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Contribution to the Structural Analysis of the Trans-Indus Ranges

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ABSTRACT

The Trans-Indus Ranges surrounding the Bannu Basin are among the most conspicuous structures of the frontal Himalayan thrust and fold belt in Pakistan. The structural control on the kinematic development of the area is linked to the detachment and southward translation of the sedimentary carapace from the underlying basement. This differential movement is interpreted to have resulted in the development of the Khisor Range mountain front. A local basement block is responsible for the tectonics generating the Trans-Indus Ranges.

INTRODUCTION AND REGIONAL SETTING

In the northern Indus Basin and south of the Salt Range the peculiarly formed Trans-Indus Ranges surround the Bannu Basin. The rectangular arrangement of the individual mountain ranges has attracted geological research during the last decades (Blisniuk et al. 1998; Ahmad et al. 2003; Alam et al.2005; Amjad Ali 2010; Khan et al. 2010 and Bannert 2014). The lack of seismic sections crossing the Bannu Basin in NW-SE and SW-NE directions makes it difficult to arrive at a sound geological explanation for the formation of the Trans-Indus Ranges. A recent synoptic study of the Western Fold Belt and the western Himalayan Southern Deformed Zone south of Main Boundary Thrust resulted in a new view on the Trans-Indus Ranges (Bannert 2014).

The Late Cretaceous/Palaeocene (Allemann 1979; Hunting Serve Corp. Ltd. 1960) is the time of the hard collision between the continental Indo-Pakistan Plate and the continental Afghan Block, at that time already amalgamated to the Eurasian Plate (Tapponier et al.1981).

The collision of the NW-edge of the Indo-Pakistan Plate started as an oblique one (Bannert et al. 1992) and is completely different from the slightly later head-on collision in the Himalaya sensu strictu with its south-verging tectonic nappes.

In the Pakistani foreland, the Sulaiman Block of the Western Fold Belt (Figure 1), which occurs west of the Indus River and southwest of the Bannu Basin, contains structures that strike in a NE-SW direction (Figure 1). Whereas in the Peshawar-Islamabad region, south of the Main Boundary Thrust the Samanak and Attok-Kalachitta ranges and Kohat- and Potwar plateaus strike in a dominantly east-west direction. South of both structural districts is the Indus plain occupying most of central Pakistan.

The Mianwali Re-entrant occurs at the western termination of Potwar Plateau marked by the dextral Kalabagh Fault. This structure has facilitated 70 km thrusting between the Kohat and Potwar Plateaus (Figure 1). Amjad Ali (2010) determined the length of the Kalabagh Fault to be 120 km.

The western side of the Mianwali Re-entrant is formed by the Makarwal Anticline (Danilchik, and Shah et al., 1987), which separates it from the Bannu Basin farther west (Figure 1). The southern margin of the Bannu Basin is marked by the Khisor Range and Marwat Anticline. The Makarwal, Marwat, Khisor and Marwat-Kund 654 ranges are collectively referred to as the Trans-Indus Ranges.

All previous proposals have failed to explain the right angle bending of the Surghar-Makarwal Anticline and Marwat-Kund Anticline (Blisniuk et al. 1998; Ahmad et al. 2003; Alam et al.2005; Khan et al. 2010).

Detailed geologic maps exist for the Marwat- and Khisor ranges, the Marwat-Kund Anticline (= Bhittani Anticline or Pezu Range; Hemphill, W.R. et al. 1973; Ahmad, S. et al. 2003; Khan et al. 2010), and for the southern part of Makarwal (= Zinghar) and Surghar ranges (Danilchik, and Shah 1985). These maps, together with available GOOGLE Earth imagery, form the basis for the structural interpretation presented in the current study below.

The still open question lies in the Bannu Basin. What kind of compression caused the Marwat Anticline and Khisor Anticlinorium to move south-eastwards and how were the conspicuous Marwat-Kund and Surghar-Makarwal anticlines formed?

PREVIOUS WORK

The Geological Survey of Pakistan (GSP), in co-operation with the United States Geological Survey (USGS) in the mid-1960s, carried out the first systematic mapping of the area, publishing a geological map of the Bannu Quadrangle (W.R. Hemphill et al. 1973). The geological map of the Kohat Quadrangle was published in 1973, after mapping was completed by M.A. Rashid and M. Hussain from GSP and C.R. Meissner and J.M. Master from USGS (Meissner et al. 1973). More than a decade later, Danilchik, and Shah (1987) provided a new geological map of the Makarwal Anticline. This work was followed by McDougall J.W. and S.H. Khan (1990), who analysed the tectonics involved with the strike-slip Kalabagh Fault, while Blisniuk et al. (1998) detailed two phases of deformation affecting the Marwat Anticline and Khisor Anticlinorium. A study by Ahmad, S. et al. (2003) attributed the variation in deformation between the Kohat fold belt and the Trans-Indus Ranges to strain partitioning from the northwest and south of the Spinghar Thrust, a western part of Main Boundary Thrust. In recent years, new contributions to the geology of the Trans-Indus Ranges were initiated by the University of Peshawar resulting in the work of Amjad Ali (2010). He stated that the Himalaya-related deformation that shaped the Trans-Indus Ranges is distinguished into three

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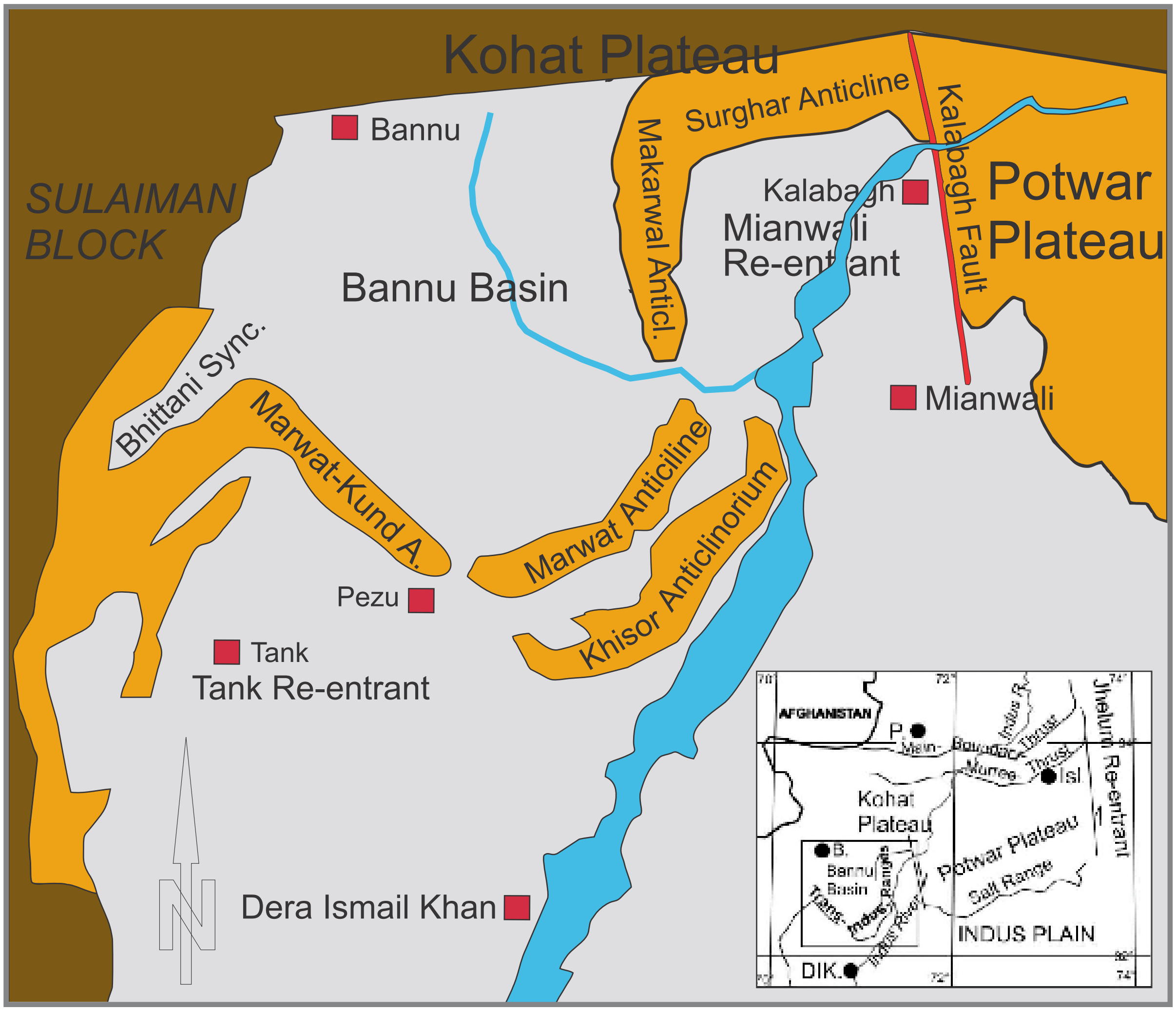


Figure 1 - Trans-Indus Ranges surrounding Bannu Basin.
Insert map: B = Bannu, DIK = Dera Ismail Khan, I = Islamabad, P = Peshawar

discrete episodes including pre-molasse, syn-molasse and post-molasse. The post-molasse deformational episode started in the region at the time when the thrust slab underneath the Kohat-Bannu Basin transitioned up section at the site of Trans-Indus ranges. This ramping led to the creation of the present day Trans-Indus Ranges and the internal deformation of the thrust slab which is still continuing. Khan et al. (2010) analysed the deformation style of Bhittani Range extension (= Marwat-Kund Anticline) with its west-vergent thrust tetctonics manifested in the Pezu-Khigri Thrust. In the abstract of his dissertation Amjad Ali (2010) concluded “that the post-molasse deformational episode started in the region at the time when the macroscopic thrust slab underneath the Kohat-Bannu Basin ramped up section at the site of Trans Indus ranges. This ramping led to the creation of the present day Trans-Indus Ranges and the internal deformation of the thrust slab which is still continuing. The arcuate nature of the Trans Indus ranges is interpreted to be original, partly controlled by some pre-existing basement irregularities and possible strain partitioning. It is interpreted that the onset of compression at the northern and southern Surghar Range and Manzai ranges was synchronous caused by north-south and east-west compression induced by proto Main Boundary Thrust and Kurram Fault respectively. At the time when proto MBT was transmitting south directed stresses at the site of the northern Surghar Range, left lateral wrenching along the Proto Kurram zone was transmitting east directed compressive stresses resulting in the north-south oriented folds in the Manzai and southern Surghar Range. The onset of thrusting is believed to be the earliest at the site of Surghar and Manzai ranges followed by wrenching along Pezu, Kundal and Makarwal faults. This wrenching episode was subsequently followed by thrusting at the site of Khisor and Marwat ranges.

All previous work contributed various information concerning the nature of the Trans-Indus Ranges. However, the bending of the western Surghar Range into the N-S striking Makarwal Range and the bending of the Marwat-Kund

Anticline (= Pezu-Bhittani Range of other authors) from its SW to NE strike into the NW to SE strike thus forming the western frame of the Bannu Basin still lacks a convincing discussion.

In this paper we name the structure of the Khisor Range "Khisor Anticlinorium". It is built of a considerable number of anticlines. Amjad Ali (2010) in his dissertation named the northernmost of these anticlines of the anticlinorium "Khisor Anticline". The core of the Khisor Anticlinorium is Saiyiduwali Anticline south of Amjad Ali's Khisor Anticline.

STRATIGRAPHY

Rock units in the study area are outlined below from oldest to youngest ages (Table 1).

The oldest rock unit mapped in the Trans-Indus Ranges is the Infra-Cambrian Salt Range Formation (Table 1). It is commonly regarded as the detachment horizon for Surghar- and Makarwal anticlines, the Marwat Anticline and Khisor Anticlinorium, and the Salt Ranges farther east (Ahmad, S. et al. 2003; Blisniuk et al. 1998).

The Khisor Anticlinorium contains the oldest strata in the region including Cambrian and Early Permian not observed elsewhere in the Trans-Indus-Ranges. The Cambrian Jhelum Group is exposed as the Khewra Sandstone, thick- bedded sandstone with clay intercalations in the upper part. The overlying Kussak Formation is a sandy and dolomitic unit rich in glauconite. It is followed by the dolomites of Jutana Formation. They are overlain by the Khisor Formation, mostly gypsiferous marl, interbedded with shale and dolomite layers (Alam et al. 2005).

The Early Permian Nilawahan Group includes the Tobra Formation (cobbles and sandstone), followed by Warchha Formation sandstone, and Sardhai Formation (sandy limestone and sandstone).

Portions of the Late Permian Zaluch Group crop out across the Trans-Indus Ranges. This includes rocks of the Amb Formation (sandy limestone and sandstone) (Alam 2008), calcareous and dolomitic Wargal Formation, and finally the sandy Chiddru Formation. The thickness of the group in this region is variable. In the Makarwal Range the Wargal- and Chhidru formations are 100 m thick (Danilchik, D. and Shah 1987) and consist of limestone and sandy limestone.

The Triassic strata exposed in the Trans-Indus Ranges includes a mix of clastic and dolomitic sediments (Table 1). From bottom to top these rocks include the Mianwali Formation (dolomite and shale), followed by Tredian Formation (sandstone, shale and dolomite) and finally the dolomites of Kingriali Formation.

The Jurassic rocks in the region include the Datta Formation, which consists of sandstones, followed by Shinawari Formation a sequence of intercalated sandstone, siltstone and shale. The youngest Jurassic unit is the limestone dominated Samana Suk Formation.

Cretaceous strata do not crop out in the Khisor Range (The Khisor Range is missing all Cretaceous to Pliocene rocks). In the other areas they are represented by the Chichali Formation (sandstone, partly glauconitic), Lumshiwal Formation sandstones, and finally limestones of Kawagarh Formation.

According to Danilchik, et al. (1987) and Shah (1990), the Paleocene Hangu Formation records a change from terrestrial sedimentation to marine facies sedimentation. It is overlain by Lockhart Formation limestone and shale of Patala Formation.

In the Surghar- and Makarwal ranges, Paleocene Sakesar Formation overlies unconformable Hangu Formation.

During the Neogene, the erosion of the rising Himalaya provided a massive source of clastic sediments to the Himalayan foreland resulting in the deposition of the Mitha Khatak Formation, which consists of pebbly sandstone with intercalated thick reddish-brown siltstone. A basal conglomerate carries abundant limestone and chert pebbles derived from underlying Sakesar Formation limestone. Pebbles of granite and quartzite indicate a source area that contained the Permian Tobra Formation (Burbank, and Beck 1989). The formation is typically ~100 m thick and crops out along the western and southern sides of the south-plunging Makarwal Anticline (Figure1). Blisniuk et al. (1998) equated the Mitha Khattak Formation (Figure1) as equivalent to the Lower Siwalik Chinji Formation.

The Siwaliks are widespread around the Bannu Basin and can be divided in the Lower Siwaliks (Chinji Formation), Middle Siwaliks (Nagri Formation) and Upper Siwaliks (Dhok Pathan Formation).

The late Miocene Lower Siwalik Chinji Formation forms the core of the Marwat-Kund Anticline in the western Bannu Basin (Figure 1) and the anticlines of northwestern Tank Re-entrant. It is 2000 m thick in the Makarwal Anticline (Danilchik, and Shah 1987) and is conformable/transitional with the overlying Middle Siwaliks.

The early Pliocene through early Pleistocene (Danilchik and Shah 1987) Middle Siwaliks or Nagri Formation consists almost entirely of grey coloured, thickly bedded, sandstone; cross-bedding, pebbles, and intercalated thin conglomerates are common. The unit is ~ 2150 m in the Makarwal Range (Figure1) and commonly forms prominent ridges. Nagri Formation is widely exposed in the Marwat- and Khisor anticlines where it is ~ 1800 m thick. Hemphill, W.R. et al. (1973) interpreted an easterly directed sedimentation from cross-bedding measurements. There is a sharp contact with the overlying Dhok Pathan Formation.

The middle Pliocene Upper Siwaliks or Dhok Pathan Formation is characterized by recessive weathering. It comprises light brown siltstone to sandstone intercalated with clay-bearing siltstone to claystone that was deposited along easterly to northeasterly sediment transport direction (Hemphill, W.R. et al.1973). The unit is more than 800 m thick in the Makarwal Range

The Malagan Formation overlies Dhok Pathan Formation along both flanks of Marwat-Kund Anticline and along the western flank of the Marwat Anticline. It is a 120 m to 700 m thick succession of medium to coarse-grained sandstone with intercalated conglomeratic layers that increase in abundance north-eastwards. Where present, the conglomerates have a high percentage of intrusive and metamorphic rocks, and quartzite thought to be sourced from uplift in the south (Blisniuk et al. 1998) Table1 and Figure 5.

Table 1- Stratigraphy of the Trans-Indus Ranges after Danilchik & Shah 1987, Bender & Raza 1995, and Alam et al. 2005. Neog.= Neogene

AGE	MAKARWAL RG.	Lithology	Surghar Rg.	Khisor Rg,	Litholgy
Quaternary	Alluvium	sd	Alluvium	Alluvium	sd
Neog. Pliocene	Siwalik Group	sst, silt	Dhok Pathan	Dhok Pathan	sst,silt,sh
Neog. Miocene			Nagri	Nagri	cgl,sst,silt
			Chinji	not exposed or hiatus	
Mio/Oligocene	Mitha Khatak Fm.	sst,silt,cgl	Mitha Khatak Fm.		
Eocene	hiatus ?				
	Sakesar Fm.	lst	Sakesar Fm.		
	Nammal Fm.	marl	Nammal Fm.		
Paleocene	Patala Fm.	sh	Patala Fm.		
	Lockhart Fm.	lst	Lockhart Fm.		
	Hangu Fm.	sst, silt	Hangu Fm.		
Cretaceous	Kawagarh Gr.	lst	hiatus ?		
	Lumshival Fm.	sst	Lumshival Fm.		
	Chichali Fm.	glauk.sst	Chichali Fm.		
Jurassic	Samana Suk Fm.	lst	Samana Suk Fm.		
	Shinawari Fm.	lst,sh,sst	Shinawari Fm.	Shinawari Fm.	lst,sh,sst
	Datta Fm.	sst	Datta Fm.	Datta Fm.	sst
Triassic	Kingriali Fm.	dol	Kingriali Fm.	Kingriali Fm.	dol
	Tredian Fm.	sst,sh,dol	Tredian Fm.	Tredian Fm.	sst,sh,dol
	Mianwali Fm.	do,sh	Mianwali Fm.	Mianwali Fm.	lst,do,sh
Late Permian	Zaluch Gr. Chiddru Fm.	sdy lst	Chiddru Fm.	Chiddru Fm.	lst,sst,sh
	Zaluch Gr. Wargal Fm.	coral lst	Wargal Fm.	Wargal Fm.	lst,dol
	Zaluch Gr. not exposed or hiatus			Amb Fm.	lst
Early Permian	not exposed or hiatus			Nilaw Sardhai Fm.	sh
				Nilaw Warcha Fm.	sst
				Nilaw Tobra Fm	sst,cgl
Odovician through Carboniferous	not exposed or hiatus				
Cambrian	not exposed or hiatus			Helu Khisor Fm.	gy,dol,sst
				Helu Jutana Fm.	dol
				Helu Kussak Fm.	dol.sh,sst
				Helu Khewra Sst.	sst
Pre-Cambrian	Salt Range Fm.?				

cgl = conglomerate **dol = dolomite** **glauc = glaucognite**
gyp = gypsum **lst = limestone** **sd = sand**
sdy = sandy **sh = shale** **sst = sandstone**

STRUCTURE AND KINEMATICS

On a first glance the structures of the Trans-Indus Ranges appear simply built. This applies to the Marwat-Kund Anticline and the Tertiary successions of the Marwat Anticline and Khisor Anticlinorium. The cores of the latter comprise by Mesozoic and Paleozoic rocks, which are, however, complicated folded and subjected to thrusting and even back-thrusting (Ahmad, S. et al. 2003).

The tectonics of the Trans-Indus Ranges has been explained in a number of different ways. This is especially true for the kinematics of the Bannu Basin (Figure 1).

The following structures will be discussed in this chapter:

- Surghar Anticline - Makarwal Anticline
- Marwat Anticline and Khisor Anticlinorium
- Marwat-Kund Anticline
- Bannu Basin

Surghar Anticline

The Surghar Anticline is a conspicuous anticline with a sharp, almost 90° bend from east-west strike to north-south strike of its anticlinal axial plane (Figure 1). Danilchik, and Shah (1987) produced a detailed geological map of the entire southern and western anticline structure. In the region of the change in axial plane orientation three distinct anticlines striking NW have been mapped. They are compatible with a west to east compression force affecting the structure. The Makarwal Anticline western limb, however, does not show any significant deformation, that might be related to the sharp axial bending to the south (Figures 2 and 3).

The sharp bending of the western Surghar Anticline into the N-S trending Makarwal Anticline has been analysed by Ajmad et al. 2003. The E-W striking Surghar Anticline detached in Paleozoic/Mesozoic rocks and formed a S-verging anticline above a N-dipping frontal thrust named Surghar Fault. Surghar Fault, however, is not directly exposed along Surghar Range. The southward bend of Surghar Anticline is located north of Malla Khel (Figures 2, 3 and 4). Rocks younger than Jurassic Samana Suk Formation bend gently from the E-W strike into the N-S strike. However, the Triassic rocks in the bend and N of Malla Khel are folded along N-S fold axes indicating W-E pressure in the lower part or core of western Surghar Anticline.

Satellite images revealed a possible thrust fault as a reaction to the southward bend of the Surghar Anticline into the Makarwal Anticline. We call it the Western Surghar Thrust in Figures 3 and 4. The thrust begins west of Punnoo Mine in the upper part of Sakesar Limestone. To the west it thrusts over the Patala Formation and can be followed southward beyond the latitude of Malla Khel. Below the Western Surghar Thrust a smaller thrust was observed in the Barooch Nala in the upper part of Samana Suk Formation striking NNE and dipping 290/70 to WNW (Figures 5 and 6). It is a result of the fault-bend of Surghar-Makarwal Anticline axis-plain.

Makarwal Anticline

Danilchik and Shah (1987) mapped the southern part of the Surghar Anticline calling it the Makarwal Anticline (Figure 4). The western limb dips moderately to the west, while the eastern limb dips steeply to the east. Ahmad et al. (2003) mapped the Makarwal Active Back Thrust along the eastern limb of the structure. They suggested a ramp anticline focused above an existing steep normal fault running along the western frame of Mianwali Re-entrant. Moreover, they mapped a number of gently west dipping thrust faults and concluded that there is a shallow detachment at the base of Cretaceous Lumshiwal Formation. The southern plunge of the Makarwal Anticline is dissected by movement along a north-south fault, which may be interpreted as a step fault with the up-throw of the eastern side.

Marwat Anticline and Khisor Anticlinorium

Marwat Anticline and Khisor Anticlinorium are the result of thin-skinned tectonics (Alam et al. 2005). The core of the anticlines consists of Paleozoic through Cretaceous strata. There are two opinions concerning the detachment horizon:

1) below the base of Cambrian Jhelum Group in the Marwat Anticline ~3.5 km below sea level. Alam et al.(2005) assume no salt occurs below the Jhelum Group.
2) Kemal (1992) quoted after Monalisa and Khwaja (2005) assumes Salt Range Formation evaporates beneath the Bannu Basin.

So far, no well penetrated Khisor Formation, so the question of the occurrence of salt cannot be answered at present (Figure 7). In the Khisor Anticlinorium Alam et al. (2005) interpreted a detachment to occur at the base of Cambrian rocks, however, the occurrence of Cambrian formations in the core of the Sayiduwali Anticline north of Saiyduwali (Figure 8) does not preclude the existence of the Salt Range Formation underlying and providing the detachment for the formation the Marwat Anticline and Khisor Anticlinorium.

Marwat-Kund Anticline

Marwat-Kund Anticline is a fault-bend fold that extends the NE-striking Bhittani Anticline along the western frame of Bannu Basin (Figure 1). The Bhittani Anticline is part of the Sulaiman Block foreland. Marwat-Kund Anticline is thrust to the SW along the Pezu-Khirgi Fault (Khan et al. 2010).

East of Pezu, the Marwat-Kund Anticline reaches the western tip of Marwat Anticline. A slight bending of the Nagri Formation rocks towards east-west direction can be seen in satellite images (Figure 9). A possible thrusting to the southeast of Marwat-Kund Anticline Nagri Formation upon Nagri Formation of the Marwat Anticline may occur; however, this remains to be confirmed through further field work.

Bannu Basin.

Bannu Basin centers the spectacular structure of the Trans-Indus Ranges (Figure 10). Marwat Anticline and Khisor Anticlinorium along the southeast margin of the basin can be explained as detached duplexes (Blisniuk et al. 1998; Ahmad et al. 2003). The Marwat-Kund Anticline, striking SE-NW, forms the frame in the southwest and bends without visible faults into Bhittani Anticline that strikes NE-SW and is part of the Western Outcrops of the Sulaiman Block.

Bannu Basin is void of tectonic features such as faults, or lineations in satellite images or signs of uplifted portions. So far, no indication of buried anticlines has been observed. As can be seen in Figure 10, the lowest area is just east of the center and occupied by the Kurram River. The basin may contain up to 400 m of Quaternary sediment fill (MonaLisa et al. 2005 after Kemal 1992).

DISCUSSION AND INTERPRETATION

After analyzing three wells drilled in the Bannu Basin (Pezu-1, Marwat-1 and Chonai-1; Figure 7) Shabih et al. (2007) concluded an uplift of underlying sediments from Pezu-1 towards the northeast towards the southern plunge of Makarwal Anticline.

MonaLisa et al. determined focal solutions for four earthquakes in the Bannu Basin and Tank Re-entrant. Event No. 9 near Pezu (Figure 11) displays a right-lateral displacement and a thrust component to the southeast. The events 3 and 8 are from the northern margin of Tank Re-entrant and provide evidence of NW-SE compression and thrusting to the SE. They concluded, based on this data, that basement faulting is most probably involved.

Following this interpretation, we assume that the basement below the Bannu Basin gave way to the heavy load in the northwest. There, the transition between the N-S aligned western Indo-Pakistan Plate boundary subjected to wrench-faulting (Bannert et al. 1992; Iqbal and Bannert 1998) and the W-E aligned Eurasian Plate subduction zone caused an enormous obduction of west to east thrust sheets (Bannert 2014). The thrust sheets from the west contain predominantly

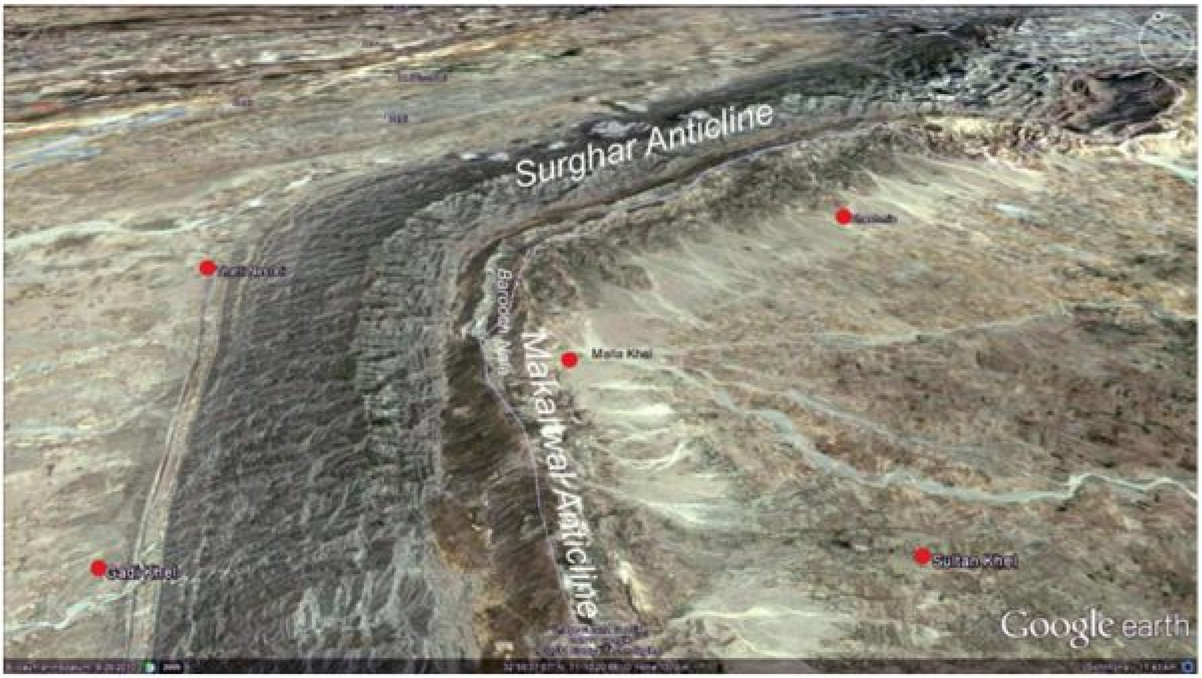


Figure 2 - Makarwal Anticline and western part of Surghar Anticline as seen from the southwest. Centre coordinates at 32°55'N/71°10'E. The view goes to the north.

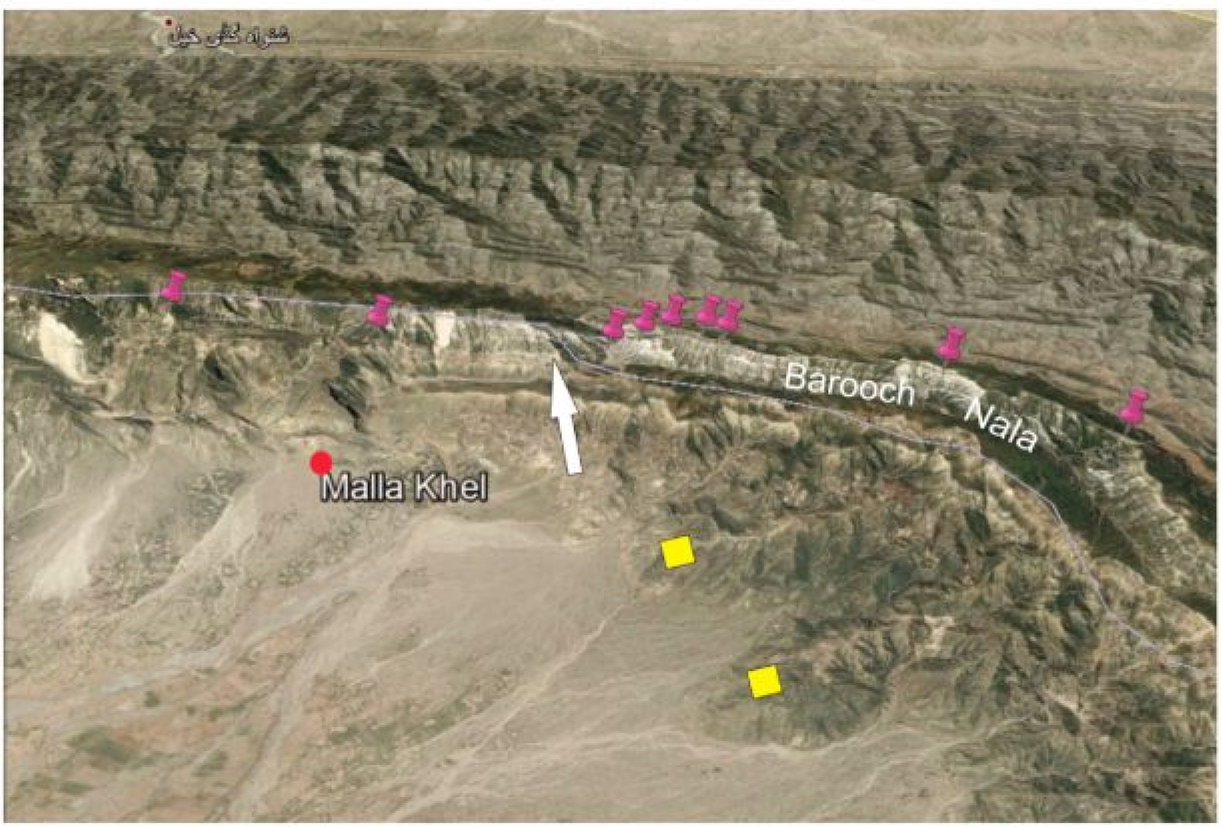


Figure 3 - GOOGLE Earth image of the bend of Surgarh Anticline into the Makarwal Anticline near Malla Khel. Magenta dots mark the Western Surghar Thrust. Yellow squares indicate N-Z striking anticlines within Triassic and Jurassic sediments. White arrow points to Barooch Nala outcrop shown in Figure 5. North is to the right.

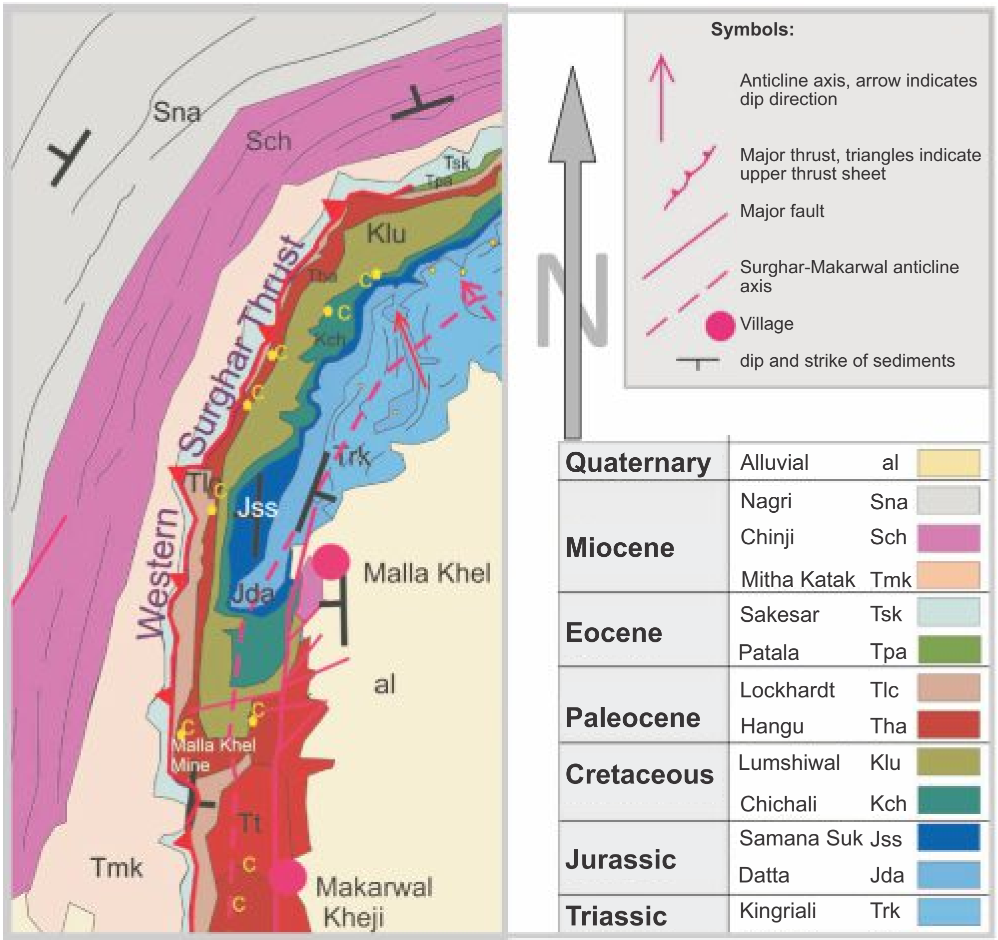


Figure 4 - The bend of Surghar-Makarwal anticlines north of Malla Khel. Yellow symbols c = coal mines.

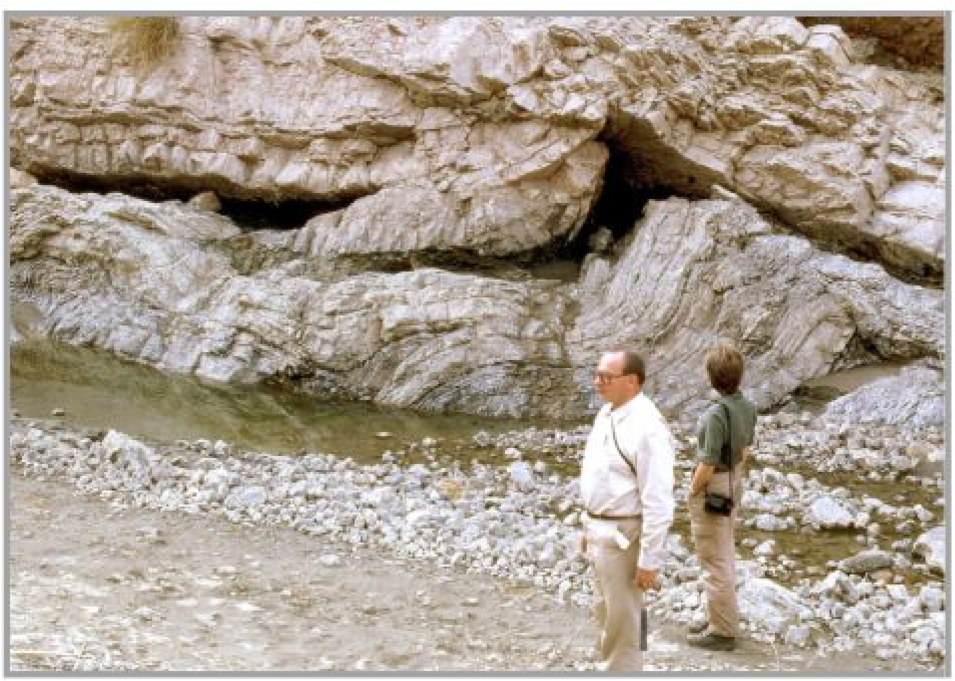
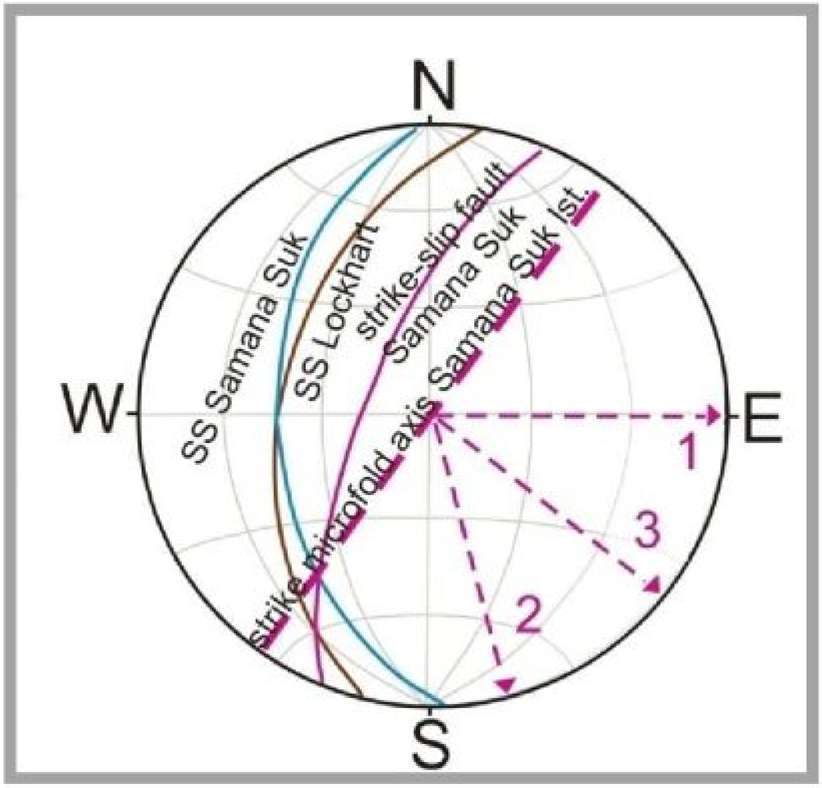


Figure 5 - Upper Jurassic Samana Suk limestone in Barooch Nala at 32°55'N / 71°08'E. A thrust dipping 290/70 (WNW) folded the underlying limestone with a fold axis striking 212° (SW).



1= compression affecting the Makarwal Anticline

2= compression affecting the Surghar Anticline

3= resulting compression affecting the Samana Suk limestone leading to its folding below the Western Surghar Thrust
SS= bedding plane

Figure 6 - Schmidt-net plot of field measurements of Samana Suk deformation.

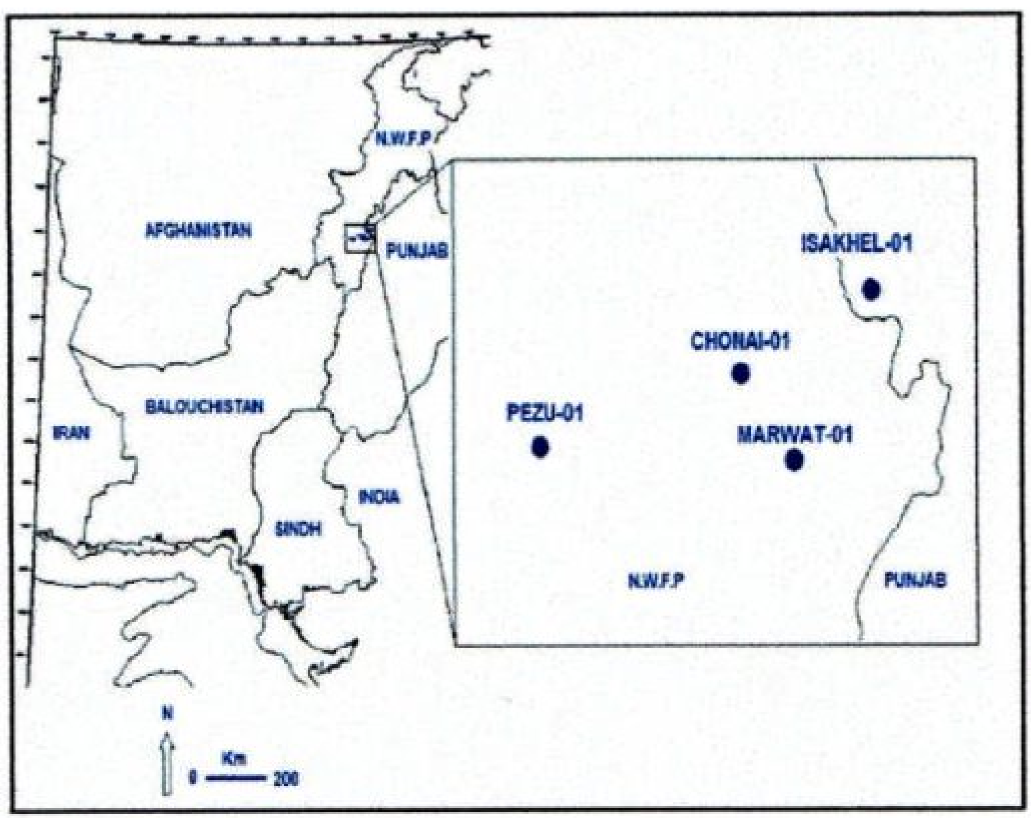
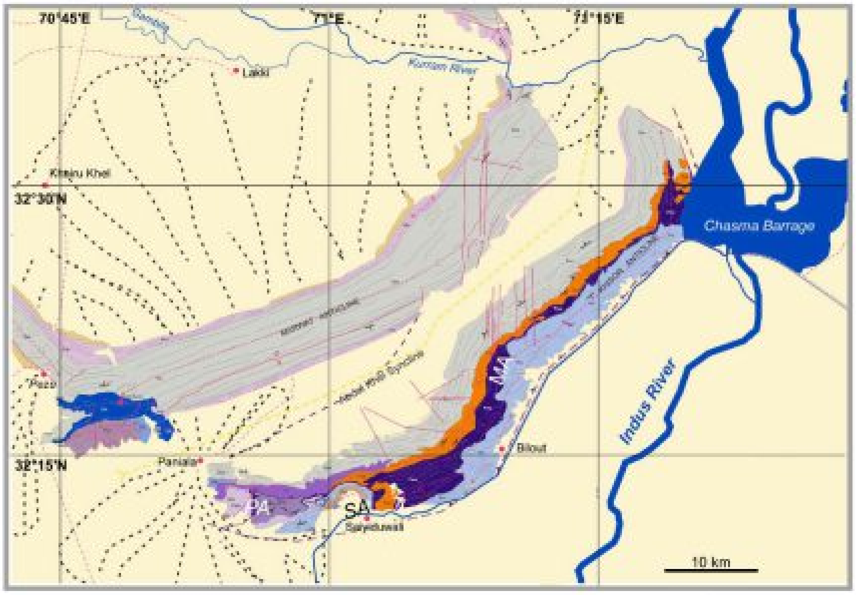


Figure 7 - Location of wells drilled in the Bannu Basin after Shabih et al. (2007).



Quaternary	Alluvial	
Pliocene	Malagan	
	Chitarwata	
	Dhok Pathan	
Miocene	Nagri	
	Chinji	
	Mitha Kattak	
Eocene	Sakesar	
	Patala	
Paleocene	Lockhart	
	Hangu	

Legend for the Marwart - and Khisor Ranges

Cretaceous	Lumshiwal	
	Chichali	
Jurassic	Samana Suk	
	Dadda	
Triassic	Kingriali	
Permian	Zaluch Gr.	
	Nilawahan Gr.	
Cambran	Khisor	

SA = Saiyiduwali Anticiline

PA=Paniala Anticline

MA=Mir Ali Anticline

Figure 8 - Geological map of Marwat Anticline and Khisor Anticlinorium (after satellite image interpretation and literature review)

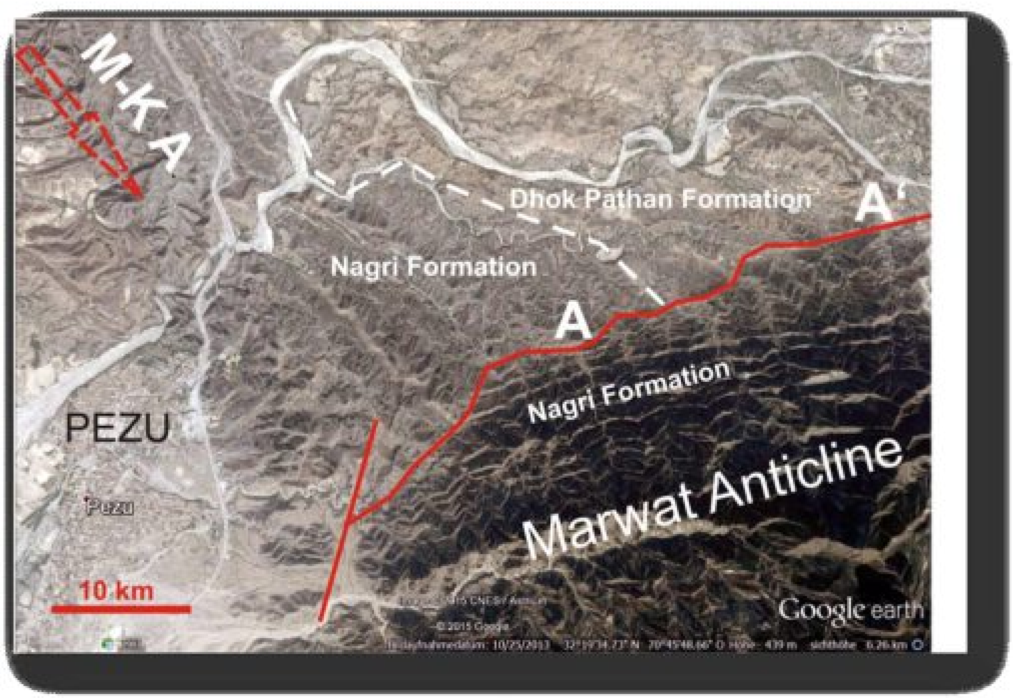


Figure 9 - Satellite image of the Pezu area showing the contact of Marwat-Kund Anticline (M-KA) and the western tip of Marwat Anticline (Sheikh Budin Hills). Between A and A' Dhok Pathan Formation might thrust Nagri Formation rocks upon Nagri Formation of the Marwat Anticline. Red lines are faults.

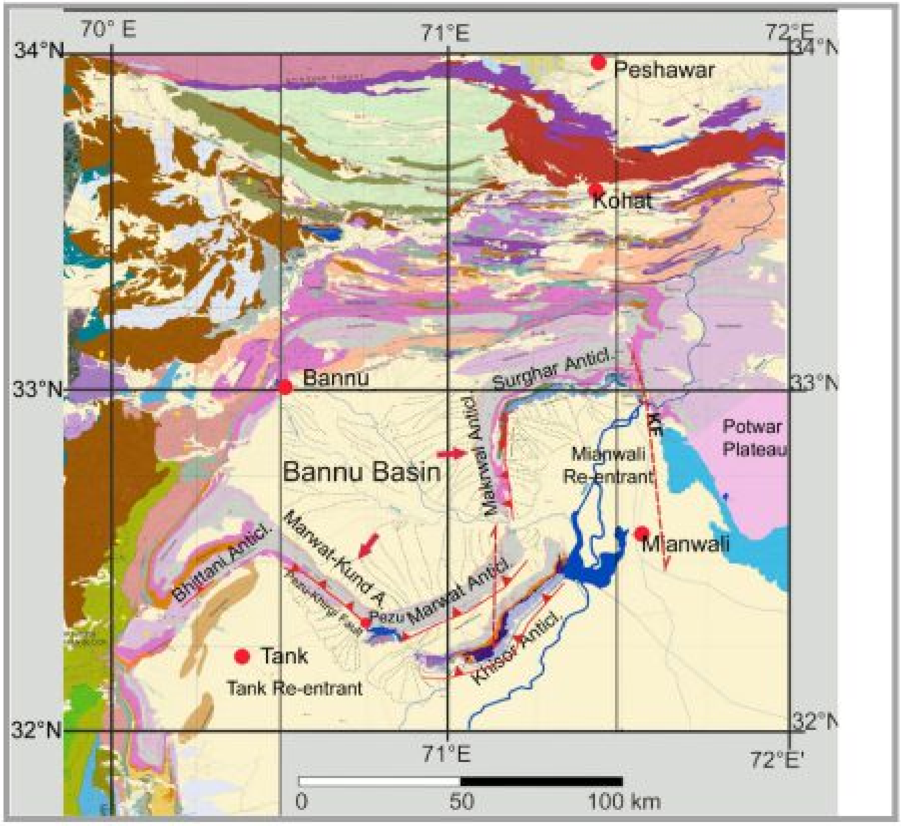


Figure 10 - Geological interpretation of LANDSAT-ETM imagery of the larger Bannu Basin area stippled lines represents the drainage network; red arrows are resulting pressure along Makarwal Range and Marwat-Kund Anticline. Legend in Figure 8.

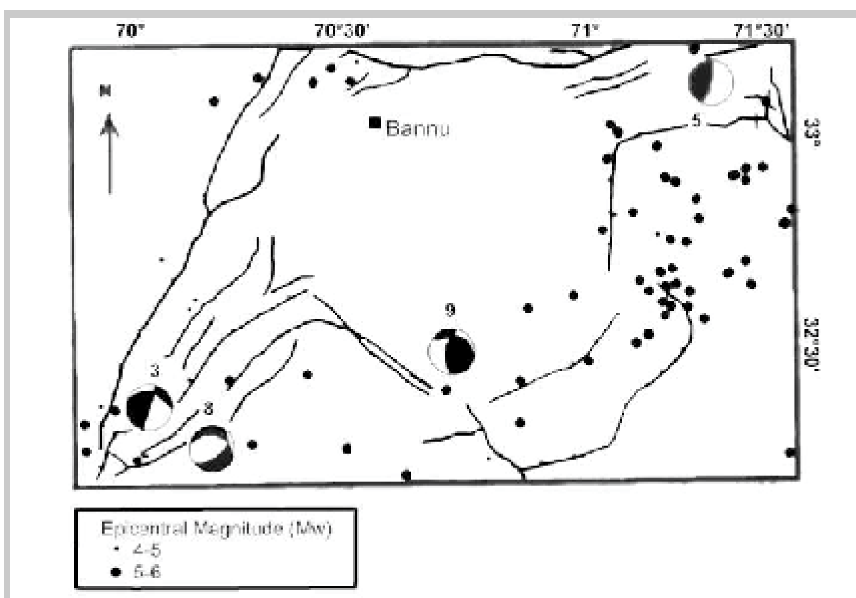


Figure 11 - Focal Mechanism Solution map of the Bannu Basin after Mona Lisa and Khwaja (2005), Figure 3.

trench material, ophiolitic sea-floor and associated volcanites tectonically superimposed on the Indo-Pakistan shelf sediments. The thrust sheets from the north are mainly Mesozoic shelf sediments with intercalated trench material and Waziristan Igneous Complex obducted in complicated staples and thrust partially above the earlier, westerly derived stacks. According to Jadoon et al.(1992) the Indo-Pakistan Plate basement thins towards the west approaching the Bela-Waziristan-Opholite Zone. The Bannu Basin basement gave way in a stronger downwards bulge as a horizontally block, which had to escape upwards and to the southeast (Figures 12 and 13).

Due to its south-eastward movement of the block the pressure along the south-western rim and the north-eastern rim increased and forced continuously southeast-wards growing pressure-ridge anticlines to be built. The event No. 9 earthquake near Pezu (MonaLisa and Khwaja 2005) supports this picture. In front, Khisor Anticlinorium and later Marwat Anticline developed as single "horses" or duplexes. No major structures are reported from the internal Bannu Basin. Seismic survey conducted in the eastern part of Bannu Basin show a northward dip of the sediments (Khan et al. 1986, Figure 5). However, due to the short extension of the published part of the line it might not be really representative for the whole of Bannu Basin.

Moreover, the Marwat Anticline and Khisor Anticlinorium are not the direct extension with Marwat-Kund Anticline in the west and Makarwal Anticline in the northeast. Marwat-Kund Anticline ends near Pezu where it is faulted against the western Marwat Anticline (Figure 9).

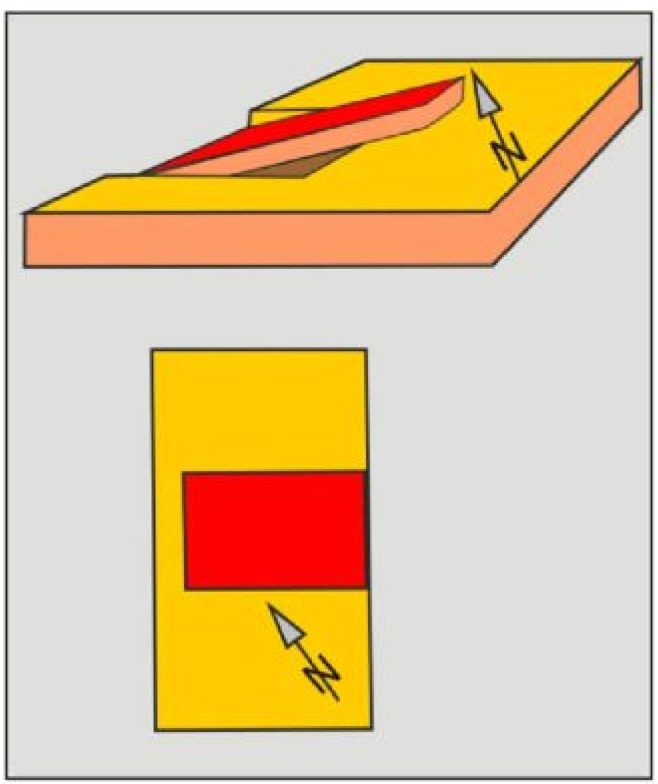


Figure 12 - Schematic view of the assumed basement deformation underneath the Bannu Basin.

Ahmad et al. (2003) explain the different deformation affecting Kohat fold belt and Trans-Indus Ranges by strain-partitioning from the northwest and south of Spinghar Thrust, the western part of Main Boundary Thrust.Our reconstruction (Figure 14) shows the initial stage, when the Himalayan induced Potwar Kohat deformation was already in full progress. In the western collision zone the Kurram nappes and the Waziristan Igneous Complex put their full load on the northward bending northern Sulaiman Block. Together with the underlying basement, probably thinning westwards (Jadoon et al. 1992) basement failures resulted. The basement block began moving southeastward. This lead to the initial detachment of Khisor Anticlinorium.

Figure 14 summarizes the tectonic pattern leading to the configuration of the Bannu Basin frame. The leading front of the southeast directed basement block causes an increased pressure along the flanks of the block. The result is the formation of fault-bend anticlines growing along the path of the southeastward moving basement. Marwat-Kund Anticline developed a SW-directed thrust along its western flank, called Pezu-Khirgi Fault by Khan et al. (2010). MonaLisa et al. (2005) found evidence for a strike-slip fault along the eastern flank of Marwat-Kund Anticline. It could be the site of the root of Bhittani Thrust (Khan et al. 2010, Figure 5). The fault-bend Surghar-Makarwal Anticline in the east developed an almost identical structure compared to Marwat-Kund Anticline in the west. Both are still growing into a southerly direction.

Based on pebble analyses from the molasse sediments of the Trans-Indus Ranges (Blisniuk 1996; Khan et al. 1988), Blisniuk et al. (1998) timed the basement normal faults in front of the Khisor Range as more than 3.5 Ma. Prior to the SE-directed thrusting of Marwat Anticline and Khisor Anticlinorium these NW-dipping faults determined the sedimentation pattern in the molasse.

Along the Surghar Range the onset of thrusting is reported to be ~1 Ma (Khan et al., 1988, Blisniuk et al. 1998 and Pivnik and Khan 1996). The post-molasse deformational episode is reported to be still continuing as reported by (Frost, 1979; Yeats et al., 1984 and Blisniuk et al. 1998).

Bannu Basin centers the structure of the Trans-Indus Ranges. Whereas the Marwat Anticline and Khisor Anticlinorium along the southeast margin of the basin can be explained as detached duplexes (Blisniuk et al. 1998; Ahmad et al. 2003) the bending of the Marwat-Kund Anticline and Surghar-Makarwal Anticline do not fit in such a picture.

The plate collision of the northwestern Indo-Pakistan Plate with the Afghan Block resulted in two regional tectonic patterns. From the south, ±N-S aligned structures of the mostly Mesozoic platform sediments of the northern Sulaiman Block of the Western Fold Belt arrive west of Bannu Basin. They are overlain by large obducted masses of former Tethys sea-floor rocks, slope and trough sediments upon the younger shelf sediments of the Indo-Pakistan Plate. We assume that these piles of eastward thrusted rocks forced the westward thinning basement rocks underneath to collapse and escape southeastward. In this process it came to the peculiar formation of the Trans-Indus Ranges. Oldest anticline of the Bannu Basin frame is Khisor Anticlinorium. Marwat Anticline is younger and nowadays absorbs the southeastward directed main pressure.

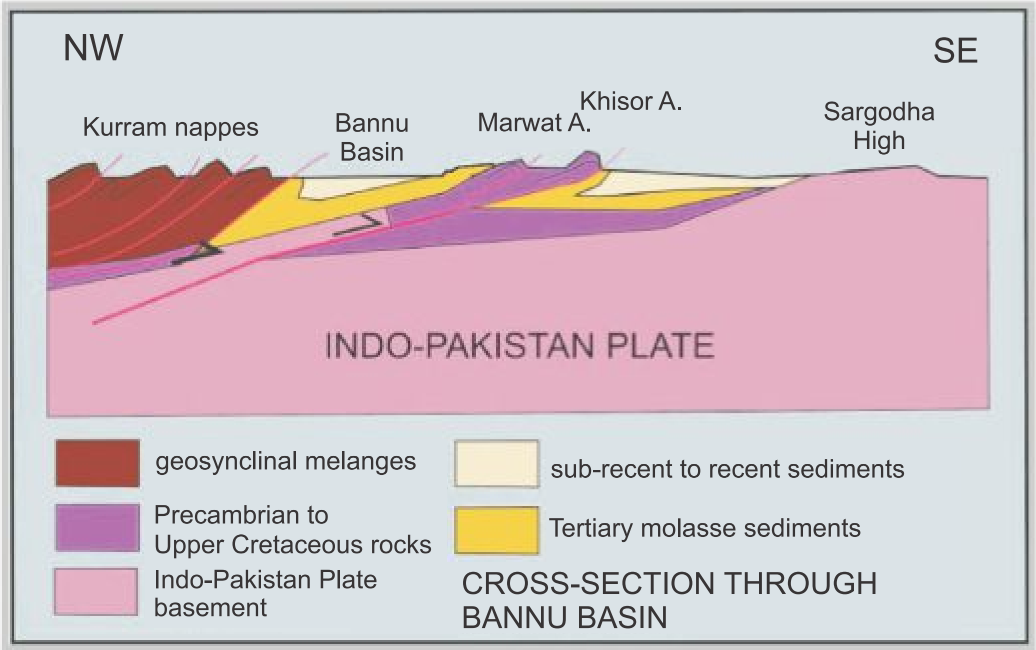


Figure 13 - Schematic cross-section through the basement deformation underneath the Bannu Basin.

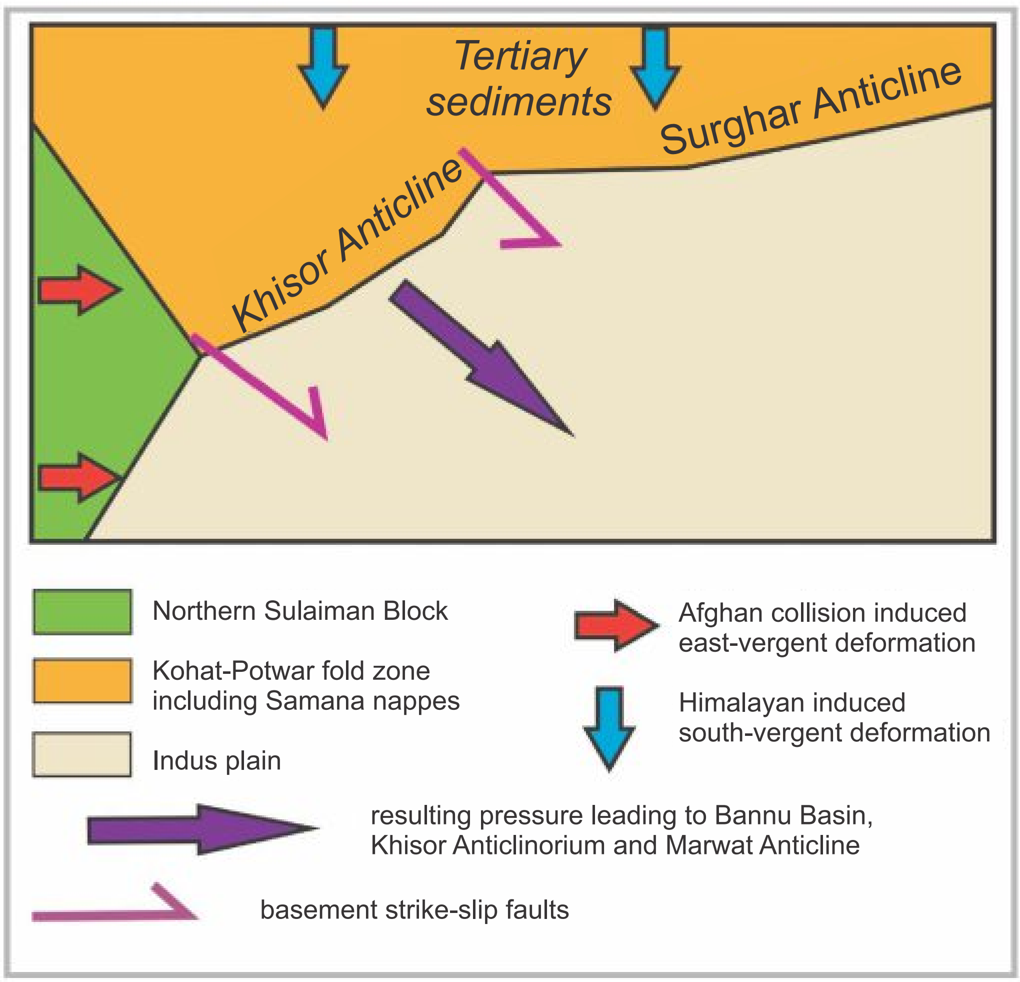


Figure 14 - Schematic view of the early stage of Bannu Basin and Khisor Anticlinorium development.

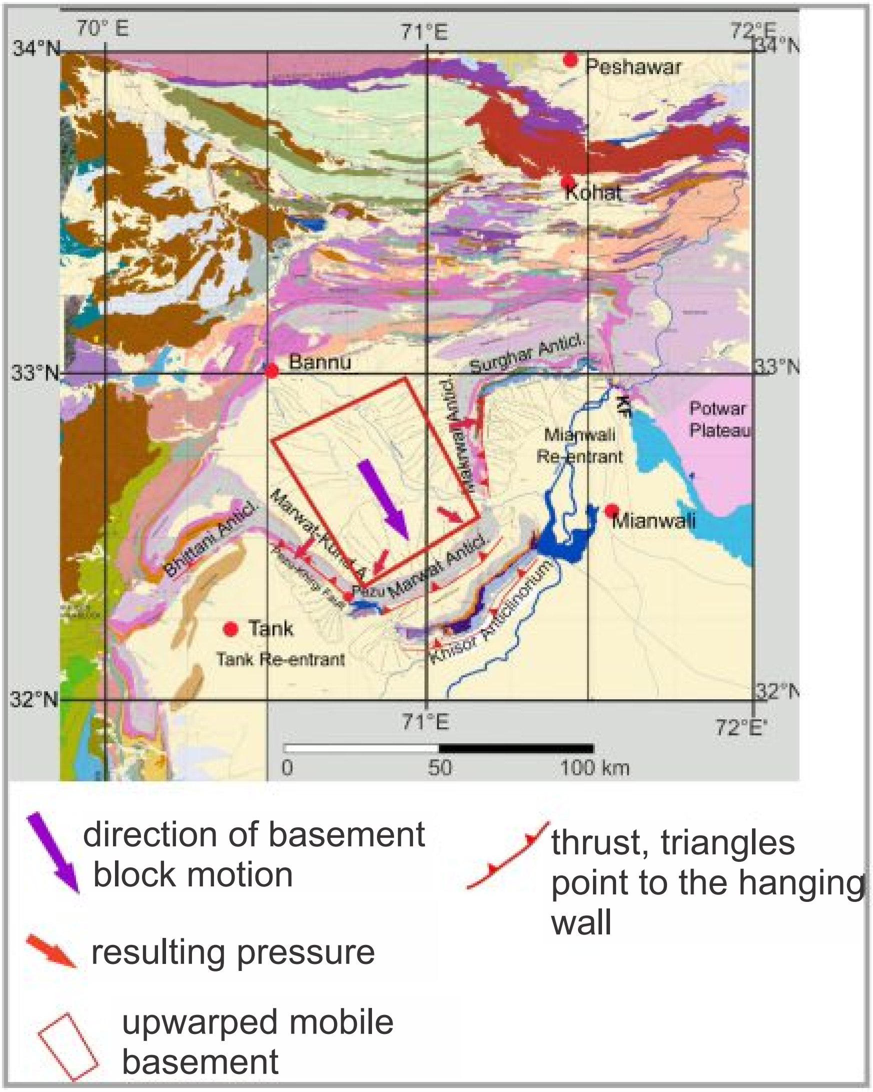


Figure 15 - Schematic view of the early stage of Bannu Basin and Khisor Anticlinorium development.

The frontal corners of the southeastward moving basement block forced the southwestern and northeastern sediments into fault-bend "pressure anticlines" continuously growing in a southerly direction along with the moving basement. These anticlines already collided with Marwat Anticline near Pezu in the southwest and near Kurram River in the northeast. There, we notice some prominent N-S directed fault pattern, which extend southward into Khisor Anticlinorium. In this area Khisor Anticlinorium has a peculiar bend, which indicate a sinistral wrench fault in the basement. This is the area where the Bannu Basin basement collides with the basement of Mianwali Re-entrant/Sarghoda High. We conclude that the main southeast directed motion is now in the southwestern part of Khisor Anticlinorium.

Future research on the nature of Bannu Basin needs to focus on a synoptic view including the Trans-Indus Ranges. Hopefully, future seismic sections through the center of the basin will provide new data that allow an improved image of the tectonic history of the Trans-Indus Ranges.

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