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Structural analysis of the Kharthop and Kalabagh Hills area, Mianwali District, Punjab, Pakistan

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Abstract

The Surghar Range and the Kalabagh Hills are the extension of the Western Salt Range and are comprised of Precambrian to Mesozoic platform and Plio-Pleistocene fluvial sediments. The Eastern Surghar Range is a thin-skinned deformed structural province characterized by contractile structures. The dominant structural geometry of the range includes south-verging frontal thrust and folds and steeply south dipping back thrusts. This geometry developed as a result of ramping from a basal decollement at the base of Precambrian to Cambrian rocks. The contractile deformation systematically changes to transpersonal deformation in the east along the Kalabagh Fault Zone and a combination of s alt tectonics and compressional deformation in the vicinity of the Kalabagh Hills. The structures related to salt intrusions include the development of normal fault in the vicinity of Kalabagh Hills that are believed to be gravitational collapse caused by the flowage and upsection migration of Precambrian Salt Range Formation.

Keywords: Structural analysis; Kharthop; Kalabagh Hills; Surghar Range

1. Introduction

The study area includes Eastern Surghar and Kalabagh Hills of the Western Salt Range and Trans Indus ranges NW of Kalabagh town, Mianwali District, Punjab, Pakistan. These mountain ranges comprise an arcuate mountain belt that form the southeastern margin of the Kohat Plateau, flanks of the Bannu Basin in the east, south and southwest which represent the southern-most frontal thrust system of the Himalayan orogenic belt in North Pakistan (Alam et al., 2005; Alam, 2008).

Geographically, the study area is bounded by Kohat Plateau in the north and northeast, Indus River towards east and Kalabagh Reentrant in the south (Fig. 1). The Surghar Range forms the leading thrust front of the Kohat fold and thrust belt and is believed to be the western analog of the Salt Range in the east (Burbank and Raynolds, 1984; Yeats and Lawrencce, 1984). The Salt Range Thrust (SRT) along with its western analog, the Surghar Fault (SF) is the tectonic boundary separating Kohat-Potwar Plateau in the north and Punjab Foreland Basin in the south (Ahmad et al., 1999). Along the Salt Range and Surghar faults there is a south ward transport of the Salt Range, Potwar and Kohat plateaus in the form of large allochothonous block over the Punjab Plain. Thus, the SRT and SF is the surface expression of the leading edge of a decollement related thrust (Lillie et al., 1987; Ahmad et al., 1999).

The Kalabagh Fault Zone extends 120 kilometers from the southwestern corner of the Salt Range near Khushab to southern Kohat Plateau (Fig.1) and is characterized by right lateral transpressional deformation (Harland, 1971). The Kalabagh Fault Zone intersects with the Indus River near Kalabagh town (Fig. 2). Within the study area the Kalabagh Fault juxtaposes the Indian shelf sequence underlain by Eocambrian evaporites against deposits of the Indus River forming west verging folds and northeast dipping thrust and normal faults.

The SurgharRange exposes a thick succession of Mesozoic Platform rocks to Plio-Pliestoene molasse sediments. The exposed stratigraphic sequence in the study area consists of Pre-Cambrian to Eocene rocks unconformably overlain by the Siwalik Group rocks. The structural geometry of this important part of the frontal thrust zone is not clearly known. It is still debatable that whether

the juncture of the Western Salt Range and Surghar Range is characterized by an oblique ramp or is it a dominantly strike-slip fault. The main aim of this study is to describe the style of deformation to examine the relationship between the major and minor structures of the area with respect to the Kalabagh Fault and Salt Range Thrust.

2. Previous Work

The earliest published description of the geology of the Trans Indus and Salt ranges is attributed to Wynne (1878; 1880). He carried out pioneer survey of the Salt range and briefly described the lithological units of the area. Simpson's (1904) studied coal deposits of the Makarwal area and named it "The Maidan Range Coal Field". Fremore (1935) described the stratigraphy of the Surghar Range. A detailed study, regarding the stratigraphy and structure of the Salt Range and adjoining areas, is presented by Gee (1945; 1989).

The first systematic geological study of the coalfields of the Surghar Range started in early 1961 by Danilchick in which regional mapping of Surghar Range and detailed investigation of Makarwal Coal Field was carried out. Danilchick (1961) also worked on the Iron Formation of Surghar and Western Salt Range. Kummel (1966) described the stratigraphy of the Salt Range and Trans Indus Ranges. Fatmi (1968; 1972) described the paleontology and stratigraphy of the Trans-Indus Ranges. Danilchick and Shah (1967) revised the stratigraphic nomenclature of the Surghar Range and conducted detailed studies on the coal occurrences of the region. Sohn (1970) described the Triassic fauna of the Surghar Range and the Salt Range.

Abid et al. (1983) gave a brief account of the petrography, geochemistry and provenance of the Dhok Pathan Formation from upper part of the Surghar Range. Khan (1983) and Khan and Opdyke (1987) on the basis of magnetic polarity data suggested that the Siwalik Group rocks of the Trans-Indus Ranges are younger than the Siwaliks of Potwar Plateau. Akthar (1984) gave detailed account of the stratigraphy of the Mesozoic and Early Tertiary rocks of the Surghar Ranges. Danilchick and Shah (1987) prepared a fairly detailed report on the stratigraphy, coal resources and economic geology of the Makarwal area of Surghar and named it as "Makarwal Coal Field". Kazmi et al. (1979a 1979b); Dejong (1986); Jaume et al. (1988); Mc Doughall et al. (1990; 1991) and Pivink et al. (1993) discussed structural studies related with the fold and thrust belt of Kohat-Potwar Plateaus.

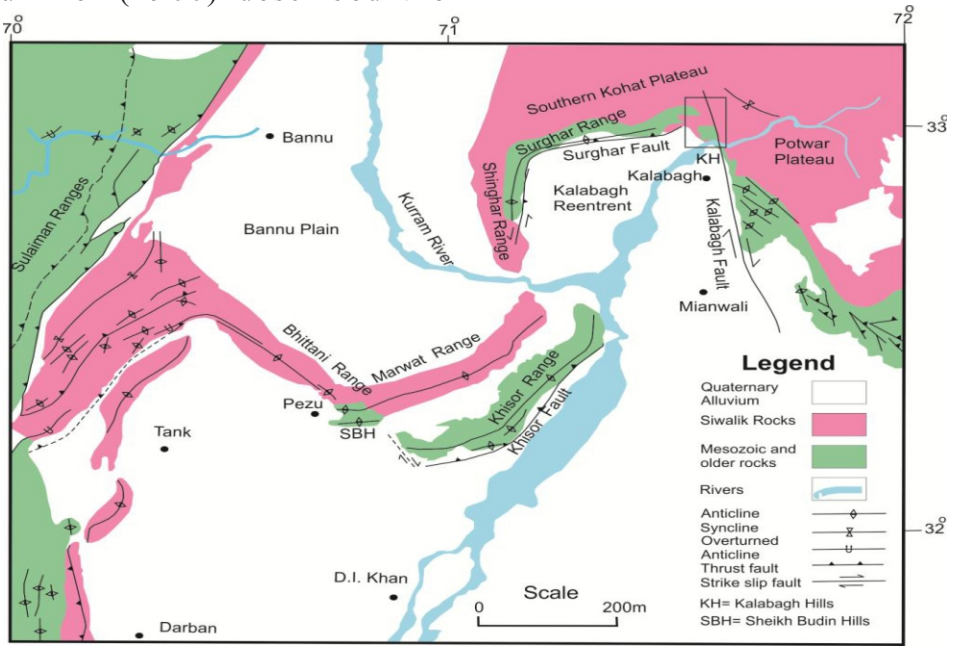

Fig.1 . Structural map of the Western Salt Range and Trans Indus Range(After Hemphil and Kidwai, 1976). The inset shows the location of the study area.

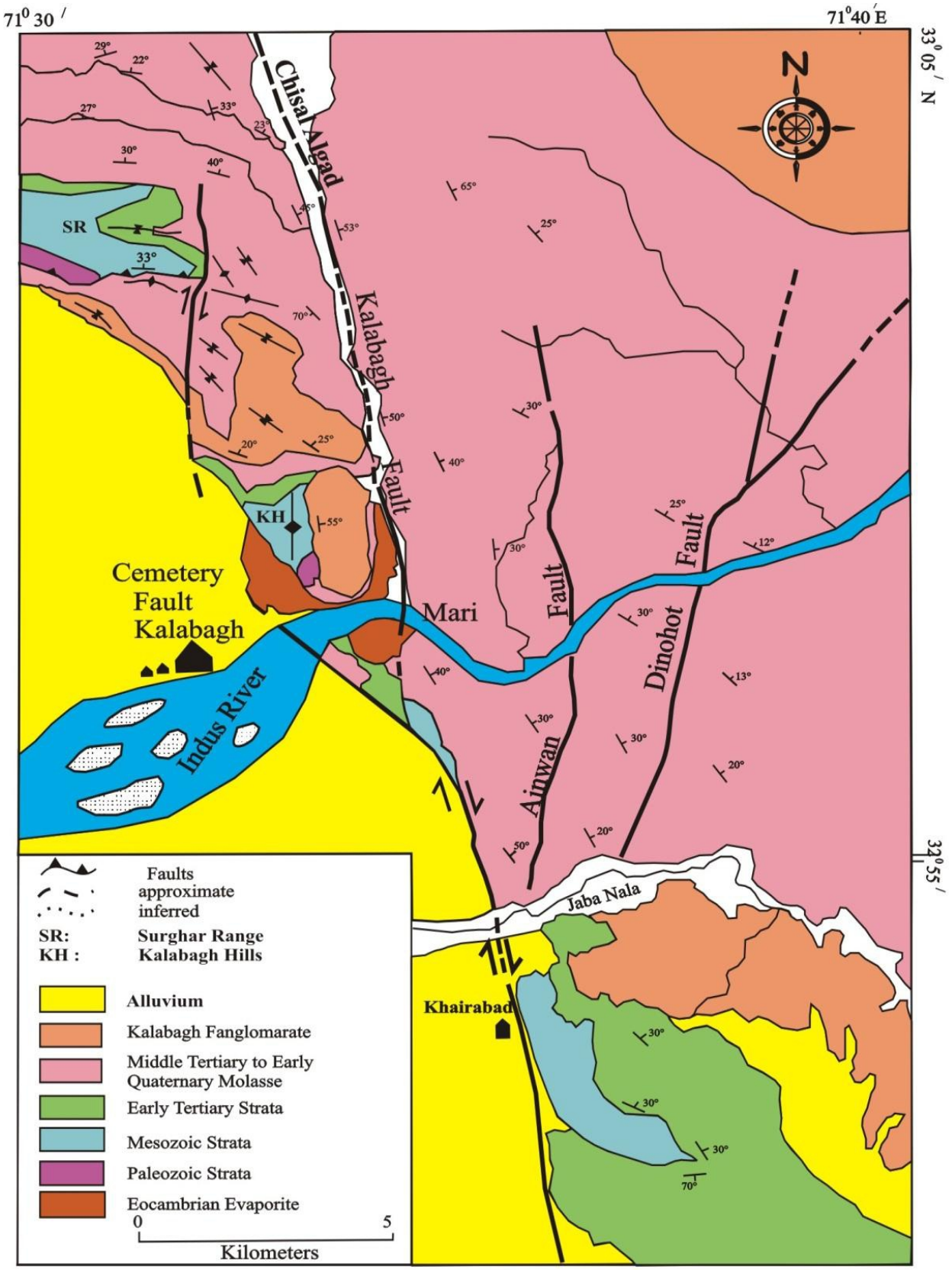

Fig.2. Geological map of the Western Salt Range and Kalabagh Hills showing major tectonic features in the region (After Mc Doughal and Khan, 1990).

3. Stratigraphy

A thick succession of Precambrian to Eocene rocks unconformably overlain by the rocks of Lower Siwalik is exposed in the study area (Table 1). The oldest rock unit mapped in the study area belongs to the Salt Range Formation of Pre-Cambrian age which has a faulted contact with the younger platform and molasse sediments present in the area (Fig. 3). The Salt Range Formation forms the base of the outcropping succession in the Kalabagh Hills. The proper stratigraphic sequence of the study area represents Zaluch Group of Permian at the base overlain by the rocks of Triassic. The Triassic sequence is preceded by Jurassic succession. In Surghar and Kalabagh Hills region the Jurassic sequence is represented by three formations i.e. Datta, Shinawari and Samana Suk. The Datta Formation constitutes the basal part of the Jurassic sequence and is overlain by the Shinawari Formation. The Shinawari Formation has a dis-conformable contact with the limestone of the Samana Suk Formation. The Jurassic rocks are followed by the Cretaceous formations towards the top. The Cretaceous sequence is represented by two formations namely Chichali and Lumshiwal whereas the overlying Paleocene sequence is represented by Hangu, Lockart and Patala formations. The Hangu Formation has a conformable contact with the overlying Lockhart Formation while the Lockhart Limestone has a gradational contact with the shale of the Patala Formation. The Patala Formation is overlying by the Nammal Formation that is mainly consisted of limestone, marl and shale. The Nammal Formation has a transitional contact with the Sakessar Limestone. At the top of Eocene rocks, a hiatus occurs at the end of which fluvial sedimentation started in the region. The fluvial molasse sediments of Siwalik Group are well exposed in the study area. Chinji and Nagri formations represent the rocks of Siwalik Group in Surghar and Kalabagh Hills area.

4. Structural Geology

Structurally the study area is dominated by Kalabagh and Surghar faults. The Surghar Fault divides the eastern part of the Trans-Indus Ranges into two distinct tectonic domains, on the northern and southern side of the fault, respectively (Fig.3). Each domain is described in detail as follows.

4.1. Northwestern domain

The northwestern domain lies north of Surghar Thrust and west of the trace of Kalabagh Fault (Fig.3). This domain includes two tectonostratigraphic sections that are the Southeastern Kohat Plateau and the Eastern Surghar Range. The structural style of the Surghar Range is characterized by four faults, where the Surghar Thrust is the most prominent. The Surghar Thrust is characterized by undulating map pattern having an east-west structural trend and is gently tosteeply north-dipping thrust(Figs. 4 and 5). The oldest rocks outcropping at the base of hanging wall strata belongs to Wargal Limestone of Permian suggesting that this fault is detached at the base of the Permian or older rocks. The hanging wall cutoffs along the Surghar Thrust are older in the west and become younger in the east, suggesting a decrease in the vertical uplift along the fault. The hanging wall strata of the Surghar Fault constitute the topographic expression of the entire Surghar Range in the study area. Within the hanging wall of the Surghar Fault a couple of back and fore thrusts, having limited map extension being observed.

The northern most of the back thrusts is named as Khartop Fault 1. This fault is northeast oriented and steeply dips towards south. Along this fault, the steeply dipping Eocene rocks are upthrown over the Siwalik Group rocks in the north. South of the Khartop Fault 1 lies Khartop Fault 2 that is vertical to steeply south dipping and emplaces Permian to Eocene rocks over the Eocene rocks in the north. The stratigraphic relationship along this fault suggests that it is characterized by greater vertical throw as compared to Khartop Fault1. A local scaleout of the syncline thrust is present in the core of the Surghar Syncline that displays east-west trend. It is low-angle north dipping thrust and brings Eocene rocks in its hanging wall over the Chinji Formation of the Miocene in the footwall (Ahmad et al., 2003).

Table 1. Stratigraphic framework of Eastern Surghar Range and Kalabagh Hills.

ERA	PERIOD	AGE		FORMATION		THICKNESS (m)
Cenozoic	Quaternary	Holocene Pleistocene		Alluvium		
				Kalabagh Conglomerate		
	Tertiary	Miocene	Early to Middle Miocene	Siwalik Group	Nagri Formation	1000
			Early Miocene		Chinji Formation	250
		Eocene	Early Eocene	Sakessar Formation		230
				Nammal Formation		100
		Paleocene	Late Paleocene	Patala Formation		50
			Middle Paleocene	Lockhart Formation		55
			Early Paleocene	Hangu Formation		?
Mesozoic	Cretaceous	Late Cretaceous		Lumshiwal Formation		?
		Early Cretaceous		Chichali Formation		35
	Jurassic	Late Jurassic		Samana Suk Formation		?
		Early to Middle Jurassic		Shinawari Formation		35
		Early Jurassic		Datta Formation		200
	Triassic	Late Triassic		Kingriali Formation		90
		Middle Triassic		Tredian Formation		45
		Early Triassic		Mianwali Formation		108
Paleozoic	Permian	Late Permian		Chhidru Formation		60
				Wargal Formation		145
Precambrian				Salt Range Formation		?

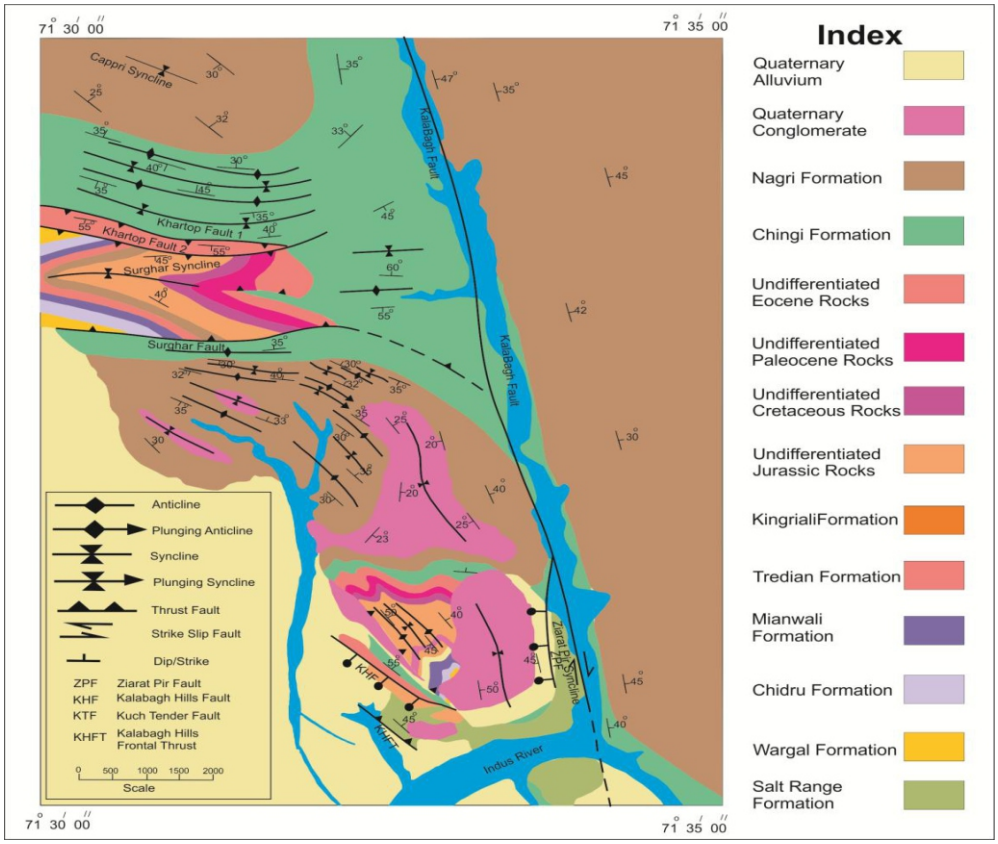

Fig.3. Geological map of the Kalabagh Hills and Eastern Surghar Range.

The hinterland side of the Surghar Range that is the Southern Kohat Plateau consists of gently north dipping Siwalik Group rocks with a prominent synclinal fold in the extreme north. This fold is named as Chappri Syncline and is characterized by north-west oriented trend and its core is occupied by the rocks of the Nagri Formation. The axial trend of this fold is oblique to the outcrop trace of the Kalabagh Fault and shows a distinctive feature of the area.

Towards east of the Kalabagh Fault no rocks older than Siwaliks crop out. The surface outcrop of the Siwaliks is characterized by a north-northwest structural trend that is in conformity with the Kalabagh Fault. The Kalabagh Fault is oriented north-northwest and runs with in the Siwalik Group rocks (Fig.6). The Kalabagh Fault is recognizable in the field by its trend and dip discordance within the Siwalik strata across the fault trace (Figs.7, 8 and 9).Northwest oriented folds are present towards south that showsan oblique relationship to the main strand of the Kalabagh Fault Zone (Fig.3).

4.2. Southern domain

The southwestern domain lies south and southwest of the Surghar and Kalabagh faults, respectively (Fig.3). South of the Surghar Range in the footwall of the Surghar Fault a series of anticlinal and synclinal folds constitute the structural geometry of this domain (Fig.7). All these folds display east-west orientation in the west and changes to northwest orientation towards east (Fig. 3). Previously, a north-south trending Surghar Fault (Fig.8) was mapped in this domain by (McDoughall and Hussain, 1991), but has not been identified during the present mapping. None of the structural features mapped in the study area show any evidence of such a fault. Toward south the Kalabagh Hills appear as a north-northwest and south-southeast trending anticlinorium cored by the rocks of Permian strata of Zaluch Group (Fig.3). A number of macroscopic scale faults are mapped within the Kalabagh Hills that play an important role in the tectonic model of Western Salt Range (Fig.3).

The structural features of the Kalabagh Hills can be grouped and described as follow.

4.3. Folds

The folds identified based on scale of observations in the Kalabagh Hills (Western Salt Range) are of two types. These folds are identified and interpreted on the basis of stratigraphic repetition and include alternate anticlinal and synclinal structures (Fig.3). Most of these folds are asymmetric based on the attitude data along the limbs of these folds and are mostly tight. All these folds display north-northwest axial trend and collectively construct an anticlinorium and has been named as Kalabagh Anticlinorium (Fig.3).Underneath the Kalabagh Conglomerate, rocks as old as Permian crop out in the core of a regional anticlinal fold (Fig. 3), Kalabagh Anticlinorium. The Kalabagh Anticlinorium along with its associated folds is characterized by north-northwest trend and is detached at the level of Permian rocks (Fig.3).

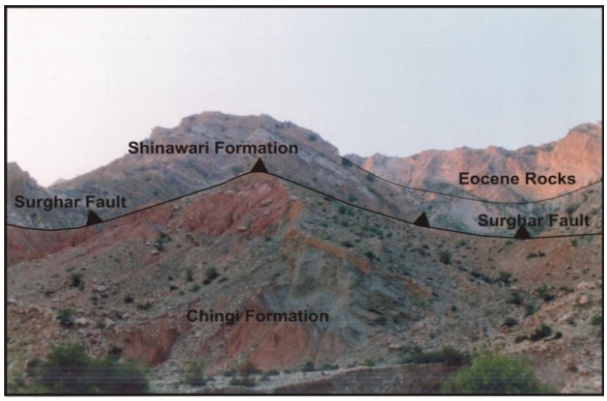

Fig.4. A north looking view of the Surghar Thrust that brings Shinawari Formation in its hanging wall over the Chinji Formation in its foot wall.

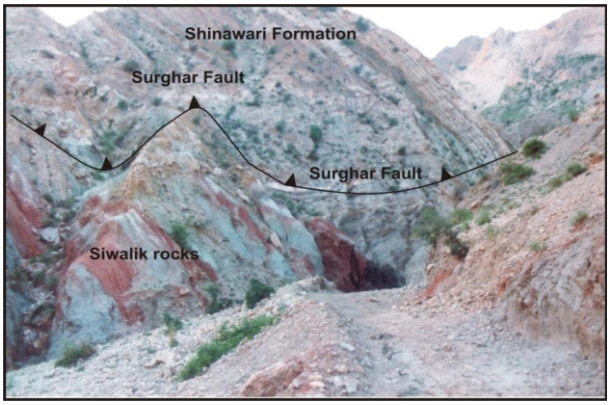

Fig.5. A west looking view of the Surghar Fault along which Shinawari Formation has a faulted contact with the Siwaliks rocks.

Fig. 6. A view of Kalabagh Fault exposed along Shakardara-Kalabagh road (Note the trend and dip discordance along the fault).

Fig.7. Southeast looking view of Kalabagh Fault from Shakardara-Kalabaghroad (Note the trend discordance with Siwaliks along the fault trace).

Quaternary Kalabagh Conglomerate forms the skyline of the Kalabagh Hills within the core of Ziarat Pir Syncline. The orientation and style of these folds is very significant in order to determine the deformational pattern of the Kalabagh Hills. These folds are well developed within Datta Formation and Sakessar Limestone which include a wide range of fold types i.e. S, M and Z (Fig. 8). Sheath folds are also observed at several localities within the hanging wall of a thrust fault that borders the western flank of Kalabagh Anticlinorium.

4.4. Faults

Number of major faults are observed in the area of Kalabagh Hillswhich are described as under Kalabagh Fault is the most prominent fault mapped within the southwestern domain. It is oriented north-northwest and almost follows the map trace of the Chisel Algad (Fig.3). The Siwalik Group rocks are juxtaposed along this fault that has significant strike and dip discordance across the fault line (Fig.9, 10 and11). It is well exposed immediately north of the Indus River and juxtaposes the Precambrian Salt Range Formation against the eastward dipping Siwaliks of Pliocene. Absence of Cambrian to Eocene rocks supports the presence of Kalabagh Fault (Fig.12). Along the map trace of the Kalabagh Fault, the Precambrian Salt Range Formation disappears immediately north of the Kalabagh Hills and the fault runs within Siwaliks (Fig.3 and 9). The dip data and stratigraphic relationship along the fault trace suggests that the eastern block of Kalabagh Fault has been down thrown towards east and the salt diapirically intrudes the surface along the fault surface.

Ziarat Pir Fault is a normal fault lying immediately west of the Kalabagh Fault. It appears as a splay of the major Kalabagh Fault (Fig.3) and along this fault, the eastern flank of the Ziarat Pir Syncline is downthrown to the west. West of Ziarat Pir Fault, the Kalabagh Conglomerate forms the skyline of Kalabagh Hills exposed in the core of the Ziarat Pir Syncline.

The western flank of the Kalabagh Anticlinorium is marked by another fault named as the Kalabagh Hills Fault. The Kalabagh Hills Fault is steeply east dipping and brings the Permian-Eocene sequence over the Quaternary Kalabagh Conglomerate in the west. Along its entire map trace the fault appears as a high-angle reverse fault with its eastern block up thrown towards west.

West of the Kalabagh Hills fault, a west-dipping fault occurs and is named as Kuch Tender Fault (Ahmad et al., 2003)(Fig. 3). Along this fault, the stratigraphic relationship suggests that its western side is down thrown towards east. The Jurassic rocks are in faulted contact with the Eocene rocks along this fault.

4.5. Structural Configuration

To understand structural configuration, three cross-sections have been constructed along line AA$^{/}$, BB$^{/}$ and CC$^{/}$ of “Fig. 3” to

understand the structural style within the Surghar Range and Kalabagh Hills and their relationship with the Kalabagh Fault. Cross –section along line AA/(Fig.11) of Fig. 3 has been constructed in order to understand the structural relationship of the rocks in both the northwestern and southwestern domains. In the northwestern domain, open folds exposed at the level of Chinji and Nagri formations of Miocene characterize the hinterland of the Surghar Range that of the Southern Kohat Plateau. Couple of steeply south dipping back thrusts i.e.Khartop Fault 1 and Khartop Fault 2 occupies the boundary between the Southern Kohat Plateau and the Surghar Range. The northern most of these faults that is the Khartop Fault 1 is characterized by little vertical uplift as suggested by its hanging wall and footwall cutoffs and is interpreted to be splay from Khartop Fault 2, is of deeper level and exhibits great vertical uplift.The Khartop Fault 2 merges in the subsurface with major frontal ramp of the Surghar Fault. The major structural break that is Surghar Fault in the region marks the boundary between northwestern and southwestern domains along the front of the Surghar Range.The Surghar Fault is gently north dipping and emplaces Jurassic rocks over the Siwaliks Group rocks in the south.

Fig.8. Photograph shows tight to isoclinally folded Samana Suk Formationoutcropping along the eastern flank of the Kalabagh Anticlinorium.

Fig. 9. Upright Anticline within the Chinji Formation located south of the Surghar Fault.

Fig. 10. Upright Syncline within the Siwalik Group Rocks located in the footwall of Surghar Fault.

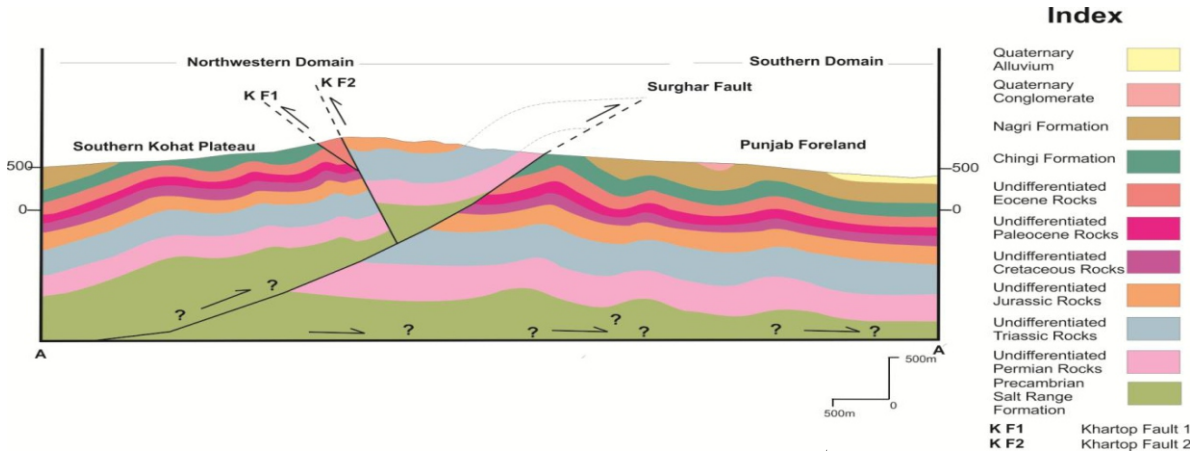

Fig. 11. Geological cross section along line AA/ of Fig.3.

The Surghar Fault is interpreted to be a major splay from a deeper level detachment at the base of Cambrian or Precambrian rocks. The Surghar Fault trajectory displays typical ramp geometry in the subsurface and exhibit greater vertical uplift as suggested by its hanging wall cutoffs. South of the Surghar Fault the Siwalik Group strata of the Punjab Foreland (southwestern domain) is openly folded with a slight asymmetry towards south suggesting southward migration of deformation along the basal detachment.

Cross-section constructed along line BB′ (Fig.12) of Fig. 3 is oriented such that cross the eastern and southwestern domain to study the structural relationship between the Kalabagh Fault and the Kalabagh Hills (Fig.12). Arguably, the most spectacular example of large-scale collapse of crustal blocks associated with salt flowage and migration can be seen along the line BB′ (Fig.12). Northeast to southwest traverse along the cross-section, the Kalabagh Fault appears as a steeply southwest dipping reverse fault along which the eastern side has been downthrown. Along the Kalabagh Fault, a salt plug migrating upward has been interpreted as suggested by its map relationship (Fig.3, 12). Southwest of the Kalabagh Fauth the Ziarat Pir Fault bounds the eastern flank of the Ziarat Pir Syncline. The Ziarat Pir Fault is steeply west dipping along which the eastern flank of the Ziarat Pir Syncline is downthrown to the west. West of the Ziarat Pir Syncline, the Kalabagh Hills are disharmonically folded into a regional anticlinal arch cored by the Precambrian Salt Range Formation. The western flank of these Hills is up thrown towards west along a steeply east dipping reverse fault named as Kalabagh Hills Fault.

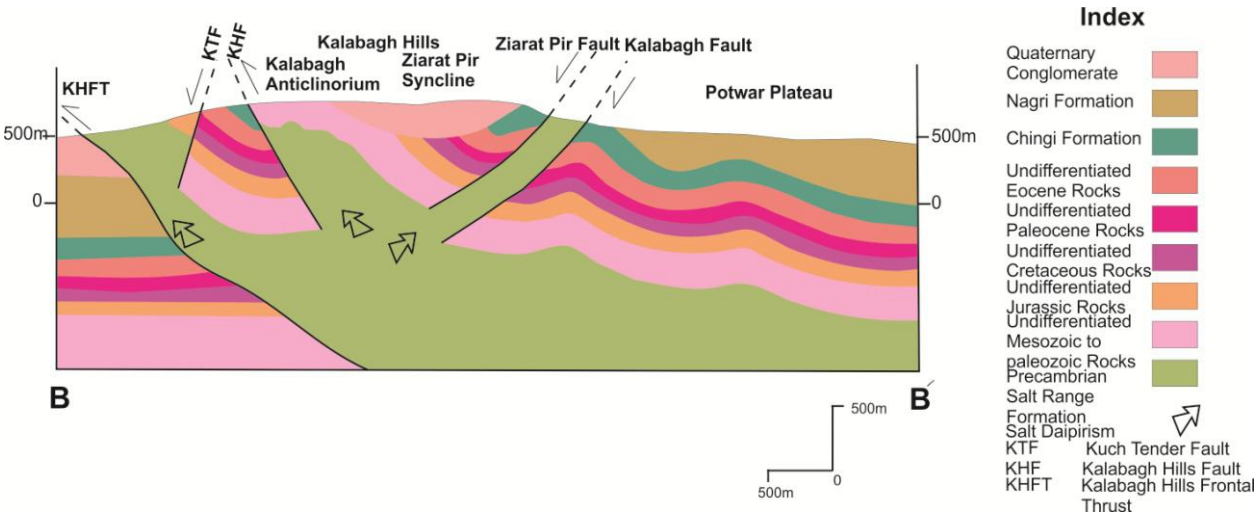

Fig.12. Geological cross section along line BB′ of fig.3

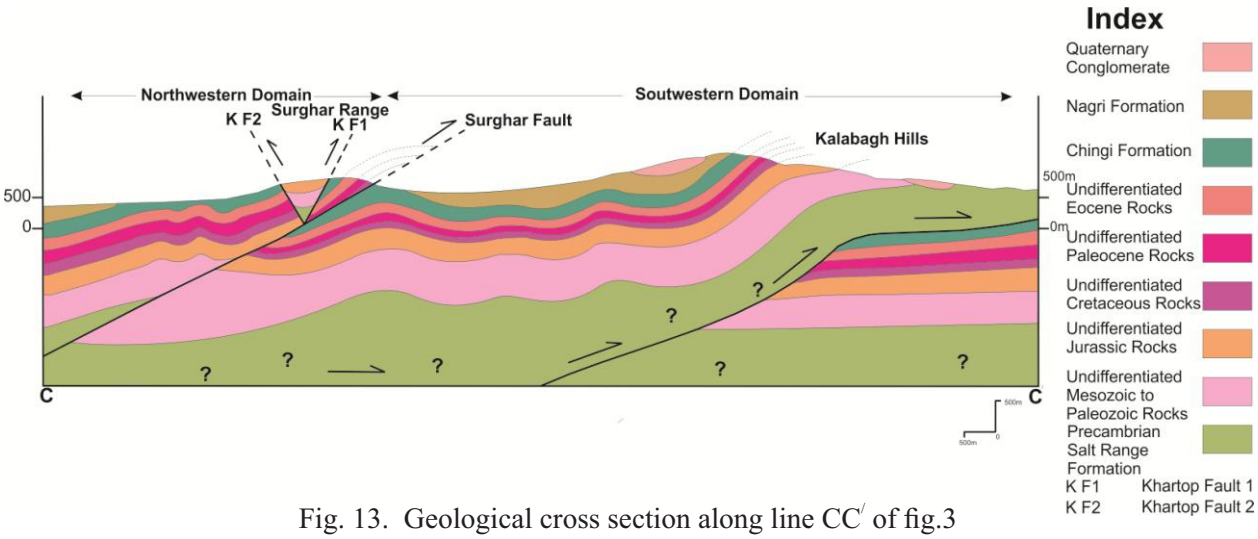

Fig. 13. Geological cross section along line CC′ of fig.3

The Kalabagh Hills Fault is also related to a salt plug that is migrating up section. Further west of Kalabagh Hills Fault, a steeply west dipping normal fault named as Kuch Tender Fault appears on the cross-section that is attributed to gravitational collapse of the hanging wall of the Kalabagh Hills Fault. In the extreme west the Kalabagh Hills Frontal Thrust emplaces the Precambrian Salt Range Formation over the Quaternary sediments of the Punjab Foreland.

Cross-section along line CC$^{/}$ (Fig.13) of the "Fig.3" is constructed to carry out the interpolation of the mapped structures in the Eastern Surghar Range and Kalabagh Hills area and is oriented parallel to the direction of thrusting in the northwestern domain and oblique in the southwestern domain. On a traverse from northwest to southeast along the transect the Surghar Range seems to have evolved as a result of frontal ramping from a basal decollement that emerges at the surface as a south verging fore thrust named as Surghar Fault. The Surghar Fault thrust sheet constitutes the main topographic expression of the range. Towards north of the Surghar Fault a steeply north dipping reverse fault appears to be a break backward type of splay from the main Surghar Fault and is characterized by less vertical uplift. South of the Surghar Range, a regional basal decollement is interpreted to be located at the base of Precambrian Salt Range Formation, up to the Kalabagh Hills where the salt migrates up section along a gently northwest dipping ramp. The Kalabagh Hills is interpreted to be an anticlinal structure formed as a result of frontal ramping and salt diapirism. The compressional structures within the Kalabagh Hills are bounded by extensional faults that contribute a lot to the complexity of structural style. The extensional tectonics is believed to be the youngest as it cross cut the earlier compressional structures. The development of these structures is largely due to the salt migration along the compressional structures, followed by salt plugs extruding to the surface and finally large-scale crustal collapse of the Kalabagh Hills occurred.

4. Discussion and conclusions

The earliest account of the Surghar Range has been mainly attributed to decollement related ramping Mc Doughal and Khan (1990). The location of the ramp is defined by an early formed thick-skinned basement related normal fault. The structural relationship between the Surghar Range and Kalabagh Hills was explained by a north-south trending strike-slip fault, which is responsible for 8-10 km offset between the Surghar Range and Kalabagh Hills. This idea was followed by another interpretation suggesting that the eastern Surghar Range is a hybrid terrain of thrusting and transpression (Ahmad et al., 2003). The current account of the structural analysis of Eastern Surghar suggests that the Eastern Surghar Range is a thin-skinned deformed range that is characterized by contractile structure including south facing folds and a frontal thrust fault. The structural geometry of the range is mainly attributed to a south translating decollement at the base of Precambrian rocks i.e. Salt Range Formation. The Surghar Range evolved when a north-dipping ramp emerged from the basal decollement and juxtaposed Permian-Jurassic rocks against the Plio-Pleistocene Siwaliks. A couple of back thrusts (Fig.11) are interpreted as splay from this ramp as a result of the accommodation of strain with the hanging wall of Surghar Fault. These back thrusts were previously regarded as high-angle reverse faults (Ahmad et al., 2003). No evidences of transpression and surface expression of a north-north west trending Surghar Fault has been found beside careful field observation as reported by previous workers (Ahmad et al., 2003; Mc Doughall and Khan, 1990).

Previous studies of the Kalabagh Fault or KFZ in the vicinity of the Kalabagh Hills suggests that the Kalabagh Fault Zone truncates folds and thrusts in Eocambrian to Quaternary sedimentary rocks cropping out near Kalabagh (Mc Doughall and Khan, 1990). The structure of Kalabagh Hills is regarded as a doubly plunging anticline cored by Paleozoic Limestone that is overlain by deformed Quaternary Kalabagh Conglomerate on its northern limb. This anticline is believed to have offset by 12-14 km in a right lateral sense along the Kalabagh Fault.

The interpretation was followed by an entirely different style of deformation than believed by Mc Doughall and Khan (1990) for the structural evolution of Kalabagh Hills. According to this second interpretation two contrasting suits of structures are preserved within the Kalabagh Hills that are compressional and extensional in nature and the Kalabagh Fault Zone is a transtentional boundary rather than a compressional boundary.

The current studies in the vicinity of Kalabagh Hills and along the trace of Kalabagh Fault suggest that the Kalabagh Fault is dominantly a strike slip fault over most of its trace except in the vicinity of the Kalabagh Hills. West of the Kalabagh Hills the Kalabagh Fault is divisible into 300 meters wide zone incorporating a second order fault namely Ziarat Pir Fault. Within the fault zone a deep-rooted salt body is migrating up section. The fault zone is believed to be undergoing dominant strike slip deformation of transpressional nature but the diapiric flow of the salt and its final extrusion have resulted in the development of Ziarat Pir Fault that exhibits a normal sense of movement. It is believed that this extension is not crustal extension but is rather gravitational collapse recording the crustal uplift resulting from salt intrusion. It is believed that the structural architecture of the Kalabagh Hills is mainly the result of contractile deformation and the presence of normal faults is the result of gravitational collapse caused by the flowage of ductile substrata underneath the Permian rocks.

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