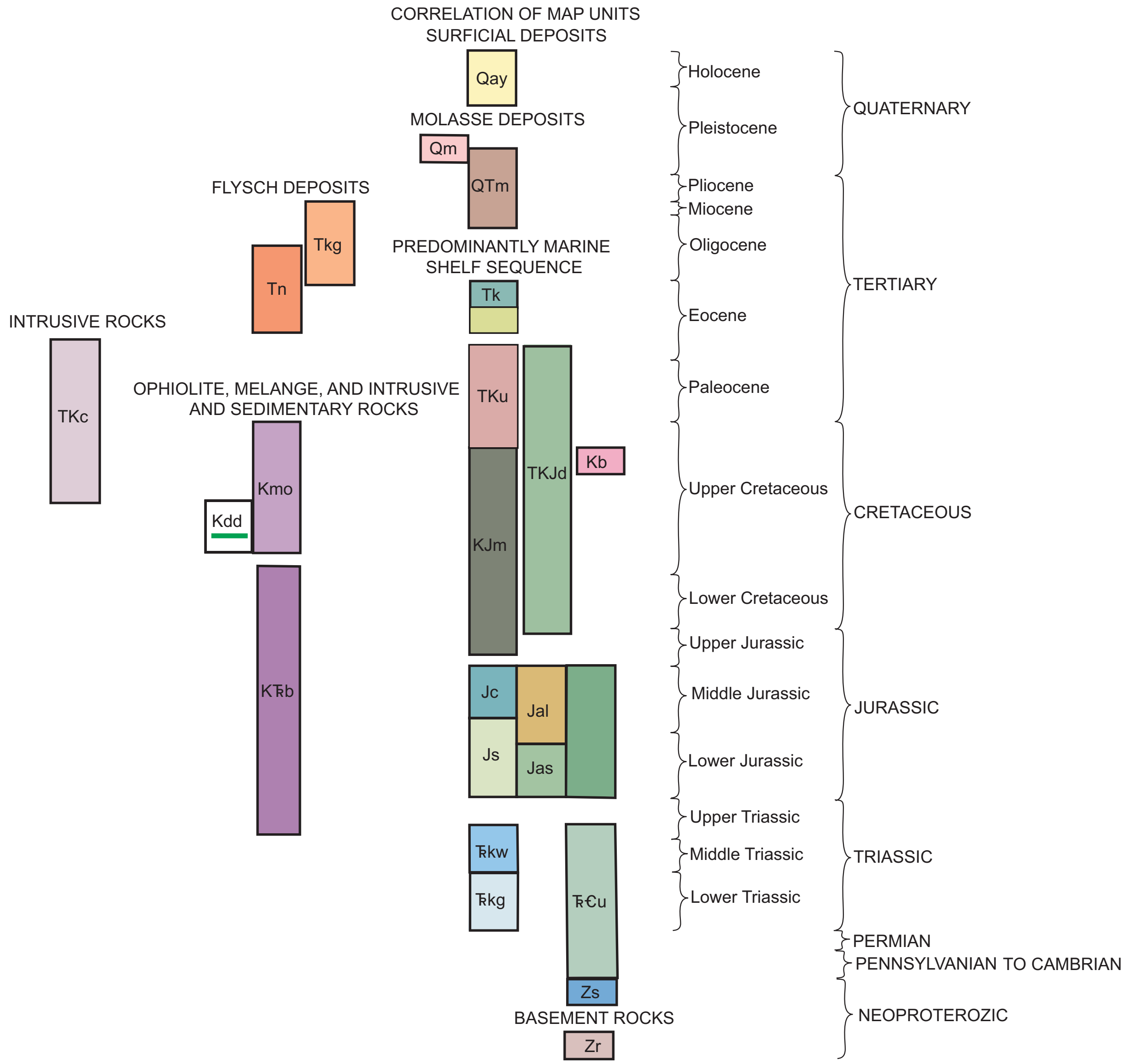



**Figure 4 (previous page, above, and following page).** Generalized geologic map of study area.

interpreted to be part of the India shield which is shown only in cross sections where overlying rocks have been detached along the contact with the Salt Range Formation (Zs) (figs. 5*A*, 5*B*, 5*C*).

## Pre-Eocene Marine Shelf Sequence

The marine shelf sequence is composed in ascending order of the Salt Range Formation (Zs), Khanozai Group (Ŧkg, Ŧkw), Spingwar Formation (Jas), Loralai Formation (Jal), Alozai Group (Ja), Shirinab Formation (Js), Chiltan Limestone (Jc), Mona Jhal Group, undivided (KJm), Bibai Formation (Kb), and Tertiary and Cretaceous units, undivided (TKu).

The marine shelf sequence is inferred to overlie the Salt Range Formation which is Neoproterozoic in age and composed of gypsiferous marl, salt, gypsum, and shale (Gee, 1945 and Asrarullah, 1967). The formation is shown only in the cross sections but is exposed along the southern end of the Salt Range (fig. 1) about 350 km northeast of the study area (fig. 1). The base and top of the formation is interpreted to be a décollement with overlying rock units deforming above the salt contact (figs. 5*A*, 5*B*, 5*C*).

The Khanozai Group is composed of the Gwal Formation (Ŧkg) and overlying Wulgai Formation (Ŧkw). The Gwal Formation is Lower Triassic and consists of shale interbedded with limestone, and locally includes basaltic lava flows. The formation is approximately 480 m thick and crops out in the northeastern part of the study area southwest of Muslim Bagh. The Wulgai Formation is Middle and Upper Triassic and

LIST OF MAP UNITS

| | |
|---|---|
| Qay | Alluvium (Holocene to upper Pleistocene) |
| Qm | Quaternary molasse deposits (Pleistocene)—Dada Conglomerateand Bostan Formation |
| QTm | Quaternary–Tertiary molasse deposits (lower Pleistocene to Oligocene)—Sibi Group, Multana Formation, and Urak Group |
| Tkg | Khojak Group, undivided (Miocene to Eocene)—Shaigalu Sandstone and Murgha Fagirzai Shale |
| Tn | Nisai Formation (lower Oligocene to lower Eocene) |
| Tk | Kirthar Formation (lower to middle Eocene) |
| Tg | Ghazij Formation (lower Eocene) |
| TKc | Chagai Intrusion (Eocene to Late Cretaceous)—Shown only in cross section *A-A'* |
| Kmo | Muslim Bagh Ophiolite Complex (Late Cretaceous) |
| Kdd | Dolerite dikes (Late Cretaceous) |
| KꞦb | Bagh Ophiolite Complex (Late Cretaceous to Late Triassic) |
| TKu | Tertiary and Cretaceous units undivided (Eocene to Upper Cretaceous)—Brewry Limestone, Karkh Group, Dungan Formation, Sanjawi Limestone, Rodangi Formation, and Siazgi Limestone |
| TKJd | Dungan Formation and Mona Jhal Group, undivided (Eocene to Lower Cretaceous and Upper Jurassic) |
| Kb | Bibai Formation (Upper Cretaceous) |
| KJm | Mona Jhal Group (Upper and Lower Cretaceous and Upper Jurassic)—Sembar Formation, Goru Formation, Parh Limestone, and Mughal Knot Formation |
| Jc | Chiltan Limestone (Middle Jurassic) |
| Js | Shirinab Formation (Middle and Lower Jurassic) |
| Ja | Alozai Group (Middle and Lower Jurassic) |
| Jal | Loralai Formation (Middle and Lower Jurassic) |
| Jas | Spingwar Formation (Lower Jurassic) |
| Ꞧkw | Wulgai Formation of Kkanozai Group (Upper and Middle Triassic) |
| Ꞧkg | Gwal Formation of Khanozai Group (Lower Triassic) |
| ꞦЄu | Triassic to Cambrian rock units, undivided—Shown only in cross sections |
| Zs | Salt Range Formation (Neoproterozic)—Shown only in cross sections |
| Zr | Neoproterozic rocks—Shown only in cross sections |

SYMBOLS

| | |
|---|---|
| | Contact |
| T A | Strike-slip fault—Dotted where concealed; queried where location uncertain. Opposed arrows indicate relative movement. In cross sections, T indicate movement toward viewer; A, movement away from viewer |
| | Thrust fault—Older-on-younger strata relationship. Sawteeth on upper plate. Some faults (for example, Ghazaband-Zhob fault) have components of both thrust and strike-slip movement |
| | Thrust fault—Younger-on-older strata relationship. Sawteeth on upper plate |
| | Anticline |
| | Syncline |
| | Axis of Sibi-Urak trough |
| | Trace of bedding plane—Shown schematically in cross sections only |

composed of shale interbedded with limestone and siltstone. The formation is approximately 180 m thick and exposed in the north-central part of the study area southwest of Muslim Bagh (fig. 4). These two formations tectonically underlie the Bagh Ophiolite Complex (fig. 4).

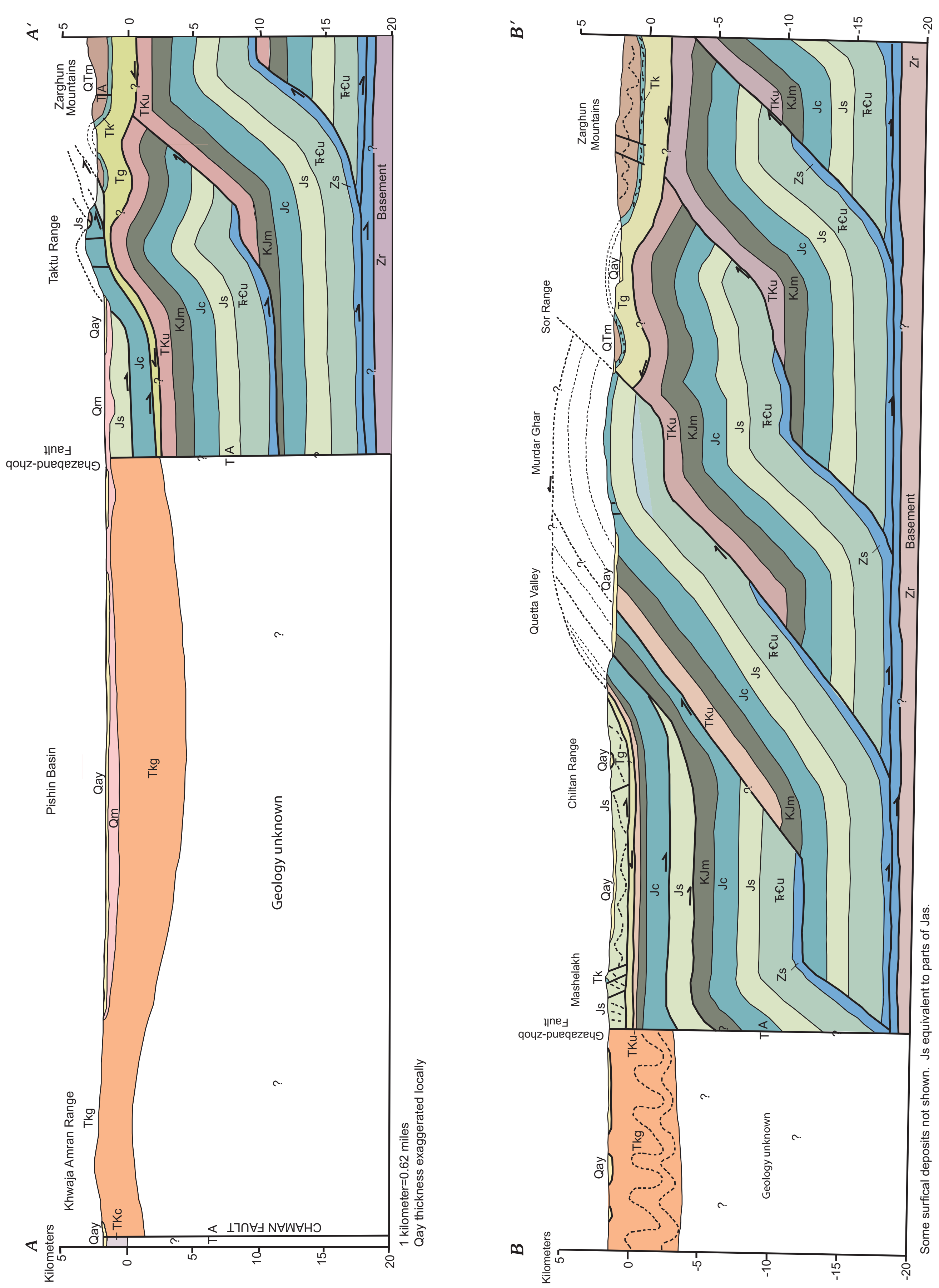
The Alozai Group (Ja) undivided is composed of Lower and Middle Jurassic rocks in ascending order of the Spingwar (Jas) and Loralai (Jal) Formations undivided as exposed in the northeast part of map area (fig. 4). The Spingwar Formation (Jas) is composed of Lower Jurassic limestone interbedded with shale and is locally intruded by diabase sills. The unit is exposed in the north-central part of the study area south of Muslim Bagh (fig. 3) and is approximately 1,300–2,000 m thick (Hunting Survey Corporation, Limited, 1960). The Loralai Formation (Jal) contains Middle and Lower Jurassic limestone and minor shale. The formation is exposed in the northeastern part of the study area (fig. 6, loc. 9) and is 130–650 m thick (Hunting Survey Corporation, Limited, 1960).

The Shirinab Formation (Js) consists of Lower and Middle Jurassic limestone, shale, and sandstone. The unit is exposed mainly in the southwestern part of the study area (fig. 4) and is thicker than 1,500 m in the Quetta Valley area (Khan and others, 1986).

The Chiltan Limestone (Jc) contains Middle Jurassic limestone with local veins and nodules. The limestone is exposed predominately in the western part of the study area and on the northwestern end of the Sibi-Urak trough (fig. 4). The thickness of the limestone is approximately 1,800 m in the Quetta area (Hunting Survey Corporation, Limited, 1960).

The Bibai Formation (Kb) is Upper Cretaceous and divided into upper and lower zones. The upper zone is a thick sequence of volcanic-boulder conglomerate, interbedded with ash beds and tuff units. The tuff units also interfinger with a sequence of sandstone, argillaceous tuff, and mudstone. The lower zone is composed of interbedded agglomerate, tuff, and basalt lava flows. The formation is mapped northeast of Quetta, but in the eastern part of the study area it is included in the lower part of the Mughal Knot Formation of the Mona Jhal Group. The unit is approximately 3,000 m thick in the Ziarat region (fig. 6, loc. 8) (Kazmi, 1979).

The Mona Jhal Group (KJm) is Upper Jurassic and Cretaceous and was originally defined as the Parh Group by the Hunting Survey Corporation, Limited (1960) but renamed and redefined by Fatmi and others, (1986) to include, in ascending order, the Sembar Formation, Goru Formation, Parh Limestone, and Mughal Knot Formation. The rocks


A
A′
Kilometers
Khwaja Amran Range
Pishin Basin
Taktu Range
Zarghun Mountains
CHAMAN FAULT
Ghazaband-zhob Fault
Geology unknown
Basement
1 kilometer=0.62 miles
Qay thickness exaggerated locally
B
B′
Mashelakh
Chiltan Range
Quetta Valley
Murdar Ghar
Sor Range
Zarghun Mountains
Geology unknown
Basement
Some surfical deposits not shown. Js equivalent to parts of Jas.

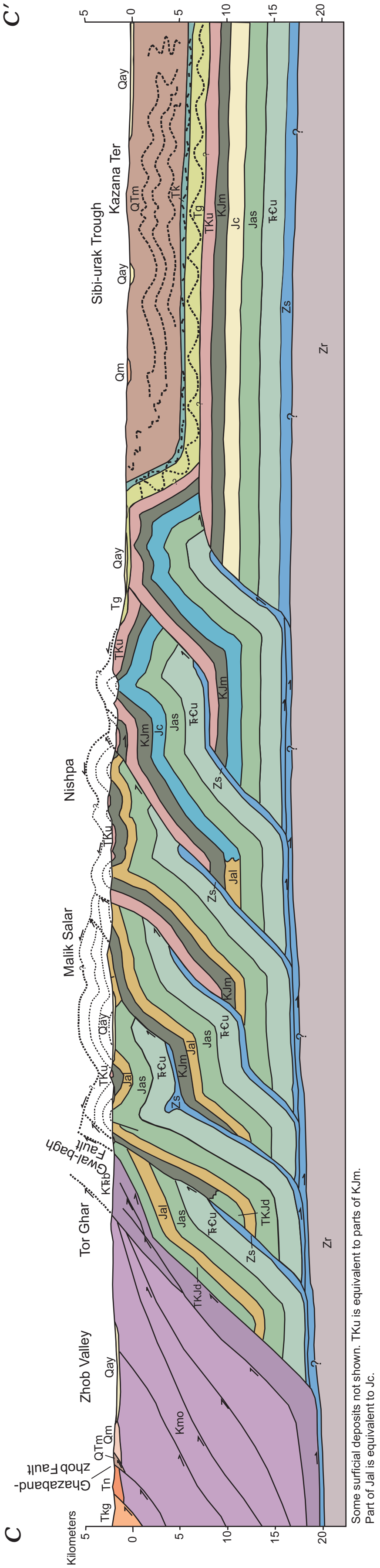
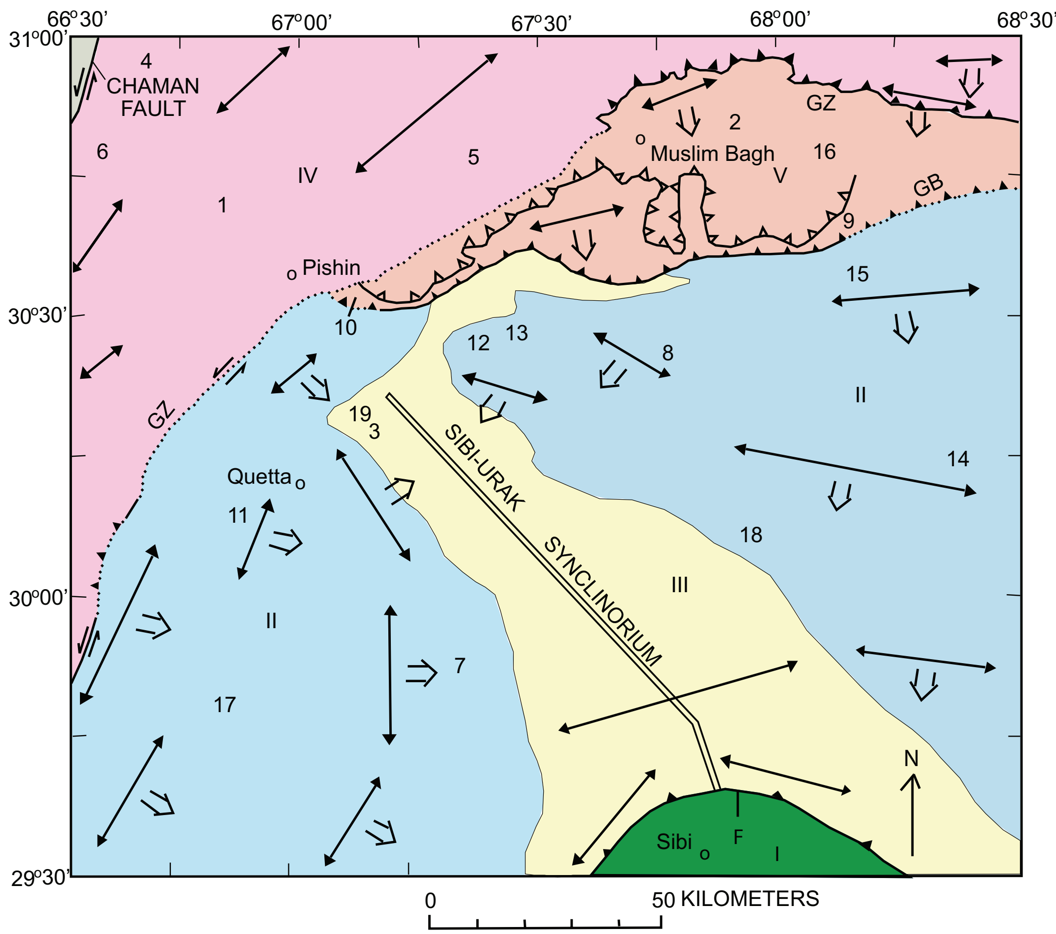



**Figure 5 (above and facing page).** Cross sections *A–A′, B–B′, C–C′*. See figure 4 for location of cross sections and unit descriptions.

are predominantly exposed along the flanks of the Sibi-Urak synclinorium (fig. 6). The Sembar Formation (Upper Jurassic and Lower Cretaceous) is shale with interbedded limestone, mostly exposed around the flanks of the Sibi-Urak synclinorium east of Gogai (fig. 6, loc. 13). The thickness at the type section in the Marri-Bugit area, approximately 30 km east of the map area, is approximately 135 m but thins near Quetta and Ziarat (fig. 6, loc. 8) (Fatmi, 1977). The Goru Formation (Lower and Upper Cretaceous) is composed of limestone interbedded with siltstone and shale and exposed mostly along the flanks of the Sibi-Urak synclinorium east of Gogai (fig. 4, fig. 6, loc. 13). The unit is about 60 m thick in the Quetta area (Fatmi, 1977). The Parh Limestone (Upper Cretaceous) consists of limestone intercalated with shale and marl and is about 300–600 m thick (Fatmi, 1977). The Mughal Knot Formation (Upper Cretaceous) contains mudstone and shale intercalated with sandstone and limestone. The formation is exposed in the northeastern part of the study area, southeast of Muslim Bagh (fig. 4) and the Ziarat-Kach area (fig. 6, locs. 8 and 12) and is 150–300 m thick in the Kach area (Fatmi, 1977).

The undivided Tertiary and Cretaceous units (TKu) consist of Upper Cretaceous to Eocene rocks and include in ascending order the Brewry Limestone (Hunting Survey Corporation, Limited, 1960), Karkh Group, Dungan Formation of Cheema and others (1977), Sanjawi Limestone, Rodangi Formation, and Siazgi Limestone. These rocks are exposed around the flanks of the Sibi-Urak synclinorium. The Brewry Limestone (Upper Cretaceous and Paleocene) is exposed in the Chiltan Range (fig. 4, fig. 6, loc. 11), southwest of Quetta, and southeast of Kach (fig. 6, loc 12) and Gogai (fig. 6, loc. 13). The thickness ranges from 25 to 60 m (Hunting Survey Corporation, 1960). The Karkh Group (Upper Cretaceous and lower Eocene) consists of limestone, marl, and shale interbedded with sandstone and sparse mafic lava flows. The group is exposed west of Mach (fig. 4) and ranges in thickness from 90 to 375 m (Hunting Survey Corporation, Limited, 1960). The Dungan Formation (Paleocene and Eocene) is composed of limestone and minor shale interlayered with limestone. The formation is exposed along the western and eastern flanks of the Sibi-Urak trough and is more than 310 m thick (Hunting Survey Corporation, Limited, 1960). The Sanjawi Limestone (Paleocene and lower Eocene) is exposed in the east-central part of the study area near Sanjawi (fig. 6, loc. 14) and ranges in thickness from 60 to125 m (Hunting Survey Corporation, Limited, 1960). The Rodangi Formation (upper Paleocene and lower Eocene) consists of limestone, marl, interbedded shale, and subordinate sandstone. The unit is exposed west of Shan Muhammad (fig. 6, loc 17) with a thickness of 150–250 m (Hunting Survey Corporation, Limited,1960). The Siazgi Limestone (Paleocene and lower Eocene) is exposed in the northeastern part of the study area, west and south of Chinali (fig. 6, loc. 15) with maximum thickness of 310 m (Hunting Survey Corporation, Limited, 1960).




EXPLANATION

Structural domains

- I — Foredeep
- II — Sulaiman fold and thrust belts (predominantly marine shelf sequence)
- III — Sibi-Urak synclinorium (molasse deposits)
- IV — Pishin flysch province (flysch deposits)
- V — Muslim Bagh Ophiolite Complex and Bagh Ophiolite Complex (ophiolite, melange, and intrusive and sedimentary rocks)

Contact

Thrust fault—Sawteeth on upper plate. Dotted where concealed. Opposed arrows show component of strike-slip movement. GZ, Ghazaband-Zhob fault; GB, Gwal-Bagh fault, F, Frontal fault

Thrust fault beneath Muslim Bagh Ophiolite Complex—Dotted where concealed or approximate. Sawteeth on upper plate

Strike-slip fault

Sibi-Urak synclinorium axis

Fold axis or fault-plane trend

Greatest principal strain direction

Structural, topographic, and geographic features

1 Pishin Basin
2 Zhob Valley
3 Urak
4 Khwaja Amran Range
5 Toba Kahar Range
6 Kjojak Pass
7 Mach
8 Ziarat
9 Bagh
10 Gwal
11 Chiltan Range
12 Kach
13 Gogal
14 Sanjawi
15 Chinali
16 Nisai
17 Shad Muhammad
18 Hamai
19 Sor Range

**Figure 6.** Diagram showing structural domains.

## Tertiary Marine Shelf Sequence

The Tertiary marine shelf sequence is composed of the lower Eocene Ghazij Formation (Tg) and overlying lower to middle Eocene Kirthar Formation (Tk).

The Ghazij Formation is predominantly exposed around the flanks of the Sibi-Urak synclinorium and was divided into three zones by Hunting Survey Corporation, Limited (1960). The lower zone is composed of shale with interbedded sandstone and ranges in thickness from about 915 m in the Sor Range (fig. 4) to about 1,220 m in the Mach area (Hunting Survey Corporation, Limited, 1960). The middle zone contains sandstone, minor siltstone and shale, and locally coal beds. Thickness ranges from 30 m (S.R., Roberts, oral commun., 1994) to about 90 m (Hunting Survey Corporation, Limited, 1960) in the Sor Range, about 300 m in the Mach area (Hunting Survey Corporation, Limited, 1960), and possibly as much as about 2,440 m in the Bahlol area (Hunting Survey Corporation, Limited, 1960), approximately 100 km east of study area. The upper zone consists predominantly of claystone and minor conglomeratic sandstone. Thickness ranges from about 215 m in the Mach area (fig. 6, loc 7), to about 300 m near Harnai (Hunting Survey Corporation, Limited, 1960) (fig. 6, loc. 18), and as much as about 535 m in the Sor Range (fig. 3) (Warwick and others, 1998; Johnson and others, 1999).

The Kirthar Formation contains limestone interbedded with marl and shale. The unit was previously called the Brahui Limestone by Hunting Survey Corporation, Limited (1960), but later changed to the Kirthar Formation by Cheema and others (1977). Locally, the formation is combined with the Spintangi Limestone of Hunting Survey Corporation, Limited (1960). The unit is exposed mainly along the edge of the Sibi-Urak trough with a thickness of 1,270 m (Cheema and others, 1977) in the Gaj River area, south of the study area, but is thinner in the study area.

## Flysch Zone

The flysch zone is composed of lower Eocene to lower Oligocene Nisai Formation (Tn) and overlying Eocene to Miocene Khojak Group undivided (Tkg) that consists of the Eocene to Oligocene Murgha Fagirzai Shale and overlying Oligocene to Miocene Shaigalu Sandstone. The Shaigalu Sandstone and Murgha Fagirzai Shale form a thick flysch sequence that filled a trough (Pishin flysch province) in the northwestern part of the study area (fig. 6, loc. 1) where it has been intensely folded.

The Nisai Formation is composed of limestone interbedded with minor marl, shale, sandstone, and conglomerate. The unit was defined originally as the Nisai Group by Hunting Survey Corporation, Limited (1960) and redefined as Nisai Formation by Cheema and others, (1977). The unit is exposed in the northeastern and southwestern part of the study area. North of Nisai (fig. 6 loc. 16), the unit is about 1,200 m thick (Cheema and others, 1977).

The Shaigalu Sandstone of the Khojak Group is composed of sandstone interbedded with shale with local limestone beds. The unit ranges from 950 to 1,900 m thick in the Khwaja Amran Range (Hunting Survey Corporation, Limited, 1960) (fig. 6, loc. 4) with a maximum thickness of 6,250 m in the Toba Kakar Range (fig. 6, loc. 5) in the northern part of the study area.

The Murgha Fagirzai contains shale and sandstone, with some limestone and conglomerate. Parts of the unit have been pervasively metamorphosed to chlorite-sericite slates, schist, and quartzite. The unit ranges in thickness from 468 to 625 m in most areas (Hunting Survey Corporation, Limited, 1960), but is about 1,250 m thicker in the Khojak Pass area (fig. 6, loc. 6).

## Quaternary–Tertiary Molasse Deposits

The Quaternary–Tertiary molasse deposits (QTm) are composed, in ascending order, of the Pliocene to Oligocene Sibi Group, Pleistocene to Oligocene? Multana Formation, and lower Pleistocene to Oligocene Urak Group undivided, which represent erosion of highlands resulting from deformation.

The Sibi Group contains shale interbedded with sandstone and subordinate conglomerate, and minor brown limestone. The group is equivalent, in part, to the Shin Matai, and Uzdha Pasha Formations of the Urak Group. The group is exposed mostly in the southern part of the Sibi-Urak trough, southeastern part of the study area. Hunting Survey Corporation, Limited (1960) reported 7,190 m thickness in the Sibi-Urak synclinorium area (fig. 4).

The Multana Formation consists of conglomerate, sandstone, and shale and is exposed north of the Zhob Valley in the northeastern part of the study area (fig. 4). The formation is about 6,770 m thick near the town of Naweoba (Hunting Survey Corporation, Limited, 1960) and approximately 110 km northeast of the study area.

The Urak Group undivided, includes in ascending order, the Nari, Gaj, Uzdha Pasha, Shin Matai, and Urak Formations (Kazmi and Reza, 1970). The Nari Formation is composed of sandstone interbedded with claystone and limestone beds. The unit is about 200 m thick in the Sor Range (fig. 6, loc. 19) (Cheema and others, 1977). The Gaj Formation contains shale and subordinate sandstone and limestone. The Gaj Formation is about 90 m thick (Williams, 1959; Cheema and others, 1977) in the Sor Range (fig .5, loc. 19) (Cheema and others, 1977). The Uzdha Pasha Formation is composed of sandstone and interbedded claystone and conglomerate. The equivalent Nagri Formation is approximately 600 m think in the Urak area (fig. 6, loc. 3) (Cheema and others, 1977). The Shin Matai Formation is composed of a cyclic alternation of sandstone, claystone, and conglomerate. Cheema and others (1977) indicated that the equivalent Dhok Pathan Formation is 120–300 m thick in the Quetta area (fig. 4). The Urak Formation contains conglomerate, interlayered with subordinate sandstone, siltstone, and claystone. Cheema and others (1977) report that the equivalent Soan Formation is 1,500–3,000 m thick in the Quetta area (fig. 4), however, a thickness of 470–940 m may be more accurate. In the Salt Range area, about 350 km northeast of the study area (fig. 1), the upper part of the Urak Group (Urak, Shin Matai, and Uzdha Pasha Formations) is equivalent to the upper part of the Siwalik Group (Soan, Dhok Pathan, and Nagri Formations, respectively) (Cheema and others, 1977). The Siwalik Group probably represents a different basin of deposition from that of the Urak Group.

## Quaternary Molasse Deposits

Composed of the Pleistocene Dada Conglomerate and the overlying Bostan Formation, the Quaternary molasse deposits (Qm) represent erosion of highlands produced by deformation. The Dada Conglomerate contains conglomerate and sandstone and is exposed in the Sibi-Urak trough in the southern part of the study area with a thickness of about 1,000 m (Hunting Survey Corporation, Limited (1960). The Bostan Formation consists of conglomerate, clay, and sandstone and is exposed mainly in northern part of study area in the Pishin Basin and north of the Zhob Valley (fig. 6, locs. 1 and 2). Cheema and others, (1977) reported thickness of 750 m in the Pishin Basin.

## Ophiolite, Melange, Intrusive Rocks, and Sedimentary Rocks

This package of rocks is composed of the Bagh Ophiolite Complex (KTRb) and Muslim Bagh Ophiolite Complex (Kmo). The Bagh Ophiolite Complex is mainly a melange with some sediments of Upper Triassic to Upper Cretaceous ages. The complex was originally mapped as part of the Parh and Alozai Groups (Hunting Survey Corporation, Limited, 1960) as melange (Gansser, 1979; Ahmad and Abbas, 1979) and as the Triassic Parh Group by Otsuki and others, (1989). The complex was redefined as the Bagh Ophiolite Complex by Mengal and others, (1993, 1994) for rocks exposed near the village of Bagh (fig. 6, loc. 9) with an exposed thickness of 500 m. The complex is bounded on the north by the overlying Muslim Bagh Ophiolitic Complex and on the south by the Gwal-Bagh fault (fig. 4), and is composed of seven major fault-bounded lithologic units (Mengal and others, 1993). These units, which are not mapped separately, are, in structurally ascending order: (1) lower and upper sedimentary rock, (2) ophiolite rock, (3) hyaloclasite-mudstone, (4) basalt-chert, (5) ultramafic and mafic rock, (6) mudstone melange, and (7) serpentine melange.

The seven units are described as the following: (1) the lower sedimentary rock unit is characterized by interbedded shale and limestone of Late Triassic in age based on ammonites, *Halobia* sp., and radiolarian fauna (Kojima and others, 1994). The upper sedimentary rock unit is composed of shale interbedded with limestone of Early to Late Jurassic based on radiolarian fauna (Kojima and others, 1994); (2) the rock unit of Early Cretaceous (Komija and others, 1994) contains blocks of the basalt-chert unit and the ultramafic and mafic rock unit, melange with limestone blocks, plagiogranite, and sheeted dike rocks embedded in a mudstone matrix; (3) the hyaloclasite-mudstone unit is composed mainly of basaltic volcanic rocks interbedded with mudstone and micritic limestone divided in three subunits (Mengal and others, 1994). The lower subunit consists of siliceous mudstone and limestone intruded by basalts and dolerite and is Early Cretaceous (Kojima and others, 1994) based on radiolarian assemblages. K-Ar dates of amphibole and biotite from volcanic rock range from 81 to 68 Ma (Sawada and others, 1992). The middle subunit contains the following volcanic rocks as hyaloclasite: volcanic breccia and minor pillow lava and lava sheets, basanite, alkali basalt, and trachybasalt (Sawada and others, 1992). The upper subunit is composed of siliceous shale with limestone; (4) the basalt-chert unit is found on the southeastern periphery of the Muslim Bagh Ophiolitic Complex and is characterized mainly by thick basaltic lavas and bedded chert, micritic limestone, and hemipelagic mudstone. The basalt flows are mainly pillow lavas, some massive lavas with volcanic breccia, and a few limestone beds. The basalts are considered to be tholeiitic and show mid-ocean-ridge basalt characteristics (Sawada and others, 1992). Locally, the pillow lavas are overlain by a 30- to 50-m-thick limestone and alternating thin chert and mudstone beds. The age of this unit is Early and Late Cretaceous based on radiolarian fossils in the limestone and chert sequence (Kojima and others, 1994); (5) the ultramafic and mafic rock unit contains ultramafic and mafic cumulate that occur as tectonic slices; (6) the mudstone melange unit consists of blocks of various types of rocks surrounded by thin-bedded mudstone. Blocks are as long as 100 m and composed of mixed basalt and radiolarian chert, foliated limestone, interbedded limestone and shale, and massive limestone. The age of this unit is Early and Late Cretaceous (Sawada and others, 1992); (7) the serpentine melange unit is composed of blocks mainly of ultramafic, mafic, and metamorphic rocks widely distributed in a scaly serpentine matrix. The metamorphic rocks include amphibolite, garnet-hornblende schist, and greenschist. Other rock types are basalt, chert, limestone, and shale (Mengal and others, 1994). The age of this unit is Early and Late Cretaceous (Sawada and others, 1992) exposed structurally below the Muslim Bagh Ophiolite Complex (Kmo).

The Muslim Bagh Ophiolite Complex is exposed in the northeastern part of the study area, south of the Zhob Valley (fig. 6, loc. 2). The complex is composed of five units: (1) sheeted dikes, (2) mafic cumulates, (3) a mixed cyclic sequence of mafic and ultramafic cumulates, (4) ultramafic cumulates, and (5) ultramafic tectonites (Ahamad and Abbas, 1979; Mengal and others, 1993). The age of emplacement was previously thought to be middle Paleocene to early Eocene

(Allenmann, 1979; Otsukie and others, 1989) and the age of the rocks were described as Early Triassic (Otsukie and others, 1989). It is now thought that the age of emplacement onto the continental margin of the India plate was in the Late Cretaceous to early Paleocene (Kojima and others, 1994). The age of the complex is now described as Late Cretaceous, based on a K-Ar age of 82–67 Ma (Sawada and others, 1992) and, locally, contains chromite, magnesite, and magnetite deposits.

The five units are described as the following: (1) the sheeted dikes are dioritic and the main rock types include hornblende diorite, quartz diorite, and amphibolite. This unit is intruded by plagiogranite and trondjhemite dikes not shown on the map (fig. 4). This unit was identified as sheeted dikes by previous workers (Rossman and others, 1971; Ahmad and Abbas, 1979). The unit is approximately 2,000 m thick (Mengal and others, 1993); (2) the mafic cumulate unit is gabbroic and composed of pyroxene gabbro in the lower part and hornblende gabbro in the upper part. The unit is 400 to 1,500 m thick (Mengal and others, 1993); (3) the mafic and ultramafic cumulate unit is composed of dunite, pyroxenite, and gabbro with rock types repeated several times. The basal part is dunite that grades upward into wehrlite, then pyroxenite and finally gabbro. The dunite contains pods of harzburgite and chromite deposits. The unit ranges in thickness from 4,000 to 6,000 m (Mengal and others, 1993); (4) the ultramafic cumulate unit is composed of an intercalated sequence of dunite, harzburgite, wehrlite, and minor pyroxenite approximately 4,000 m thick (Mengal and others, 1993); and (5) the ultramafic tectonites unit contains dunite and harzburgite that consists mainly of olivine and minor pyroxene which are partially or completely serpentinized.

## Structural Domains

The Quetta-Muslim Bagh-Sibi region is a structurally complex area characterized by broad and tight folds, and reverse, thrust, and strike-slip faults (figs 7, 8, 9). We have divided this region into five structural domains (terranes) (fig. 6) to enhance our understanding of its structural complexity. These domains are separated by four major boundary faults which formed as a consequence of four major periods of deformation related to oblique convergence of the India and Eurasian plates.

The five structural domains are, roughly from south to north (fig. 6): (1) a foredeep (I) that represents Precambrian

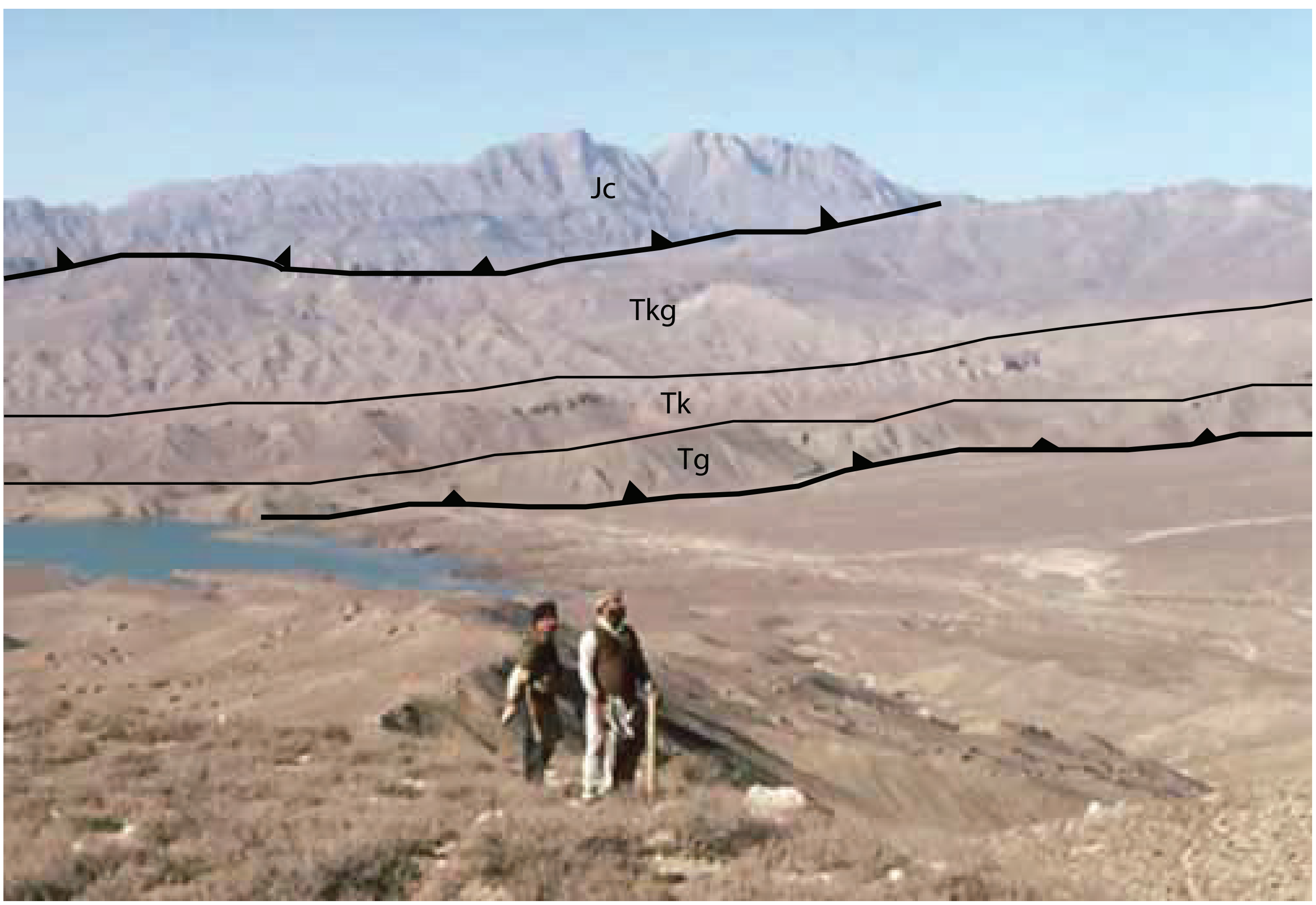



**Figure 7.** Photograph showing stacked thrust faults. Jc, Chiltan Limestone; Tkg, Flysch deposits of the Khojak Group; Tk, Kirthar Formation; Tg, Ghazij Formation. Photograph by Maldonado, 1991.

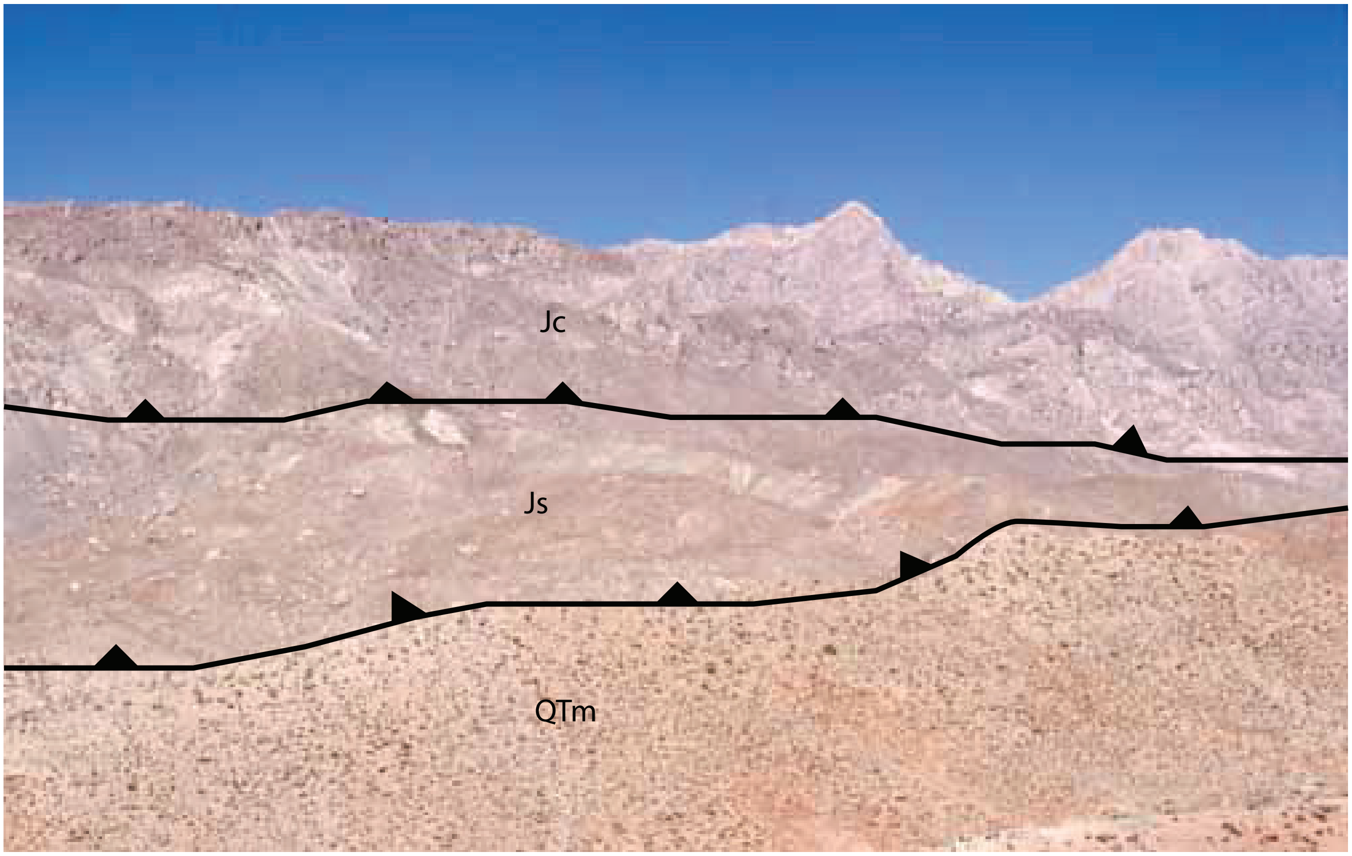



**Figure 8.** Photograph showing stacked thrust faults. Jc, Chiltan Limestone; Js, Shirinab Formation; QTm, Quaternary–Tertiary molasse deposits of the Sibi Group, Multana Formation, and Urak Group. Photograph by Maldonado, 1991.

India basement rock overlain by undeformed sedimentary cover that forms the Indus Plains and fronts the uplifted deformed region; (2) Sulaiman foreland fold-and-thrust belt (II) that forms part of the uplifted deformed region and is composed of a thick marine shelf sequence of Late Triassic to late Tertiary age, and continental rocks of Oligocene to Quaternary age; folding and thrusting resulted from basal decoupling of the sedimentary cover from the basement; (3) a major deep trough referred to as the Sibi-Urak synclinorium (III) that formed within the foreland fold-and-thrust belt and filled with molasse; (4) a thick flysch deposit (IV) of Miocene-Oligocene age; and (5) Bagh Ophiolite Complex and Muslim Bagh Ophiolite Complex (V) of Late Triassic to Late Cretaceous age.

The four major faults that bound the structural domains are (fig. 6): the Frontal (F), Ghazaband-Zhob (GZ), Gwal-Bagh (GB), and Chaman (CF) faults. The F fault is equivalent to the Main Frontal thrust (MFT) (figs. 1, 2). The GZ fault is mainly a thrust fault with sinistral strike-slip motion that separates the Muslim Bagh Ophiolite Complex from the flysch zone and locally the flysch zone from marine shelf rocks. The GB fault is a thrust fault that separates the Muslim Bagh Ophiolite Complex from the marine shelf rocks. The CF fault is a sinistral transform fault between the India (Pakistan block) and Eurasia (Afghan block) plates that connects the Makran convergence (subduction) zone from the Afghan block (figs. 2, 3).

Four major periods of deformation are recognized: (1) emplacement of ophiolitic rocks onto the continental margin of the India plate (Late Cretaceous to Paleocene); (2) collision of the India and Eurasia plates resulting in thrusting and minor folding (Eocene or early Oligocene?) of the marine shelf rock sequence and initiation of a major trough referred to as the Sibi-Urak synclinorium (figs. 4, 6); (3) deposition of molasse units (Urak and Sibi Groups, fig. 4) of Oligocene to early Pleistocene age followed by major folding and thrusting, and formation of strike-slip faults; and (4) deposition of post-Sibi Group units of Pleistocene age (Bostan Formation and Dada Conglomerate) with subsequent folding, thrusting, and strike-slip motion that continues to the present.

## Foredeep

The foredeep (fig. 6) of the Quetta-Muslim Bagh-Sibi region consists of Precambrian India basement (figs. 1, 2, 3) that is overlain by undeformed sedimentary cover that forms the Indus Plains and fronts the foreland fold-and-thrust belt of the Quetta-Muslim Bagh-Sibi region described below. The


**Figure 9.** Photograph showing folded thrust fault. Upper plate (KTRb) is partly eroded exposing the lower plate (TKu). Kdb, Bagh Complex; Tku, Tertiary and Cretaceous units, undivided. Photograph by Maldonado, 1991.

structure that separates these two domains is a blind fault referred to above as the Frontal fault (fig. 6) which separates the foreland thrust belt from its foredeep.

## Sulaiman Foreland Fold-and-Thrust Belt

The foreland fold-and-thrust belt (fig. 6) forms part of the uplifted Quetta-Muslim Bagh-Sibi deformed region. We propose that the folding and thrusting resulted from basal decoupling of sedimentary cover from the basement rocks (figs. 3, 5*A*, 5*B*, 5*C*). We also interpret decoupling to occur along salt (unit Zr shown in fig. 4), possibly the same salt formation exposed in the Salt Range (fig.1) where basal decoupling along salt has been proposed (reference here). We suggest that collision is of Eocene or early Oligocene(?) age that resulted in thrusting and minor folding of the marine shelf rock sequence with initiation of the Sibi-Urak synclinorium. This is based on a lower Eocene to lower Oligocene sedimentary unit (Nisai Formation) that unconformably overlies the Muslim Bagh Ophiolite Complex (fig. 4). Powell (1979), however, has indicated an age of Eocene for collision. We infer that convergence resulted in stacking of thrust sheets, piggy-back style as shown in cross sections (figs. 5*A*, 5*B*, 5*C*) with rock units thrust in a southerly and easterly direction (fig. 7, 8, 9). The greatest principal strain direction obtained from fold axes also indicate (figs. 3, 4, 6) south and southeast directions. Older-on-younger strata is the most common relationship, but younger-on-older strata is also present (figs. 4, 6). The cross sections (figs. 5*A*, 5*B*, 5*C*) were constructed using a passive roof-thrust duplex model that was first applied in the Sulaiman and Kirthar Ranges (fig. 1) by Banks and Warburton (1986). Humayon and others (1991) and Jadoon and others (1994) showed cross sections for parts of the map area and areas contiguous with the map area. Bannert and others (1992) also showed cross sections in their report on the western fold belt of Pakistan, which includes part of the map area at a scale of 1:500,000. The thrust faults are shown as high-angle faults (reverse faults) whose angles decrease with depth. Some of the faults have been folded, so their original geometry is not known.

### Sibi-Urak Synclinorium

The Sibi-Urak synclinorium (fig. 6) is a major deep trough that formed within the foreland fold-and-thrust belt with fold axes; it strikes in a north-northeast direction suggesting east-west convergence. The trough is filled with molasse (Urak and Sibi Groups) of Oligocene to early Pleistocene age. Locally, older rocks have been thrust over this synclinorium suggesting post-molasse deformation.

### Flysch Zone

A thick flysch sequence (fig. 6) of Eocene-Miocene age fills a trough that formed a subduction prism that was part of the Makran subduction zone (fig. 1). We interpret that this prism has been partly disrupted by the Chaman fault, a sinistral transform fault zone between the India and Eurasia plates (Afghan continental block) that separates the Makran subduction zone from the Afghan block. This fault continues to be active to the present. Another major thrust-slip fault with major sinistral motion is the Ghazaband-Zhob (GZ, figs. 3, 4, 6) fault that separates the Muslim Bagh Ophiolite Complex from the flysch zone and locally the flysch zone from marine shelf rocks. The GZ fault appears to merge with the Gwal-Bagh thrust fault (GB, figs. 4, 6) that separates the Muslim Bagh Ophiolite Complex from marine shelf rocks. The GB and GZ fault complex may also connect with the Makran subduction zone (fig. 1).

### Bagh Ophiolite Complex and Muslim Bagh Ophiolite Complex

The Muslim Bagh Ophiolite Complex (fig. 6) is part of the regional ophiolite complex known as the Bela-Muslim Bagh-Waziristan Ophiolite belt and Kohistan-Ladakh block (fig. 1). Maldonado and others (1993) proposed that these rocks were obducted onto the continental margin of the India plate (figs. 1, 2) during Late Cretaceous to Eocene, however, Kojima and others, (1994) indicated Late Cretaceous to early Paleocene. Collision with the Eurasia plate, however, occurred during early Eocene or early Oligocene time. This is based on a lower Eocene to lower Oligocene sedimentary unit (Nisai Formation) that unconformably overlies the Muslim Bagh Ophiolite Complex (fig. 4). The Muslim Bagh Ophiolite Complex is structurally underlain by the Bagh Ophiolite Complex but the Bagh Ophiolite Complex is structurally underlain by Upper Cretaceous (Jurassic?) to Lower Triassic and Eocene sedimentary rocks (fig. 4).

## Conclusions

Obduction (emplacement age) of Late Triassic to Late Cretaceous ophiolite rocks onto the continental margin of the India plate occurred during the Late Cretaceous to Eocene. A younger Muslim Bagh Ophiolite Complex was thrust over an older Bagh Ophiolite Complex resulting in a younger-over-older strata relationship. Both complexes also were thrust over younger and older sedimentary rocks (fig. 4). Collision of the India plate with the Eurasia plate occurred during the early Eocene or early Oligocene(?) forming a suture zone. This resulted in formation of five structural domains that formed a foredeep, a foreland fold-and-thrust belt, a major deep trough, a flysch zone, and an ophiolite complex. Four major faults bound the structural terrane, the Frontal, Ghazaband-Zhob, Gwal-Bagh, and Chaman faults. Folding and thrusting of strata are the main structural elements. This stage of thrusting and folding appears to be multiple and probably remained continuous, resulting in folding of older thrust faults and refolding of older folds. The main thrusting relationship resulted in older-on-younger strata, but younger-on-older strata were also observed. The older-on-younger strata may represent deformation that resulted from the plate collision, but some of the younger-on-older strata may represent obduction of the Muslim Bagh Ophiolite Complex onto rocks of the Bagh Ophiolite Complex and possibly roof-thrust faults that have been proposed for the study area and shown in some cross sections (figs. 5*A*, 5*B*, 5*C*) of the area.

The thrust fault vergent directions vary in the study area. East of Quetta, the apparent thrust fault vergent direction is predominately southward, whereas west of Quetta it is eastward (figs. 4, 6). This change in apparent vergent direction west of Quetta probably reflects subsequent bending (folding) or rotation of the terrane containing these thrust faults. The thrust faults prior to the subsequent deformation probably had similar vergent directions. The thrust fault vergent directions and principal strain directions of the folds (south to southeast) are very similar (fig. 6).

The Sibi-Urak synclinorium is a foredeep filled with continental detritus eroded from the mountain highs that formed from the plate collision. This trough and associated sediments have subsequently been folded and locally thrusted. This stage of thrusting and folding is thought to be as old as Oligocene and as young as Pleistocene and thought to continue to the present. We interpret that this deformation was due to lateral movement along strike-slip faults (such as the Ghazaband-Zhob fault) that formed as collision changed from subduction to lateral motion in this part of Pakistan. This type of deformation has moved material in southerly and westerly directions, folding strata and older structural features, and possibly forming the syntaxis that characterizes the India-Pakistan block such as the Quetta syntaxis (fig. 1).

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