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Full length article

GIS-BASED HIGH-RESOLUTION GEOLOGICAL MAP (SCALE 1:50,000): A NEW WINDOW INTO STRUCTURAL DOMAINS OF THE QUETTA AND SURROUNDING AREAS

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ABSTRACT

The Quetta and surrounding areas are part of the collision zone between the Indian and Eurasian plates, named as Kirthar and Sulaiman Fold-Thrust belts. The collision is accommodated by folding, thrusting and the Nushki-Chaman Transform Fault System. Detailed high-resolution (scale 1:50,000) mapping and structural analyses were carried out using modern remote-sensing techniques of the ArcGIS to understand mutual relationships of the structural patterns and geometries, and the regional and local stress patterns in the study area. Fieldwork was carried out to acquire the stratigraphic, structural and geomorphological data, using topographic maps and satellite images as base maps in order to plot additional information and further incorporate them in the GIS-based map. Balanced structural cross-sections were also prepared along the selected lines using ArcGIS techniques. Based on new mapping, the understudy area has been subdivided into five distinct structural domains. These domains are classified as; Domain I: broad syncline intervened by a narrow anticline; Domain II: upright folds and thrusts; Domain III: tight, over-turned thrust zone; Domain IV: flysch and molasse successions of Paleocene-Holocene age; and Domain V: suture belt (ophiolites) and associated mélanges and sediments.

Keywords: GIS, geological map, structural cross-sections, lithostratigraphy, structural domain

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1. INTRODUCTION

The Quetta and its surrounding area (Fig. 1) is part of the active collision zone between the Indian and Eurasian plates (Powel., 1979). Collision caused formation of the major fold-thrust belts; such as, the Kirthar and Sulaiman Fold-Thrust belts (Bannert et al., 1992; Bender and Raza, 1995). The map area covers western part of the Sulaiman Fold-Thrust Belt (SFTB) and northern part of Kirthar Fold-Thrust Belt (KFTB). It is bounded by Khojak-Pishin Belt (KPB) in the west and northwest and by Gazaband Fault (GF), and in the south by the KFTB (Fig. 1) and mostly comprises volcano-sedimentary successions of the Triassic through Pleistocene age.

In response to the head-on collision the relative plate movement is accommodated in part by the folding and thrusting (Fig. 1) and in part by the Nushki-Chaman Transform Fault System (NCTFS), which is considered transform boundary between the India and Afghan Block of the Eurasia (Powel, 1979; Bannert et al., 1992; Bender and Raza, 1995). The Quetta Syntaxes (QS) is an oroclinal bend at the confluence of the Kirthar and Sulaiman Fold-Thrust belts, which acts as a junction for various major faults (Bender and Raza, 1995; Haq and Davis 1997). The KFTB, to the south of the QS, is verging eastward, whereas, the SFTB is verging southward. Bannert et al. (1992) proposed that generally the rigid Afghan Block to the north-northwest of the SFTB is assumed to have played an important role to accommodate the strain.

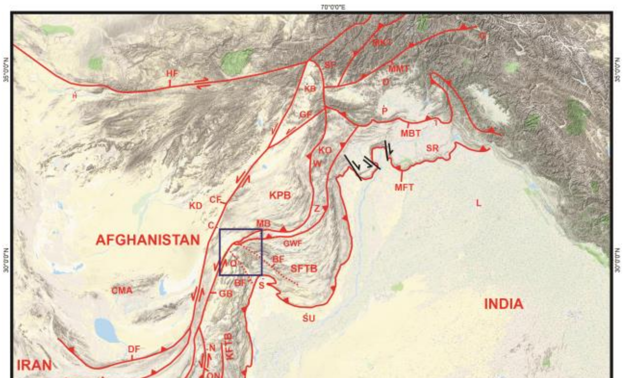

Figure 1. Terrain map showing study and surrounding areas, modified after Farah et al. (1984) and Maldonado et al. (1998); C, Chaman; CMA, Chaghi Magmatic Arc; G, Gilgit; H, Herat; I, Islamabad; KFTB, Kirther Fold-Thrust Belt; KPB, Khojak-Pishin Belt; K, Karachi; KB, Kabul; KD, Kandahar; L, Lahore; N, Nal; P, Peshawar; Q, Quetta; SFTB, Sulaiman Fold-Thrust Belt; S, Sibi; SU, Sui; SR, Salt Range; B, Bela Ophiolite Complex; D, Dargai Ophiolite complex; KO, Khost Ophiolite Complex; MAP, Makran Accretionary Prism; MB, Muslim Bagh-Bagh Ophiolite Complex; WO, Waziristan Ophiolite Complex; ZO, Zhob Ophiolite Complex; BF, Basement Fault; CF, Chaman Fault; DF, Dalbandin Fault; GF, Gardez Fault; GWF, Gwal-Bagh Fault; GB, 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; PF, Pab Rang Fault; SF, Sarobi Fault.

The area possesses active faults that have been causing major earthquakes that caused a lot of damage to life and infrastructure (Ambraseys and Bilham, 2003); (Avouac et al., 2014); main examples are the 1935 Quetta and 2008 Ziarat earthquakes. One segment of the NCTFS, i.e. the GF, that lie adjacent to the QS; has been responsible for some major earthquakes in the region during past (Ambraseys and Bilham, 2003; Avouac et al., 2014). However, till date no detailed (high-resolution large-scale) mapping of the study area has been carried out in order to understand the detailed stratigraphy, structure, and seismic behavior of the active faults. Therefore, we produced the detailed (high-resolution large-scale) map of the area for the mentioned purpose. The map area comprises over 16 topo-sheets of the Survey of Pakistan (Fig. 2), which covers parts of the eight districts of the Balochistan. The northwestern part of the map area covers parts of the Killa Abdullah and Pishin districts, the northeastern part lies in the Khanozai and Killa Saifullah districts, the eastern part lies in the Ziarat District, the southeastern part lies in the Sibi and Bolan districts and the southwestern part lies in the Mastung District. The Quetta District comprises the central part of the study area, which is the main focus of this study. Most of the study area is connected with the Quetta city by metaled roads.

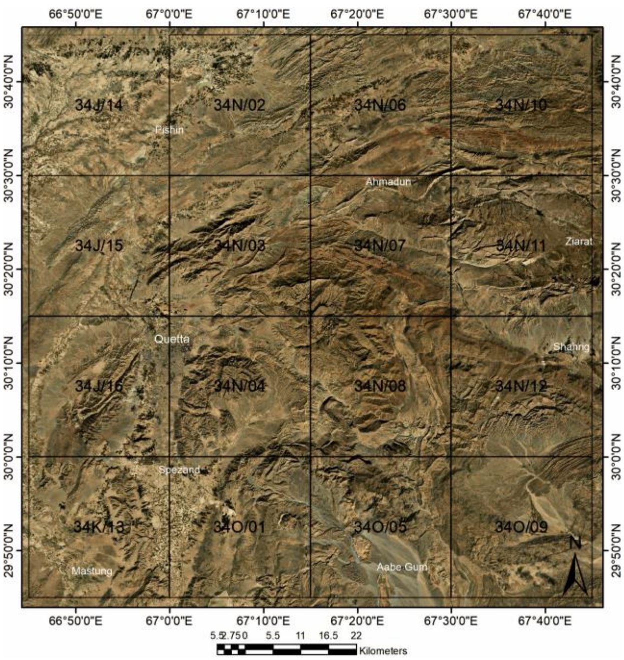

Figure 2. Satellite image showing the study area, which comprises 16 topographic sheets (of 1:50,000 scale) of the Survey of Pakistan, as mentioned on the image.

2 METHODS

2.1 Study design

Extensive fieldwork was carried out in the study area and information of the stratigraphic, structural and geomorphological aspects were obtained. For this purpose, topographic maps and satellite images were used, as base maps, for plotting additional information obtained during fieldwork. Structural information, acquired in the field, was plotted and traced along fault lines on satellite imagery, in order to measure the movements along fault planes. The types of contacts between various rock formations were checked, confirmed on the ground and plotted on the base map of the area for incorporation in our final GIS-based map. Measurement of structural attributes, e.g. dip, strike, lineation etc., were measured, particularly along planned traverses. Various faults, associated folds and their geometries were also observed and analyzed. The density and orientations of fractures in different stratigraphic units were also recorded. Ultimately a detailed geological map of the field area was prepared, which was mainly based on interpretation of satellite imagery.

2.2 Instrumentation

Various major and minor structures were plotted on the topographic maps on a scale of 1:50,000. Balanced structural cross-sections were prepared along the selected traverses, using ArcGIS, and tectonic models proposed for the purpose of sequential evolution of the mountain ranges. Field observations and published studies were used to confirm the location and nature of different faults, fault systems, their geometry and effects on the Quetta and surrounding areas.

3 STRATIGRAPHY OF THE STUDY AREA

The map area mostly comprises volcano-sedimentary successions of the Triassic through Pleistocene age (Fig. 3A, B; Table 1). The adjacent areas to the north and northeast comprise the Muslimbagh-Zhob Ophiolite and associated sedimentary succession and mélanges of the Triassic through Eocene age (Fig. 3A, B; Table 2) and the Khojak-Pishin Belt, composed of Late Paleocene - Pleistocene sedimentary succession (Fig. 3(A, B); Fig. 4), respectively. Additional lithostratigraphic units, identified more recently by some workers, not mapped before, were also incorporated. They include Triassic Gwal Formation, Jurassic units like Spingwar, Loralai, Shirinab, Takatu and Chiltan limestones, Cretaceous Bibai Group, Miocene-Pleistocene Uzdha Pasha, Shin Matai and Urak Conglomerate of the Urak Group, Pleistocene Kach Dam Conglomerate and Hanna Lake Conglomerate, Hanna Red Clays and Spin Karez Conglomerate of the Spin Karez Group. The map also shows Mesozoic Bagh Complex of the Muslimbagh Ophiolites, various lithostratigraphic units of the Nisai Group and Murgha Faqirzai and Shaigalu Members of the Khojak Formation, the Dasht Murgh Group, Malgthanai Formation etc. Various lithostratigraphic units, shown in the mapped and adjacent area, are briefly described below:

3.1 Western Sulaiman Fold-Thrust Belt and Zarghun-Sibbi Trough

Over 15 km thick succession of sedimentary rocks, of Triassic - Recent age In the SFTB (Fig. 3(A, B); Table 1), overlies the crystalline basement of the India. The northern Zarghun Sibbi Trough (ZST) comprises over 4000 m thick rocks of the Urak Group (Kazmi and Raza, 1970; Shah, 1977, 2009). Also, over 800 m thick succession of the Spin Karez Group overlies the Ghazij Formation in the Hanna-Spin Karez area (Naseer et al., 2019). In the SFTB numerous unconformities have been recognized between the lithostratigraphic units (Table 1) (Shah, 1977; 2009; Bender and Raza, 1995; Kassi et al., 2009).

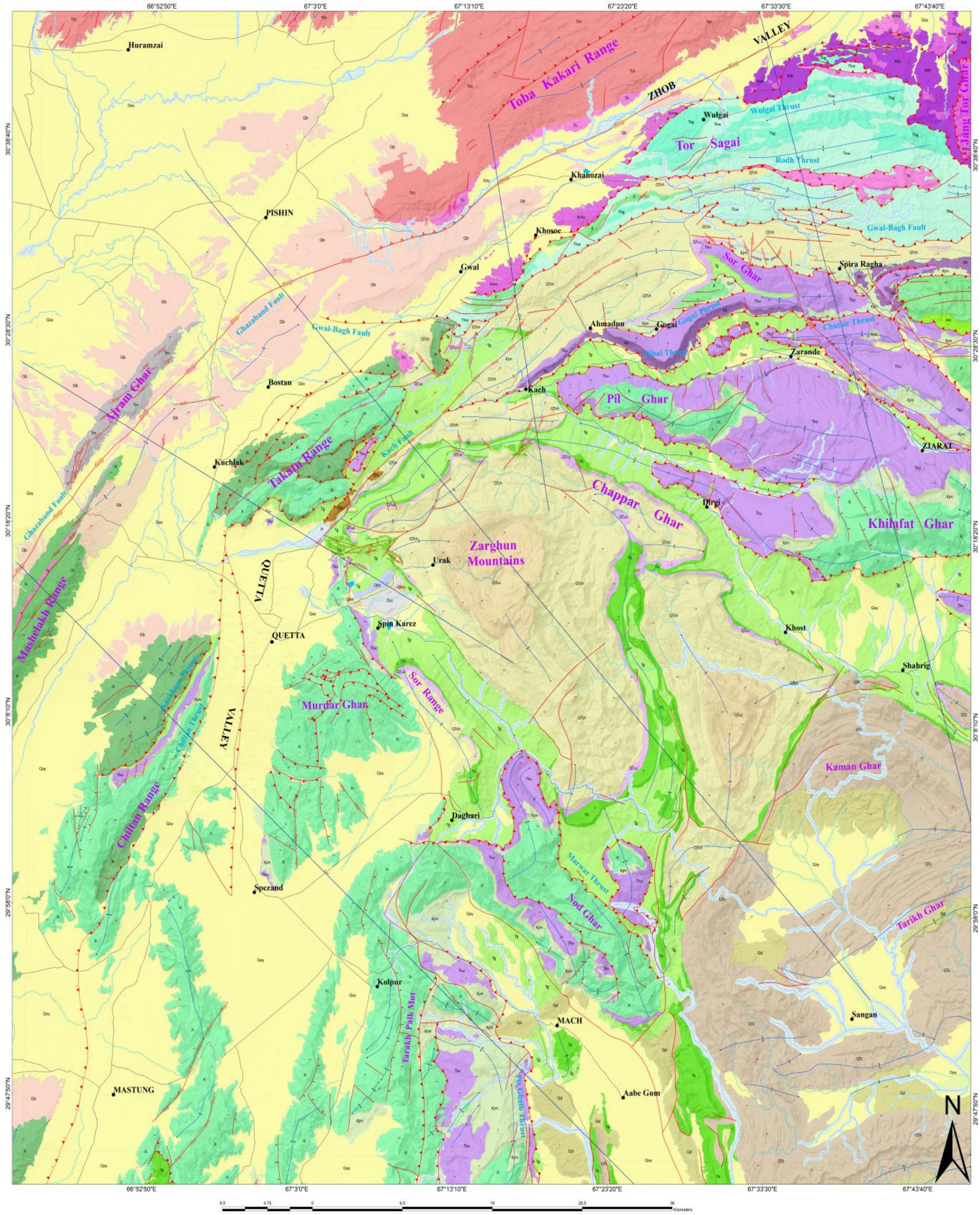

Figure 3(A). Geological map of Quetta and surrounding areas, which comprises 16 topographic sheets (1:50000 scale) of the Survey of Pakistan.

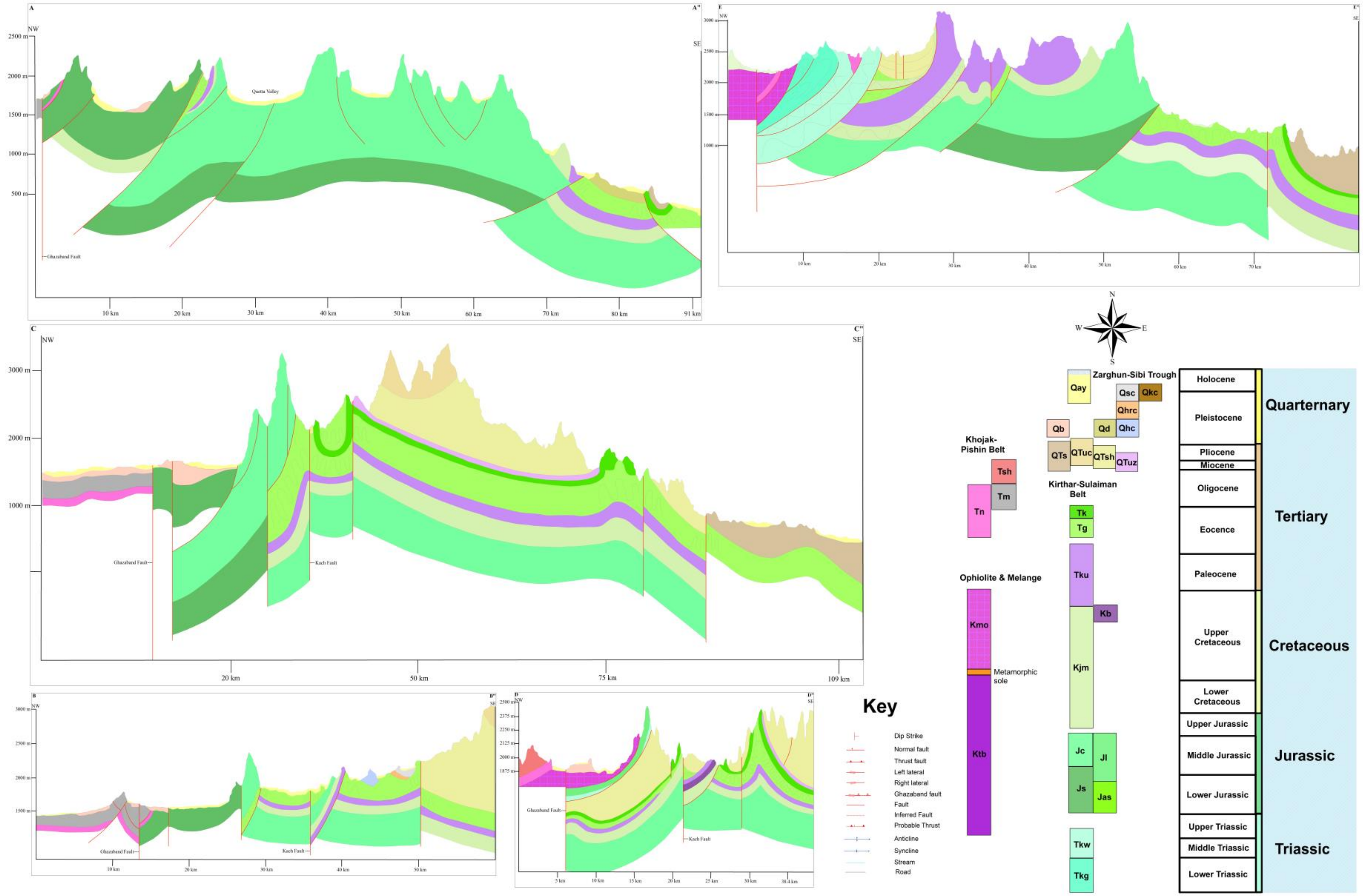

Figure 3(B). Geological cross-sections of Quetta and surrounding areas.

Table 1. Stratigraphic succession of the Western SFTB and associated ZST.

Age	**Group**	**Formation** (Map Units)	**Lithology**
Holocene		Sub-Recent/Recent (Qay)	Loose debris, sand, gravel, clay
Pleistocene	Spin Karez Group	Kach Dam Conglomerate (Qkc)	Conglomerate
		Spin Karez Conglomerate (Qsc)	Conglomerate, sandstone, clays
		Hanna Red Clays (Qhrc)	Reddish brown clays
		Hanna Lake Conglomerate (Qhc)	Conglomerate
		Dada Conglomerate (Qd)	Conglomerate
Unconformity			
Pliocene	Urak/Sibbi Group (QTs)	Urak Conglomerate (QTuc)	Conglomerate
		Shin Matai Formation (QTsh)	Mudstone, sandstone, conglomerate
Miocene		Uzda Pusha Formation (QTuz)	Sandstone, mudstone
Disconformity (Angular unconformity in some areas)			
Eocene		Kirthar Formation (Tk)	Limestone, shale
		Ghazij Formation (Tg)	Claystone, sandstone, conglomerate, limestone and coal seams
Paleocene		Dungan Formation (Tku)	Limestone, shale
Disconformity (in some areas)			
Late Cretaceous		Pab Formation / Mughal Kot Formation / Fort Munro Formation / Hanna Lake Limestone	Sandstone, siltstone, shale, limestone,
	Bibai Group (Kb)	Bibai Formation Chinjin Volcanics	*in-situ* mafic volcanic rocks, volcanic conglomerate, volcanic breccia, volcanogenic sandstone, mudstone
Disconformity (in some areas)			
Early-Middle Cretaceous	Parh Group (Kjm)	Parh Limestone Goru Formation Sembar Formation	Limestone (bio-micritic), marl and shale
Disconformity			
Jurassic		Chiltan Limestone (Jc) Loralai Limestone (Jl) Shirinab Formation (Js)	Limestone and minor shale

		Spingwar Formation	
Triassic	Khanozai Group	Wulgai Formation (Tkw)	Shale, limestone and sandstone
		Gwal Formation (Tkg)	Variegated shale and limestone
Base not exposed			

Triassic

The Triassic Khanozai Group Anwar et al (1993) comprises Lower Triassic Gwal Formation Anwar et al (1993) and Upper Triassic Wulgai Formation (Williams, 1959). They are the oldest sedimentary successions of the SFTB (Fig. 3(A, B); Table 1). The Gwal Formation (Anwar et al., 1993) comprises variegated shale, limestone and marl of Lower Triassic age. The Wulgai Formation is composed of limestone interbedded with shale. Various species of ammonites and *bivalves are* reported, which specify Triassic age to the group (Fatmi, 1977; Shah, 1977). The base of Triassic is not exposed anywhere in the SFTB.

Jurassic

Jurassic rocks comprise the Spingwar, Shirinab and Chiltan formations (Fig. 3(A, B); Table 1). The Spingwar (Williams, 1959) consists of grey to greenish grey shale, grey to whitish grey marl and limestone with some igneous sills. It's Upper Triassic to Early Jurassic age is based on fossils like ammonites, brachiopods, bivalves, crinoids, corals and shell fragments (Williams, 1959; Anwar, et al, 1991).

The Shirinab (Jones,1961);Fatmi, (1977) comprises 1500 to 3000 m thick limestone and shale succession (Williams, 1959; Jones, 1961; Fatmi, 1977). Shirinab Formation transitionally and conformably underlies the Chiltan Limestone Jones, (1961), which is named after the Chiltan Range and composed of thick-bedded limestone. The Loralai Limestone (Jones, 1961), named after the town of Loralai (Fig. 3(A, B); Table 1), comprises thick-bedded limestone and minor shale Kassi and Khan, (1993, 1997); (Durrani et al., 2012; Durrani, 2014) of Middle Jurassic age (Jones, 1961; Fatmi, 1977). The Chiltan and Loralai limestones transitionally and conformably overerlie the Shirinab and Wulgai formations.

Cretaceous

The Early to Middle Cretaceous rocks (Fig. 3(A, B); Table 1) are composed of Parh Group Jones (1961), which is divided into Sembar, Goru and Parh Formations (Williams, 1959; Jones, 1961; Gigon, 1962; Fritz and Khan, 1967; Fatmi, 1977; Allemann, 1979). The Sembar Formation of Williams, (1959) is composed mostly of shale interbedded with siltstone, arenaceous limestone and sandstone (Fig. 3(A, B); Table 1). The shale contains Belemnites, foraminifera and ammonites of Late Jurassic to Early Cretaceous age (Williams, 1959; Fatmi, 1968, 1972, 1977). It is conformably underlain by Goru Formation (Williams, 1959); (Jones, 1961), which comprises shale and siltstone interbedded with limestone containing pelagic foraminifera of the Early

Cretaceous age (Williams, 1959; Fritz and Khan, 1967; Allemann, 1979). Its Upper contact with Parh Limestone is conformable (Vredenburg, 1909); Williams, 1959), which is distinctive biomicritic limestone of light grey, white and cream colour, rich in pelagic foraminifers of Early Late Cretaceous age (Gigon, 1962; Allemann, 1979). Its upper contact with Bibai Group is conformable, whereas in Quetta area it is disconformable with the Hanna Lake Limestone (Kassi et al., 1999, 2000, 2009).

The Late Cretaceous succession is comprised of Bibai groups, Hanna Lake Limestone, Fort Munro, Mughal Kot and Pab formations. The Bibai Group (Williams, (1959); (Kazmi, 1955, 1979, 1984, 1988; Khan, 1998; Khan et al., 2000; Shah et al., 2021) is composed of volcanic and volcaniclastic rocks (Fig. 3(A, B); Table 1). The group transitionally and conformably overlies the Parh Limestone (Kazmi, 1955, 1988; Khan et al., 1999; Shah et al., 2021). In Kach-Ziarat area it is unconformably overlain by the Dungan Formation (Kazmi, 1955, 1988); elsewhere its upper contact is transitional and conformable with the Pab Formation (Khan et al., 1999; Shah et al., 2021). The limestone, interlayered with the Bibai Group, in its lower part, contains pelagic foraminifera of Campanian age Kazmi (1955, 1988), whereas, its upper part contains foraminifera Kazmi (1955, 1988) that suggest an Early to Middle Maastrichtian age.

The Hanna Lake Limestone of Kassi et al (1999, 2000, 2009) is argillaceous limestone, which is the equivalent of the Bibai Group Kazmi (1955, 1979, 1984, 1988); Kassi et al., 1993; Khan, 1998; Khan et al., 1998, 1999, 2000; Shah et al., 2021) and Mughal Kot Formation (Williams, 1959; Fatmi, 1977) (Fig. 3(A, B); Table 1). Late Campanian to Early Maastrichtian age has been proposed by (Kassi et al., 1999). It's lower contact (with the Parh Limestone) and upper contact (with the Fort Munro Formation) is disconformable.

The Fort Munro Formation (Eames, 1952; Williams, 1959; Allemann, 1979) (Fig. 3(A, B); Table 1) comprises limestone containing Orbitoides of the Upper Maastrichtian age (Williams, 1959; Allemann, 1979). Upper contact of the formation with Pab Sandstone is disconformable (Table 1).

The Pab Sandstone (Vredenburg, 1907) is brownish grey and cream colour and quartzose (Fig. 3(A, B); Table 1) containing Orbitoides of the Upper Maastrichtian age (Vredenburg 1908; Williams 1959; Jones, 1961). Its upper contact with the Paleocene Dungan Formation is conformable.

Furthermore, numerous sills and dykes are present, which have been intruded in the Triassic–Lower Cretaceous successions of the western SFTB during Late Cretaceous. They have been classified as dolerite, olivine dolerite and lamprophyres (Kerr et al., 2010); (Muhammad et al., 2019) that are related to the Late Cretaceous magmatic activity, most appropriately hotspot-related, e.g. the Deccan Trap and Chagos-Laccadive Ridge (Kerr et al., 2010; Muhammad et al., 2019).

Paleocene

The Dungan Limestone (Griesbach, 1881); (Oldham, 1893; Jones, 1961) is a thick succession of highly fossiliferous, nodular to massive limestone and marl, containing an assemblage of the larger foraminifera of Paleocene to Early Eocene age (Jones, 1961; Allemann, 1979) (Fig. 3(A, B); Table 1). It is conformably overlain by the Eocene Ghazij Formation.

Eocene

The Ghazij Formation (Oldham, 1890); (Eames, 1952; Jones, 1961; Williams 1959; Fatmi, 1974) is a thick succession of shale, claystone, sandstone, limestone, conglomerate, containing coal seams (Fig. 3(A, B); Table 1). The limestone horizons contain fresh-water lamellibranch, gastropods, mollusks, foraminifers and corals, which suggest an Early Eocene age (Iqbal, 1969a, b). It is conformably overlain by the Kirther Formation. The Kirther Formation/ Spin Tangai Limestone (Oldham, 1890); (Noetling, 1903; Jones, 1961; Cheema et al., 1977; Fatmi, 1977) is distinguishable into the lower limestone-dominant part and upper shale-dominant part (Fig. 3(A, B); Table 1). Lower part is mainly composed of thin to thick bedded argillaceous and nodular limestone, rich in foraminifera. Upper part is composed of highly fossiliferous shale containing foraminifera, mollusks, brachiopods, echinoids, bivalves and vertebrate remains (Oldham, 1890); (Vredenburg, 1908; Pilgrim, 1940; Eames, 1952; Jones, 1961; Latif, 1964; Iqbal, 1966, 1969); which suggest Middle to Late Eocene age. Its upper contact in the ZST is disconformable with the Urak Group (Kazmi and Raza, 1970; Durrani, 1997; Durrani et al., 1999).

Miocene-Pliocene

The Urak Group (Table 1), named after the village of Urak (Kazmi and Raza, (1970) (Sibbi Group of Jones, (1961) is mainly exposed in the ZST. It comprises mollase-type sediments, composed of light grey sandstone (Uzhda Pusha Formation), reddish and brownish grey claystone and sandstone (Shin Matai Formation) and conglomerate (Urak Formation) (Jones, 1961; Kazmi and Raza, 1970; Durani 1997; Durani et al., 1999; Kassi et al., 2009).

The Uzda Pusha Formation of (Kazmi and Raza (1970) is composed of sandstone, claystone and conglomerate containing vertebrate fossils (Pilgrim, 1913, 1926); (Anderson, 1928; Colbert, 1933; Lewis, 1937; Gill, 1952; Pascoe, 1963) (Fig. 3(A, B); Table 1) of Middle to Late Miocene age. Upper contact of the formation is conformable with the Shin Matai Formation (Fig. 3(A, B); Table 1), which is characterized by monotonous cyclic alterations of sandstone, claystone, containing vertebrate fossils Pascoe, (1963) suggesting an Early to Middle Pliocene age. It is conformably overlain by the Urak Formation [Urak Conglomerate of Kazmi and Raza (1970)], which is composed of conglomerate, sandstone and claystone (Fig. 3(A, B); Table 1) of Pleistocene age (Kravtchenko, 1964). The conglomerate is composed of a variety of pebbles and boulders.

Pleistocene

Quaternary rocks of the Hanna-Spin Karez area, Quetta District, comprise over 800 m thick succession that was mapped as Spin Karez Gravel (Jones, 1961). It was named (Naseer, 2019; Naseer et al., 2019) as "Spin Karez Group" and subdivided it into the "Hanna Lake Conglomerate", "Hanna Red Clays", Spin Karez Conglomerate", of Pleistocene age, and flat lying "Holocene deposits" (Fig. 3(A, B); Table 1). The "Hanna Lake Conglomerate", is thick succession of crudely bedded conglomerate in lower part and stratified conglomerate, with sandstone lenses, in upper part. Its lower contact with the Eocene Ghazij Formation is an angular unconformity. The "Hanna Red Clays" over 500 m thick succession of red-coloured mudstone rarely interbedded with thin-bedded sandstone and siltstone. It conformably overlies the Hanna Lake Conglomerate. The "Spin Karez Conglomerate" is ~100 m thick, moderately- to well-sorted conglomerate containing sandstone lenses. The Holocene rocks are 10-20m thick succession of sediments comprising gravel, clay and silt. They overlie the "Hanna Red Clays" with angular unconformity.

Near the old Kach Dam area, west of the Hanna Lake, over 100 m thick succession of the conglomerate is exposed, which extends further northward, west of the Sran Tangi. The succession has not been reported, mapped and/or described before, therefore, we arbitrarily named it as the "Kach Dam Conglomerate". It is mostly composed of cobbles and pebbles of limestones with very minor proportions of sandstone lenses. The conglomerate unit has faulted contact with the Urak Group and is envisaged to be of Pleistocene age.

3.2 Muslimbagh-Zhob Ophiolitic Belt

The Muslimbagh-Zhob Ophiolite, and associated mélanges and sediments, have been obducted on Triassic through Cretaceous sedimentary succession of the SFTB, which are considered as the boundary between the India and Eurasia (Gansser, 1979; Ahmad and Abbas, 1979; Sengor, 1987) (Figs. 1 and 3; Table 2).

Table 2. Stratigraphy of the Muslimbagh-Zhob Ophiolite and Khojak-Pishin Belt**.**

Age	Group	Formation (Map Unit)		Lithological characters
Holocene	-	Zhob River Deposits		Gravel, sand and clays
Thrust / Angular Unconformity				
Pleistocene	-	Bostan Formation		Red colored mudstone, sandstone, conglomerate
Thrust / Angular Unconformity				
Late Miocene-Pliocene	-	Malthanai Formation		Sandstone, conglomerate, red-colored mudstone
Thrust/Angular Unconformity				
Middle to Late Miocene	Dasht Murgha Group	Sra Khula Formation		Red-coloured mudstone, siltstone and sandstone
		Bahlol Nika Formation		Greyish sandstone, mudstone and conglomerate
		Khuzhobai Formation		Maroon mudstone with reddish-brown sandstone
Thrust / Angular Unconformity				
Oligocene – Early Miocene	-	Khojak Formation	Shaigalu Member (Tsh)	Sandstone with subordinate shale

			Murgha Faqirzai Member (Tm)	Shale with subordinate sandstone
Eocene	-	Nisai Formation (Tn)	Fossiliferous and reefoid limestone, marl and shale with thin limestone beds	
Nonconformity				
Cretaceous	-	Muslim Bagh - Zhob Ophiolite (Kmo)	Mostly ultramafic and mafic igneous rocks	
		Mélange Rocks (Ktb)	Mixed-up igneous and sedimentary rocks	

The ophiolites, are shown in the northwestern part of the map, to the south of Zhob Valley (Fig. 3(A, B)). They are composed of six units, which, from base to top, are: (1) ultramafic tectonites, (2) ultramafic rocks, (3) mixed cyclic succession of mafic and ultramafic rocks, (4) mafic rocks, (5) sheeted dikes and (6) Pillow Lavas and associated sediments (Ahamad and Abbas, 1979; Mengal et al., 1993). The ophiolites comprise the harzburgite and dunite, which include chromite deposits. They also comprise peridotite that stratigraphically underlie the ultramafic-mafic cumulates. The mafic and ultramafic succession underlie the basaltic pillow lava, massive lava, volcanic breccia and pelagic limestone, radiolarian chert and mudstone succession of Jurassic age (Kojima et al., 1994). Basalts are considered to be tholeiitic, showing characteristics of the mid-ocean-ridge Sawada et al. (1992) of Cretaceous age (Kojima et al., 1994). K-Ar dating of volcanics indicate 68 to 81 Ma (Sawada et al., 1992). The ophiolite preserves sub-ophiolitic metamorphic rocks at its base. Geochemistry of crustal rocks of ophiolite suggests supra-subduction zone setting (Kerr et al., 2010; Kakar et al. 2014; Muhammad et al., 2019).

The ophiolites overlie the mélange complex, comprising mixed-up igneous and sedimentary rocks of the Mesozoic age at the Bagh area (Fig. 3(A, B)), called Bagh Complex (Mengal et al. 1993, 1994; Kojima et al., 994; Naka et al., 1996). Northward the complex is bounded by the Muslimbagh-Zhob Ophiolite and to the south by the Gwal Bagh Fault (Fig. 3(A, B)). The Ophiolites are non-conformably overlain by the Eocene Nisai Formation.

Age of emplacement of the ophiolites, onto the sedimentary succession of Indian Plate, was thought to be Middle Paleocene to Early Eocene (Allenman, 1979; Otsukie et al., 1989). However, Kojima et al. (1994) proposed the age of emplacement as Late Cretaceous to Early Paleocene.

3.3 Khojak-Pishin Belt

The Khojak-Pishin Belt (KPB) comprises numerous small-size exposures / blocks of the ophiolites, the Late Paleocene–Early Oligocene Nisai Group Jones, (1961); (Kakar, 2012; Kasi et al., 2012; Bukhari et al., 2016) that nonconformably overlies the Muslimbagh-Zhobe Ophiolites (Fig. 3(A, B), Fig. 4), followed by the Oligocene Khojak Formation Jones, (1961); (Qayyum et al., 1996, 1997) and Miocene-Pleistocene rocks of the Dasht Murgh Group and Malgtanai and Bostan formations (Table 2) (Kasi, 2012; Kasi et al. 2012, 2016a, 2016b, 2018). Kasi et al. (2012; 2016a, 2016b, 2018) divided the Khojak-Pishin Belt in various tectono-stratigraphic zones of distinct lithostratigraphy bounded by thrusts and unconformities. Their Zone-I comprises the Muslimbagh-Zobe Ophiolites at the base; Zone-II comprises the Late Paleocene–Early Oligocene Nisai Group (Kakar, 2012; Bukhari et al., 2016) and Oligocene Khojak Formation, Zone-III comprises their Dasht Murgha Group. Zone-IV comprises their Mio-Pliocene Malgthanai Formation, Zone-V comprises Pleistocene Bostan Formation and Zone-VI comprises Holocene succession of Zhob valley. Kasi et al. (2012; 2016a, 2016b, 2018) first-time invoked the relation of tectonics with sedimentation / stratigraphy of the Khojak-Pishin Belt and demonstrated uplifting of Miocene and older rocks supplying sediments to the younger rocks of Dasht Murgha Group and Malgthanai and Bostan formations. They proposed that tectonic uplift and east-southeastward transport of hanging walls of the major thrusts caused subsidence of the footwalls, which provided accommodation for development of the successively younger fluvial systems, in which the Dasht Murgha Group, Malthanai and Bostan formations and the flat-laying Holocene deposits of the Zhob valley were deposited, respectively.

Ophiolites

Numerous small-size exposures / blocks of the ophiolites, and associates sedimentary and volcanic rocks, are also exposed in the Khojak-Pishin Belt (Fig. 3(A, B); Fig. 4) in the form of thrust-bound belts Kasi, (2012); (Kasi et al., 2012; 2014; 2016a, 2016b, 2018) that have not been studied and/or mapped so far by any researcher. However, we presume them to be the equivalent of the Muslimbagh-Zhob Ophiolite.

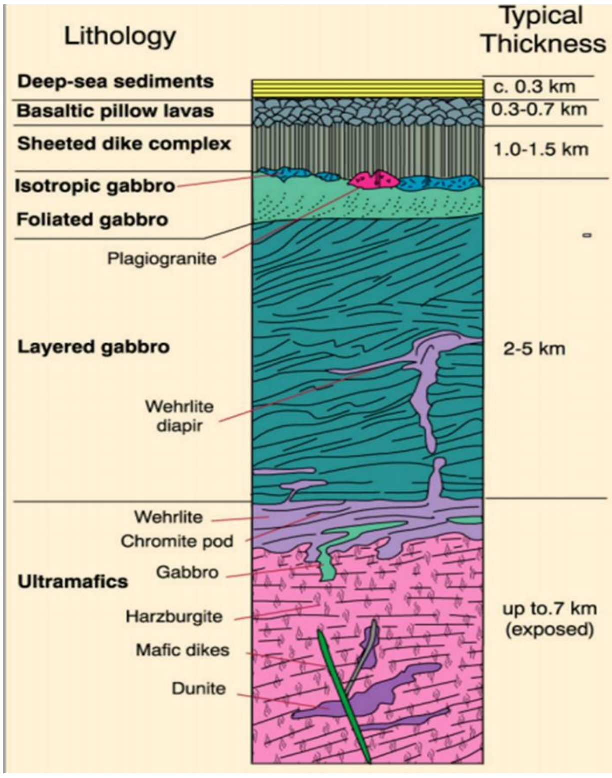

Fig. 4. Ophiolite rock sequence modal Boudier and Nicolas (1985).

Nisai Group

The Late Paleocene–Early Oligocene Nisai Formation (Jones, 1961; Shah, 1977, 2009; Ahmad and Afzal, 2002; Kakar, 2012; Bukhari et al., 2016) is a mixed siliciclastic-carbonate succession of the Khojak-Pishin Belt, which nonconformably overlies ophiolites of the Zhob Valley (Fig. 3(A, B); Fig. 4) and is conformably overlain by the fluvial and deltaic successions of the Khojak Formation. Kakar, (2012) preferred to rename it as "Nisai Group" and identified three contrasting and mapable lithostratigraphic units and named them, from base to top, as Jabrai, Malkhozgai and Nisai formations. Its upper contact is conformable and transitional with the Murgh Faqirzai Member of the Khojak Formation.

Khojak Formation

The Khojak Formation was subdivided into Murgha Faqirzi and Shaigalu members (Fig. 3(A, B); Fig. 4) (Vredenburg, 1909; Jones, 1961). Murgha Faqirzai Member dominantly comprises shale and/or slate, sandstone. Jones, (1961) assigned it Oligocene age based on foraminifera. Its upper contact with Shaigalu Member is conformable. The Shaigalu Member (Fig. 3(A, B); Fig. 4) comprises sandstone and shale. The foraminiferal assemblage suggests Oligocene age for the Khojak Formation (Jones, 1961).

Dasht Murgha Group

The Dasht Murgha Group Kasi et al. (2012; (2016a, 2016b, 2018) comprises the succession exposed northwest of the Dasht Murgha area of the Qila Saifullah District (Fig. 3(A, B); Fig. 4). Previously, it was mapped as Khojak Formation Jones, (1961) and later on Dasht Murgha Group and the Bostan Formation were mapped as Sharankar Formation (Qayyum et al., 1997a, 2001). Kasi et al. (2012, 2016a, 2016b, 2018) proposed it to be Early-Middle Miocene.

Malgthanai Formation

The name Malgthanai Formation was proposed by (Kasi et al., 2012; 2016a, 2016b, 2018) for Multana Formation of Jones, (1961), after Malgthanai village (Fig. 3(A, B); Fig. 4). It is composed of sandstone, siltstone, mudstone and conglomerate. Its upper contact with the Pleistocene Bostan Formation is thrust and lower contact with Nisai Formation is unconformable. Kasi et al. (2012; 2016a, 2016b, 2018) envisaged that the Malgtanai Formation is younger than Dasht Murgha Group and may be of Late Miocene-Pliocene.

Bostan Formation

The Bostan Formation Jones, (1961) is composed of conglomerate, mudstone and sandstone (Kasi et al., 2012; 2016a, 2016b, 2018) (Fig. 3(A, B); Fig. 4) of Pleistocene age (Jones, 1961; Cheema et al., 1977; Kasi et al., 2012; Kasi, 2014). In Zhob valley its lower and upper contacts with the Malgthanai Formation and Holocene deposits are thrusts. However, it is envisaged that its lower contact with the older rocks is an angular unconformity.

Holocene-Recent deposits

The Holocene-Recent deposits, present mostly in the Zhob valley (Fig. 3(A, B); Table 2), are represented by flat-lying deposits (Kasi et al., 2012; Kasi, 2014) (Fig. 3(A, B); Fig. 4). They are dominantly composed of loose or semi-consolidated mud, sand, siltstone and gravel, considered to be Holocene. They mostly overlie the older successions with angular unconformity.

4 STRUCTURE AND TECTONICS

The Quetta and surrounding areas (Figs. 1 2 and 3) lie in the Kirthar-Sulaiman Fold-Thrust Belt (KSFTB). Quetta Syntaxis (QS) and Zarghun-Sibbi Trough (ZST) are two key structures that lie between the Kirthar Fold-Thrust Belt (KFTB) and Sulaiman Fold-Thrust Belt (SFTB). Furthermore, the Ghazaband Fault (GF) is another feature, which is part of the Nushki-Chaman Transform Fault System (NCTFS) that separates the Khojak-Pishin Belt (KPB) from the KSFTB.

4.1 Kirthar-Sulaiman Fold-Thrust Belt

The KSFTB initiated with the collision of India Plate with the Eurasia Plate in Paleocene - Early Eocene (Molnar and Tapponier, 1975; Border, 1978; Acharya, 1979; Alemann, 1979; Bingham and Klootwjik, 1980; Otsuki et al., 1989). General trend of the KFTB is N-S; however, it accommodates multi-phase prolonged and continued deformation of the volcano-sedimentary successions of Triassic-Pleistocene age (Fig. 3(A, B); Table 1). Westward it is bounded by the NCTFS and eastward by the Kirthar Foredeep (Lawrence and Yeats, 1979; Lawrence et al., 1981). The SFTB is northeastward continuation of the KFTB, which is separated by the intervening features of QS and ZST. The KFTB comprises imbricate slices that developed during the southward-propagating piggy-back thrusting (Lawrence and Yeats, 1979; Lawrence et al., 1981).

4.2 Zarghun-Sibbi Trough

The ZST is a trough-shaped basin that accommodated over 4000 m thick succession of molasse sediments of the Miocene-Pleistocene Sibbi and Urak groups, locally derived from the KSFTB (Figs. 1 2 and 3). The mollasse successions of the ZST, between the Zarghun and Sibbi areas, are highly deformed that display obvious intervening patterns (Figs. 1 and 3). The coarse clastic sediments, of the ZST, were continuously provided by the KSFTB. Similar situation may be proposed for Siwaliks of Kohat-Potwar area (Burbank and Reynolds, 1984).

4.3 Quetta Syntaxis

Syntaxes are defined as arcuate parts of the fold-thrust belts formed due to systematic rotation in plan (Carey, 1955). Some syntaxes (e.g. the Sicilian Calabrian and Umbrian syntaxes of Italy) developed by active rotation of fold-thrust belts due to impingement across a promontory (Catalano et al., 1976), whereas, others are original curvatures, not related to the active rotation of fold-thrust belts. The Quetta Syntaxis (QS), western Pakistan (Figs. 1, 2 and 3), is a sharp bend, which separates the E-W-trending western SFTB from the N-S-trending KFTB. The QS formed due to relative movement of the GF in the west against the relatively consistent Sibbi Block in the east (Wadia, 1931; Jones, 1961; Bakr and Jackson 1964; Auden, 1974; Sarwar and DeJong, 1979; Kazmi and Rana, 1982).

4.4 Ghazaband Fault

The Ghazaband Fault (GF) is one of the most important features involved in development of the QS. In the early Cenozoic Era the interaction of Indian, Eurasian and Arabian plates caused formations of two subduction zones; one in the south, i.e. the Makran Subduction Zone, and another in the north, i.e. the Himalayan convergent margin (Molnar and Tapponnier, 1975; Treloar and Izatt 1993). After collision the plate boundaries of the Indian and Eurasian plates were linked by sinistral strike-slip faults of the NCTFS in the western Pakistan. It comprises three major splays, arranged in en-echelon pattern, namely the Ghzaband, Ornach-Nal and Chaman faults, along with associated minor transpressive faults (Siddiqui and Jadoon, 2013). The NCTFS is over 900 km long fault system, which connects various thrusts of Makran belt in the south, with the Main Boundary Thrust (MBT) and Herat Fault in Afghanistan.

GF, being a splay of the NCTFS, continues for 300 km sub-parallel to the System, starting from the Gajozai village of Khuzdar district (27˚ 11' 28" N, 65˚ 48' 30" E) to the town of Pishin (30˚ 25' 21.95" N, 66˚ 57' 00.72" E). Studies on the slip-rates have suggested rates of 8 ± 3.1 cm/year along the Chaman Fault and 16 ± 2.3 cm/year along the GF, respectively, which shows that the GF is the most hazardous in the region (Figs. 1 and 3) (Fattahi and Amelung, 2016). Since 1892 various earthquakes of over M7 occurred at western boundary of the Indian Plate (Ambraseys and Bilham, 2003), one of which (M 7.7) occurred more recently during 2013 in the Awaran District of Balochistan (Avouac et al., 2014; Barnhart et al., 2014; Jolivet et al., 2014). GF is the source of Quetta Earthquake (M7.7) that destroyed Quetta with over 60,000 fatalities and heavy loss of properties (Lawrence et al., 1981; Ambraseys and Bilham, 2003; Seliga et al., 2012).

4.5 Structural Domains

Based on the structural style, Niamathullah (1992) subdivided the area into four structural domains, whereas,Florian et al. (2011) subdivided the area into five structural domains (Fig. 4); however, we have subdivided our map area into five structural domains that are partly different from their domains. Their Structural Domain I (foredeep), to the south, is not part of our map area. Furthermore, we have subdivided the Structural Domain II of the Florian et al. (2011) into two domains (our Structural Domain II and III). Our Structural domains I, IV and V are the same as those of the (Florian et al.,2011). The structural domains are briefly described as under:

Structural Domain I: It mainly comprises the ZST, which is mainly a broad syncline intervened by a narrow anticline with flat hinge zone and steep limbs with thrusts and strike-slip faults in the north (Figs. 3(A, B), 4). It mostly comprises Eocene succession of the Ghazij and Kirthar formations and Miocene-Pleistocene molasses successions of the Urak / Sibbi Group.

Structural Domain II: This domain comprises the western SFTB situated to the east and northeast of the ZST (Structural Domain I). The western most part of the SFTB, east of the ZST, shows upright folds and thrusts (Bibai Thrust, Gogai Thrust, Chutair Thrust), dominated by echelon pattern and probable extension along fold axis (Figs. 3, 4). The succession this domain comprises the volcano-sedimentary successions of Triassic through Eocene age.

Structural Domain III: It comprises the area at the northwestern extreme of the ZST, i.e. part of the schuppen zone at Takatu range, which shows compression at the core of the QS. Here structures are very tight; over-turning is common, with well-developed thrust zone and strike-slip components in some parts. This zone is separated by Kach (strike-slip) Fault (Fig. 3(A, B)) from the Bibai and Gogai thrusts. The KFTB to the west of the ZST, at its northern extreme (Figs. 3, 4), is dominated by major thrusts; e.g. the Karkhasa Thrust, Chiltan Thrust, Pir Ghaib Thrust and a major strike-slip fault. The Ghazaband Fault, that extent northward and merge into the Zhob Valley Thrust, is partly the northwestern boundary of this structural domain. The succession in this domain also comprises the sedimentary successions of Triassic through Eocene age.

Structural Domain IV: This structural domain mostly comprises the Khojak-Pishin Belt situated to the north and northwest of the GF, having partial boundary with the Structural Domain V in the northwest and Structural Domain II to the south. This is also a NE-S-trending thrust-fold belt comprising mixed marine, flysch and molasse successions of the Paleocene through Holocene age.

Structural Domain V: This domain comprises the area covered by the suture belt i.e. the Muslim Bagh Ophiolite (MBO) and associated mélanges and sediments. The domain is generally ENE-trending belt that occurs between Zhob Valley Thrust to north and Gwal Bagh Fault to south.

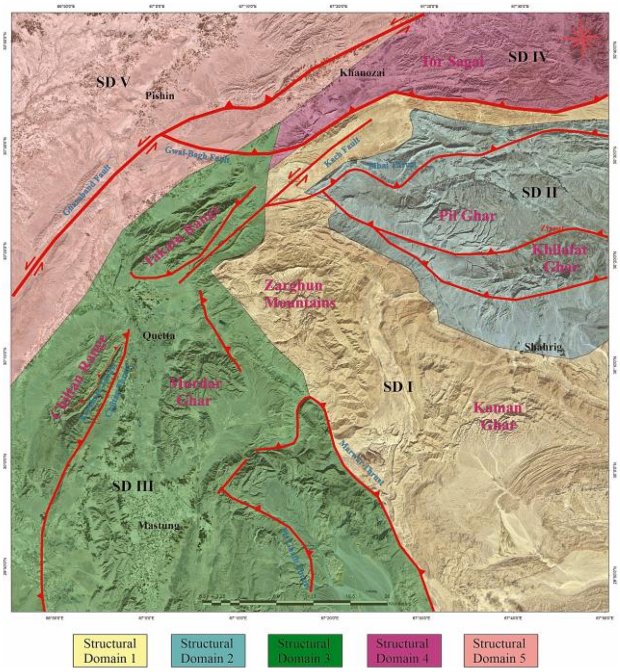

Figure 4: Generalized structural domains of the map area.

CONCLUSIONS

The collision of India plate with the Eurasia plate formed a suture zone (Florian et al., 2011) and resulted in the formation of five structural domains that formed a foreland fold-and-thrust belt, a major deep trough, a flysch zone, and an ophiolite complex. Four major faults bound the terrain, including the Frontal, Ghazaband, Gwal Bagh and Chaman faults. Folds and thrusts are the main structures and deformation continued, which resulted in folding of the pre-existing thrusts and refolding. The thrusting was on older-on-younger strata, but younger-on-older strata were also observed (e.g. the Rhod Thrust).

DECLARATIONS

Conflicts of interest/Competing interests:

The authors declare no any conflict of interest/competing interests.

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