DEFORMATION MONITORING OF MARWAT-KHISOR RANGES, PAKISTAN USING INTERFEROMETRIC SYNTHETIC APERTURE RADAR

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by

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LIST OF ABBREVIATIONS

DEM	Digital Elevation Model
DInSAR	Differential Interferometry Synthetic Aperture RADAR
E	East
ENVISAT	Environmental Satellite
ESA	European Space Academy
ERS	European Remote Sensing Satellite
GIS	Geographic Information System
GRD	Ground Range Detected
InSAR	Interferometry Synthetic Aperture RADAR
LOS	Line of Sight
N	North
NE	Northeast
NW	Northwest
PALSAR	Phase Array Type L-band Synthetic Aperture RADAR
PS	Permanent Scatterer
RADAR	Radio Detection and Ranging
SAR	Synthetic Aperture RADAR (SAR)
SBAS	Small Base Line Subset
SRTM	Shuttle RADAR Topography Mission
SLC	Single Look Complex
S	South
SE	Southeast
StaMPS	Stanford Method for Permanent Scatterer
SW	Southwest
VV	Vertical Transmitted-Vertically Received
W	West

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PEMANTAUAN PERUBAHAN BENTUK BANJARAN MARWAT-KHISOR, PAKISTAN MENGGUNAKAN RADAR APERTUR SINTETIK INTERFEROMETRIK

ABSTRAK

Teras Depan Utama (MFT) mewakili sempadan selatan Himalaya, yang menampung orogeni semasa akibat pertembungan plat tektonik antara Eurasia dan India. Corak ubah bentuk dan struktur MFT adalah penting untuk memahami aktiviti tektonik. Satu rantaian banjaran lipat-dan-tujah (Salt-Trans Indus Ranges) dikenal pasti sebagai MFT di Himalaya barat. Banjaran Garam telah bergerak ke selatan pada kadar purata 5-10 mm/tahun dipengaruhi oleh tektonik garam. Walaupun Banjaran Trans Indus telah menunjukkan tektonik Kuaternari yang aktif, kadar dan arah sesar banjaran itu tidak diketahui. Kajian ini fokus kepada Banjaran Marwat-Khisor, bahagian MFT yang termuda mengalami perubahan bentuk di Himalaya barat. Teknik penderiaan jarak jauh seperti Interferometrik Radar Bukaan Sintetik (InSAR) Penyebaran Tetap (PS), pengekstrakan garisan dan analisis geometrik 'salient' telah dilaksanakan untuk menyiasat mekanisme pengubahan bentuk dan tektonik aktif. Pemprosesan InSAR menggunakan 80 imej Sentinel-1 menunjukkan bahawa Banjaran Marwat-Khisor telah menaik dalam garis pemerhatian satelit pada kadar purata 3-7 mm/tahun bertarikh dari 18 Oktober 2014 hingga 18 Jun 2019. Banjaran Marwat-Khisor merupakan bahagian tergantung yang menaik di atas sesar Khisor yang separa timbul di mana kenaikan permukaan bumi telah dijangkakan. Plot menggunakan rajah rose bagi lineamen yang diekstrak daripada imej Sentinel-1 terarah kepada utara-selatan, barat laut-tenggara dan timur laut-barat daya, menunjukkan bahawa aktiviti

tektonik di Banjaran Marwat-Khisor bukanlah tujahan semata-mata. Banjaran Marwat-Khisor merupakan bahagian hadapan Bannu ‘salient’. Dari segi geometri, Bannu ‘salient’ mempunyai bentuk yang simetri, tidak menonjol (rata), bahagian sisi yang panjang dan corak garis arah aliran yang tertumpu. Apabila dilihat dari atas, kelengkungan Bannu ‘salient’ sama seperti kelengkungan model penopang terkawal yang menandakan kewujudan halangan di kawasan daratan yang berkaitan dengan daratan Tinggi Sargodha. Tektonik garam juga telah menyebabkan bahagian barat Banjaran Marwat-Khisor menaik dan maju ke kawasan daratan lebih daripada bahagian timurnya.

DEFORMATION MONITORING OF MARWAT-KHISOR RANGES, PAKISTAN USING INTERFEROMETRIC SYNTHETIC APERTURE RADAR

ABSTRACT

Main Frontal Thrust (MFT) represents the southern boundary of Himalaya, which accommodated the current orogeny of Eurasian-Indian tectonic plate's convergence. The deformation pattern and structural style of MFT are crucial for understanding the tectonic activities. A chain of fold-and-thrust (FAT) belts (Salt-Trans Indus Ranges) are identified as the MFT in the western Himalaya. The Salt Range had propagated southward at an average rate of 5-10 mm/year in the influence of salt tectonics. Although the Trans Indus Ranges had indicated an active Quaternary tectonics, the fault slip rate and direction was unknown. This study focused on the Marwat-Khisor Ranges (a segment of Trans Indus Ranges), the youngest part of the MFT in the western Himalaya. Remote sensing techniques such as Interferometric Synthetic Aperture Radar (InSAR) Permanent Scatterer (PS), lineament extraction and geometric analysis of salient were implemented to investigate the deformation mechanisms and active tectonics. InSAR processing of 80 Sentinel-1 images showed the Marwat-Khisor Ranges were uplifting in the satellite line-of-sight at an average rate of 3-7 mm/year dated from 18th October 2014 to 18th June 2019. The Marwat-Khisor Ranges are the hanging wall sequence that ramped up section above the partially emergent Khisor Thrust where surface uplift is expected. Rose diagram plotting of lineaments extracted from Sentinel-1 images were oriented in the north-south, northwest-southeast and northeast-southwest directions, implying that the tectonic activities of Marwat-Khisor Ranges are not pure thrusting. Marwat-Khisor

Ranges mark the hinge zone of Bannu salient. Geometrically, Bannu salient has a symmetric, flat-crested shape with long limbs and a convergent trend lines pattern. The map-view curvature of Bannu salient resembles the buttress-controlled model, implying the presence of foreland obstacles that might had extended from the Sargodha High. Salt tectonics might also cause the western Marwat-Khisor Ranges to be uplifted and propagated into foreland more than its eastern side.

INTRODUCTION

1.1 Overview

Fold-and-thrust (FAT) belt is a mountain range of en-echelon, deformed, tilted, folded strata coupled with major thrusts. Generally, FAT belt resulted from the shortening and thickening of the Earth's crust, involving either the cover only (thin-skinned) or both cover and basement rocks (thick-skinned). The kinematics evolution of FAT belt can be influenced by several factors such as the detachment horizon, the presence of pre-existed basement structure, the thickness of thrusting sediment and so on (Reiter et al., 2011; Johnston et al., 2013; Livani et al., 2018). FAT belt developed as a chain of ranges, commonly formed in compressional environments such as the convergence plate boundaries (Himalayas), the subduction zone (Zagros) and within an intraplate of colliding plates. Toe FAT belt is deep water, gravitationally driven sedimentary prisms developed on continental margins. One of the most recognized FAT belts are those formed in the foreland which are adjacent to the main orogenic belt (Poblet and Lisle, 2011). Figure 1.1 shows the structure of a FAT belt.

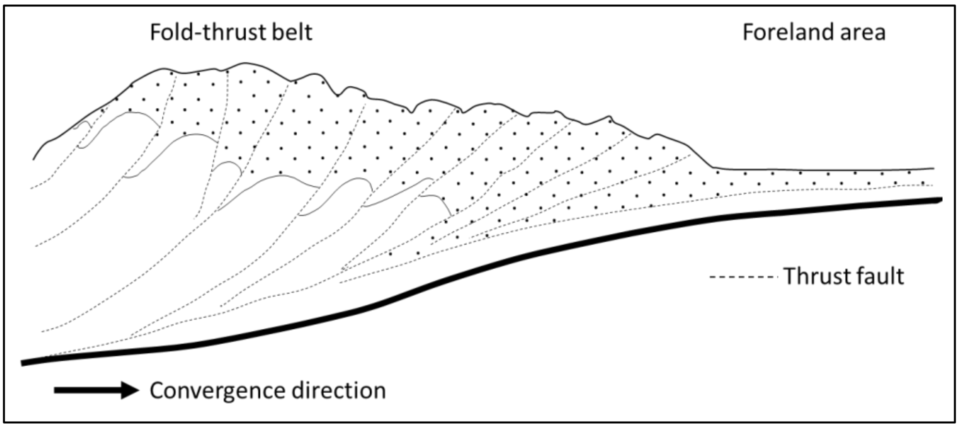

Figure 1.1. The cross-section of en-echelon structure of a fold-and-thrust belt.

In northern Pakistan, FAT belts dominated the surface structural elements. One of them is the Trans Indus Range (TIR) that marks the Main Frontal Thrust (MFT) of the western Himalaya (Figure 1.2). Tectonically, the TIR is a chain of young, active FAT belts that demarcated the southern boundary of the Pakistan Sub Himalaya zone. The east-west trend Surghar and the north-south trend Makarwal Anticlines of the Surghar Range defined the eastern TIR. The southwest-northeast trend Manzai Range and the northwest-southeast trend Pezu-Bhittani Range make up the western TIR. The central TIR comprised of the east-west to northeast trend Marwat-Khisor Ranges that propagated more into the Punjab Foreland than the entire TIR. From the map-view, TIR formed a curve surrounding the Bannu Basin. As a young belt, the seismicity of the Marwat-Khisor Range is deemed stable. Moreover, the central TIR had been explored for hydrocarbon due to the occurrence of several oil and gas seeps (Monalisa et al., 2005; Khan et al., 2014). Figure 1.2 shows the digital elevation model (DEM) of the TIR.

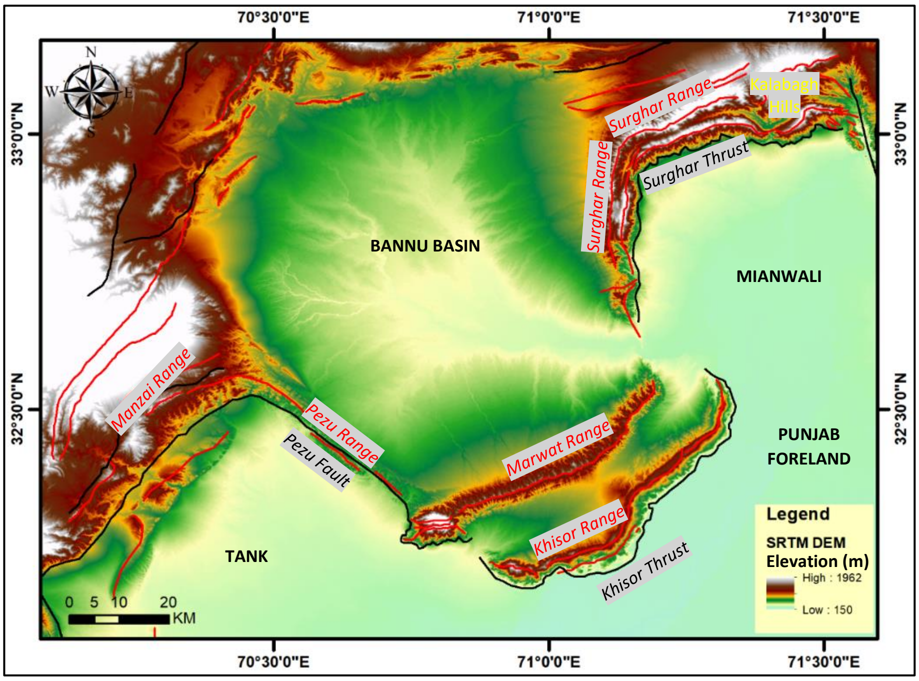

Figure 1.2. The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of the Trans Indus Range. Fold and fault are red and black colored line, respectively (Ali, 2010; Abir et al., 2017).

The Marwat-Khisor Ranges are thin-skinned deformed FAT belts that bordered the southeast Bannu Basin. Marwat Anticline is the only fold of the Marwat Range while the Khisor Range's folds included the Paniala, Saiyiduwali, Mir Ali, and Khisor Anticlines. These anticlines are mainly asymmetric, overturned, and south verging. The partly emergent Khisor Thrust bordered the southern Khisor Range and juxtaposed the Cambrian Group against the Quaternary Group which is implied as the latest thrusting activity (Alam et al., 2014; 2015). Comparatively, the across-strike structural style of Bannu Basin-Khisor Range is similar to the thin-skinned deformation of Potwar Plateau-Salt Range. The Precambrian Salt Range Formation could be the main detachment horizon of the western Himalaya's MFT (Abir et al., 2017). The Marwat-Khisor Ranges are crucial structures in understanding the tectonics of the western Himalaya's MFT.

1.2 Problem Statement

The Marwat-Khisor Ranges represent the MFT in the western Himalaya. The Khisor Thrust had emplaced the Cambrian Formation above the Quaternary molasse sediments (Alam et al., 2014; 2015). The drainage system displayed short river pattern which indicated that the ranges are tectonically uplifting (Chen and Khan, 2009). Therefore, Marwat-Khisor Ranges are young FAT belts that accommodated the ongoing Eurasian-Indian plate convergence. As an actively deforming structure, there is no detailed information about its current deformation pattern. In addition to the limited subsurface information, this led to contradicting theories on the structural style of the Marwat-Khisor Ranges. Firstly, it was proposed to be attributed to the foreland buttress effect (Klootwijk et al., 1983). Later, Ahmad et al. (2008) suggested that it related to the pre-Himalaya basement ramp and strain partitioning. Contrarily, Bannert (2014) stated that it resulted from a protruding hinterland. Lastly, Abir et al. (2017)

suggested that salt tectonic controlled the structural style of the FAT belt. In general, there is a lack of understanding on the tectonic activities in the Marwat-Khisor Ranges.

Interferometry Synthetic Aperture Radar (InSAR) is a remote sensing technique to monitor the changes of the Earth's surface. In active tectonic studies, it was utilized for monitoring seismic events (Hooper et al., 2004; Jebur et al., 2014). As of now, InSAR had been implemented in the western Himalaya. Chen and Khan (2010) measured ± 4 cm surface displacement over the Kalabagh Fault. InSAR also mapped an uplift zone in the western Salt Range which is interpreted as salt diapir (Abir et al., 2015). InSAR assessment of the 1992 Kohat earthquake revealed the caterpillar-like advancement of Kohat Plateau-Surghar Range (Satyabala et al., 2012). InSAR able to measure ground slip rate and direction, useful to understand the active tectonics of Marwat-Khisor Ranges.

Lineament analysis of satellite images often used for geological mapping. Are with dense lineaments coincided with geological structures such as fault lines, fold axis and fractures. The extracted lineaments are oriented parallel to fault lines as the results of the associated activities (Albert and Taofeek, 2016; Muhammad, 2017; Matthew and Ariffin, 2018). Lineament mapping and analysis of satellite images can provide information on the tectonic activities in an area of interest. The integration of InSAR deformation map with lineament information can provide in depth analysis on the

It is noticeable that FAT belts curved when observed from map-view. These curves are named as salient (convex-to-foreland curve) and recess (concave-to-foreland curve). Likewise, the TIR also formed salient (Marwat-Khisor Ranges). The geometry of salient varies amongst FAT belts, which reflects the tectonic environment where the FAT belt developed (Macedo and Marshak, 1999). Therefore, by analyzing the geometry salient in TIR, the structural development of Marwat-Khisor Ranges can be constrained. The integration with InSAR and lineament maps can establish better understanding on the influence tectonic environment. This study maps the current surface deformation and structural pattern of the Marwat-Khisor Ranges, Pakistan remotely using Sentinel-1 images and geological maps.

1.3 Research Objectives

1. To monitor the deformation pattern of the Marwat-Khisor Range using Interferometry Synthetic Aperture Radar.

2. To extract the lineament of the Marwat-Khisor Ranges using semi-automatic PCI Geomatica algorithm.

3. To characterize the geometry of salient in Trans Indus Range using Geographic Information System (GIS).

1.4 Contribution and Significance of Study

This study contributes to the understanding on the present-day deformation pattern of the Marwat-Khisor Ranges. It is a continuation effort of assessing the active tectonic of the western Himalaya’s MFT which had been well established for the neighboring Salt Range. This study is the first geodetic measurement on the fault slip rate and direction of the Marwat-Khisor Ranges. This information is significant for preparing future hazard associated with active tectonic in Bannu Basin region.

1.5 Scope of Study

This study assesses the tectonic activities of the Marwat-Khisor Ranges using remote sensing and GIS. InSAR and lineament extraction of Sentinel-1 images are used to map the surface deformation and the trend line pattern of the Marwat-Khisor Ranges, respectively. Digitization of geological map of the Marwat-Khisor Ranges into GIS is used to define the map-view geometry of the structure. Ground validation on remote sensing result is necessary before using it for further analysis and interpretation. Unfortunately, there is no fieldwork conducted during this study which greatly limited the interpretation of the results.

1.6 Thesis Outline

In general, the thesis contains five chapters. Chapter 1 shows the overview of the study, the problems statement, and the objectives. It also states about the significance of the study. Chapter 2 discusses on the western Himalaya's MFT emphasizing on the Marwat-Khisor Ranges. Literatures on InSAR, lineament extraction and geometric characterization of salient are also reviewed. Chapter 3 describes the geological background of study area, the methodologies and the materials used in this study. Chapter 4 shows the maps of InSAR, extracted lineament and geometry of salient of the Marwat-Khisor Ranges. The fault activities and structural development of the range and its implication for future neo-tectonic study are also discussed. Chapter 5 includes the summary of this study and several recommendations for future researchers.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The Himalaya resulted from the continental convergence between the Eurasia and the India plates that began since Eocene time. The orogeny subdivided the Indian rocks into several tectonostratigraphic zones bounded by major thrusts. Main Frontal Thrust (MFT) is the southernmost major thrust that accommodated the ongoing Himalaya orogeny (DiPietro and Pogue, 2004). In northern Pakistan, the foreland fold-and-thrust (FAT) belt of Trans Indus-Salt Range represent the MFT of western Himalaya (Ali, 2010). Salt tectonic is the fundamental deformation mechanism for the development of the Salt Ranges (Cotton and Koyi, 2000; Ghani et al., 2018). Contrarily, the development of Trans Indus Range is still debatable (Sajjad et al., 2008; Bannert, 2014; Abir et al., 2017).

Tectonic study is necessary to understand the fault activities of an actively deforming structure, which reflect its structural development. In the western Himalaya, grounded geodesy network measured consistent rigid motion across the Potwar Plateau (Khan et al., 2008). However, it consumes large workforce, time, and fund to build a grounded geodesy network. The application of remote sensing geodetic techniques provides remarkable insight on the fault activities of Salt Range and its relation to the salt tectonic (Chen and Khan, 2010; Satyabala et al., 2012; Abir et al., 2015). Hence, opting for remote sensing approach is reasonable to assess the along-strike tectonic activities of the Marwat-Khisor Ranges (central TIR).

Remote sensing is the science of acquiring information of object form distance, typically using sensors onboarded satellite or airborne units. Remote sensing uses the electromagnetic wave to image the Earth's surface from distance. Remotely sensed images are later processed to extract information depend on the user needs. Each band of electromagnetic wave has specific usage in detecting certain information. For instances, radar band is used in measuring sensor to target distance, which is later processed for calculating elevation. Another application of remotely sensed images is the extraction of feature on the Earth's surface. The selection of band depends on the type of feature needed by users.

This chapter will discuss on the geological background of the Main Frontal Thrust of western Himalaya, its deformation mechanism and map-view curvature, alongside with the application of remote sensing technique tectonic studies in FAT belt.

2.2 Main Frontal Thrust of Western Himalaya, Pakistan

The continental convergence between the Eurasia and the Indian plates developed the great Himalaya orogenic belt which subdivided the Indian's rocks into several tectonostratigraphic zones bounded by north-dipping major thrusts. The southernmost zone, Sub Himalaya, is bounded in between the Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) in the north and south, respectively (Ahmad, 2011; Jain et al., 2016). MFT is the youngest structure of the Himalaya orogeny that accommodated the present-day continental convergence. The western Sub Himalaya zone is subdivided into three regions, from east to west, the Potwar Plateau, the Kohat Plateau and the Bannu Basin bounded to the south by the Salt-Trans Indus Range (Figure 2.1). Trans Indus Range (TIR) is a chain of several fold-and-thrust (FAT) belts including the Surghar, the Marwat-Khisor, the Pezu-Bhittani and the Manzai Ranges. Salt Range bounded the Potwar Plateau while the TIR bounded the Kohat Plateau and the Bannu Basin. The Kalabagh, the southern Surghar and the Pezu-Bhittani Ranges are strike-slip zones that separated the three regions (DiPietro and Pogue, 2004).

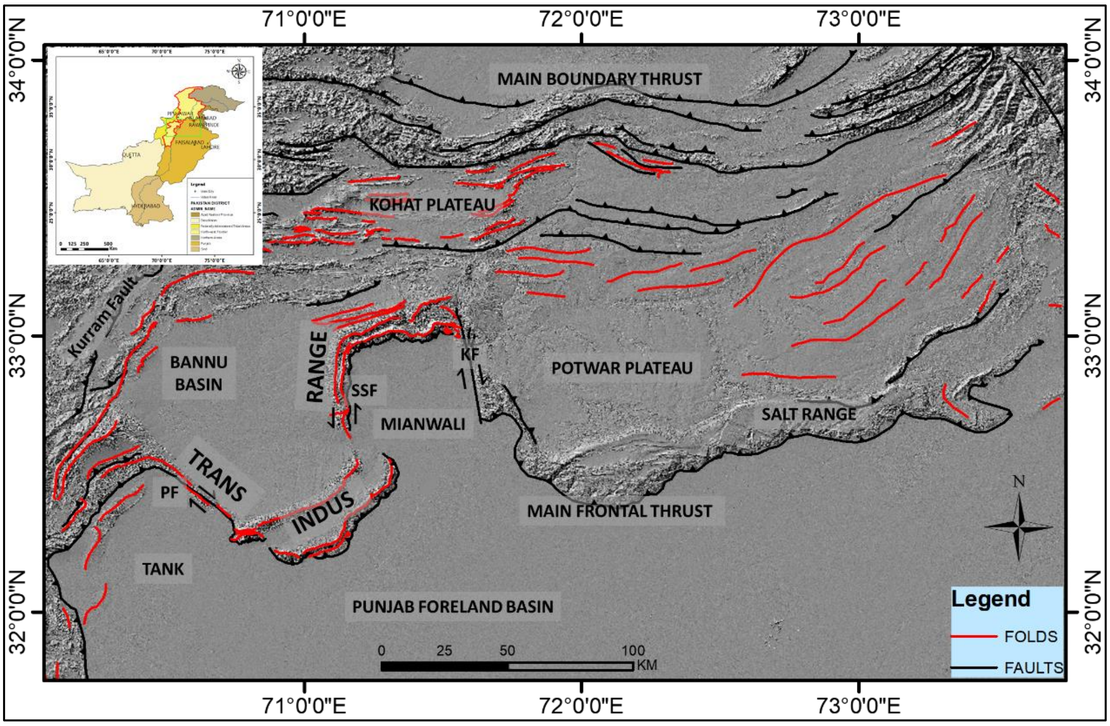

Figure 2.1. A hill-shade map using Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of the Potwar Plateau, the Kohat Plateau and the Bannu Baisn regions in the western Sub Himalaya and the Trans Indus-Salt Range (MFT) in northern Pakistan. The main structural features are highlighted. The Kalabagh strike-slip fault separated the Trans Indus Range from the western Slat Range (after Ali, 2010; Abir et al., 2017). KF: Kalabagh Fault, SSF: Southern Surghar Fault, PF: Pezu Fault.

2.2.1 Surface Geology

Salt Range that bordered the southern Potwar Plateau is subdivided into the western, central and eastern divisions. It is named after the Precambrian Salt Range Formation that was greatly exposed in the western division and gradually disappeared eastward. The east-west trend Salt Range extended westward from the Jhelum River in the east to the Indus River and deviated north into the north-south trend Kalabagh Range. The Salt Range served as a crucial geological site for tectonic study and stored numerous fossils (Sameeni, 2009).

The Trans Indus Range (TIR) is the western extension of the Salt Range. The Kalabgah Fault demarcated the TIR from the western Salt Range. TIR is a chain of several FAT belts, from east to west, the Surghar Range, the Marwat-Khisor Ranges, the Sheikh Budin Hill, the Pezu-Bhittani Range and the Manzai Range. The

Precambrian-Cenozoic rock formations outcropped along the TIR served as good geological sites. From the map-view, the TIR inherited a degree of curvature that surrounded the flat, surface depression of Bannu Basin region (Ali, 2010).

The Surghar Range that marked the eastern end of TIR has two major folds: (1) the east-west trend Surghar Anticline that extended westward from the Kalabagh Hill to Thatti Nusratti and bounded the southern Kohat Plateau and (2) the north-south trend Makarwal Anticline that extended southward from Thatti Nusratti to Dara Tang and flanked the eastern Bannu Basin. The deviation of structural trend lines between these anticlines created a sharp map-view bend near Thatti Nusrati. The Surghar Anticline represents the hanging wall of the partially emergent Surghar Fault that juxtaposes Permian-Triassic rocks against Siwalik Group in the northwest Punjab Foreland (Ali, 2010). The Bhor Sharif Syncline demarcated the southern end of Makrwal Anticline from the Bhor Sharif Anticline. The southern Surghar Thrust bounded the eastern Makarwal Anticline and may be associated with sinistral motion (Bannert, 2014).

The southwest to east-west trend Marwat-Khisor Ranges extended from Dara Tang to Sheikh Budin Hills and bounded the southeast Bannu Basin. The Marwat-Khisor Ranges represents the central division of the TIR. The ranges are dual anticlines separated by the wide Abdul Khel-Kundal Synclines. Marwat Anticline is the only major structure that built up the Marwat Range while the prominent Khisor Anticlinorium included the Paniala, Saiyiduwali, Mir Ali, and Khisor Anticlines. These anticlines are generally asymmetric, overturned, and south verging. The partially emergent Khisor Thrust demarcated the southern Khisor Range from the Punjab Foreland and juxtaposed the Cambrian Group against the Quaternary Group which is implied as the latest thrusting activity of TIR (Alam, 2008). Surface structural mapping suggested that the Marwat-Khisor Ranges represent thin-skinned deformation FAT belts. Marwat-Khisor Ranges are the hanging wall sequence of the Khisor Thrust that originated from the main basal detachment presumed to be located underneath the Cambrian Jhelum Group. Near Bilot village, a mapped thrust is postulated to be a splay fault of the Khisor Thrust (Alam et al., 2014; 2015).

The east-west trend Sheikh Budin Hills comprised of the Pezu and Chunda Anticlines separated by the narrow Chunda Syncline. The hills bounded the southern Bannu Basin and marked the highest point of the TIR. Sheikh Budin Hills are the intersection point between the Pezu Fault and the Sheikh Budin Thrust. A right lateral Paniala Fault demarcated the western Marwat Anticline from the Sheikh Budin Hills (Ali, 2010).

The southeast-northwest trend Pezu-Bhittani Range flanked the western Bannu Basin and linked the Sheikh Budin Hills with the Manzai Range. The blind Pezu Fault divided the Pezu-Bhittani Range into three segments having variation of vergence of folds. The Pezu Fault is postulated to be dominantly thrusting with slight right-lateral strike-slip faulting (Monalisa et al., 2005). The strike-slip motion converged with the Sheikh Budin Thrust which resulted in the overprinting of folds and exposure of old formations in the Sheikh Budin Hills (Ali, 2010).

The Manzai Range marked the western end of the TIR and consisted of northeast-southwest trend of en-echelon FAT belts that occupied the hanging wall of the major thrusts associated with Eocene detachment horizon. Several prominent folds are the Manzai, Khirgi and Jandola Anticlines. The changes in the orientation of the structural trend lines in the TIR formed a sinusoidal map-view curve alternating northeast-southwest surrounding the flat depression of the Bannu Basin region (Ali, 2010).

2.2.2 Tectonic Settings

During Precambrian time, a shallow marine transgression followed by rapid evaporation caused the deposition of the Salt Range Formation. The Indian Plate is unconformably underlain the Salt Range Formation which in turn is conformably overlain by the Cambrian sediments. A major unconformity separates the formations indicates tectonic uplift and/or sea regression after Cambrian until Permian (Ali, 2010; Alam et al., 2014).

Several events of uplift and/or regression had occurred during the Late Paleozoic until the Early Tertiary dominated with extensional tectonics. Three regional rift phases are identified, from old to recent, the Karroo Rift Phase, the Somali Rift Phase and the Mascarene Rift Phase. During this period, the Indian plate drifted northward and collided with the Kohistan-Ladakh Island arc in the early Paleocene. The ongoing collision led to the Indian-Eurasian plate convergence in the late Eocene (Ali, 2010; Abir et al., 2017).

The uplift and erosion events of the rock formations during Eocene/Oligocene created a major unconformity between the Eocene-Miocene sediments. The uplift is related to the Himalaya orogeny. Thick Siwalik Group sediments reflected the deposition of the greatly eroded rock formations into the foreland basin. Due to the loading of the Eurasian plate, lithospheric flexure of the Indian Plate created normal fault basement in the thrust front (MFT) of the Potwar Plateau. The same tectonic structure had been inferred for the other regions. The fault evolved into ramps when the upper sediments are thrusted over that began in Pliocene and continued until today (Blisniuk et al., 1998; Sajjad et al., 2008; Abir et al., 2017).

2.2.3 Crustal Model

Gravity survey is a passive geophysical method to measure the Earth's gravity acceleration at multiple stations. The differences in gravity reflect the variation in the density of subsurface rocks. Gravity surveys are useful for large-scale subsurface mapping that can be conducted through and, airborne and marine approach (Hwang et al., 2007; Kinsey et al., 2008). In convergent settings, low Bouguer gravity anomaly is observed over the main orogen. The gravity anomaly gradually increases towards the foreland area. In general, the higher the topography, the lower the observed gravity anomaly. The high-low 'coupled' gravity signature observed over the Himalaya can be pictured as a simple flexure model in which the lithosphere was deformed due to surface and subsurface loads. Low gravity anomaly reflects the thicken sediments (surface load) while high gravity anomaly reflects the lithosphere being closure to surface (subsurface load). During orogeny, lithosphere responded to these loads and flexed over broad regions as flanking FAT belts (Karner and Watts, 1983).

In northern Pakistan, the accumulation of gravity data obtained from extensive hydrocarbon exploration works made it possible to infer the subsurface configuration of the Precambrian basement. Generally, high Bouguer gravity anomaly is observed over the Punjab Foreland which decreased gradually towards the Potwar Plateau. The anomaly is interpreted to reflect the Precambrian rocks indicating that the basement dipped gently northward. Positive closures are attributed to the igneous intrusion of Sargodha Ridge, a concealed horst-like block with gent slopes that extended northwest from the deeply denuded Aravalli Hills. Weak residual high over the MFT (Salt Range) indicated thick salt that compensated the excess mass of sediments in the uplifted structure (Farah et al., 1977). The Bouguer gravity contour reflects the main trend of the Kalabagh and Surghar Ranges. Low gravity closure over the Bannu Basin indicated the thickening of sedimentary rocks. High Bouguer gravity anomaly observed over the Marwat-Khisor Ranges indicated a crustal thinning which is attributed to the Sargodha Ridge (Din, 2007).

High gravity anomaly observed over the Sargodha Ridge is attributed to the lithospheric flexure caused by the loading of Himalayas due to the Indian-Eurasian continental plates and subduction. Major earthquakes along the southern front of Himalayas are distributed over the junction of the Sargodha Ridge (Mishra and Rajasekhar, 2006). Flexural bulging of Sargodha Ridge had uplifted the sediments and eroded the Oligocene formation from the stratigraphic record. The presence of such forebulge unconformity created possible truncation traps and seal for petroleum system (Irfan et al.,2005).

Figure 2.2 shows the residual gravity map of the western Himalaya's Main Frontal Thrust. The map represents the gravitational attraction of near surface geological structures depicting variation in density and/or tectonic emplacement. Several anomaly closures ranging from 16 mGal in western Salt Range and eastern Marwat-Khisor Ranges to -20 mGal in Potwar Plateau and Mianwali. Low gravity closure is also observed over the Bannu Basin depression. The Marwat-Khisor Range displayed a high gravity value like the western Salt Range. High value indicates the presence of basement rock (structural high) near the surface while low value reflects the thickening of sediments (Din, 2007). The gravity anomaly data give an overview on the subsurface condition which can be used to explain the findings in this study.

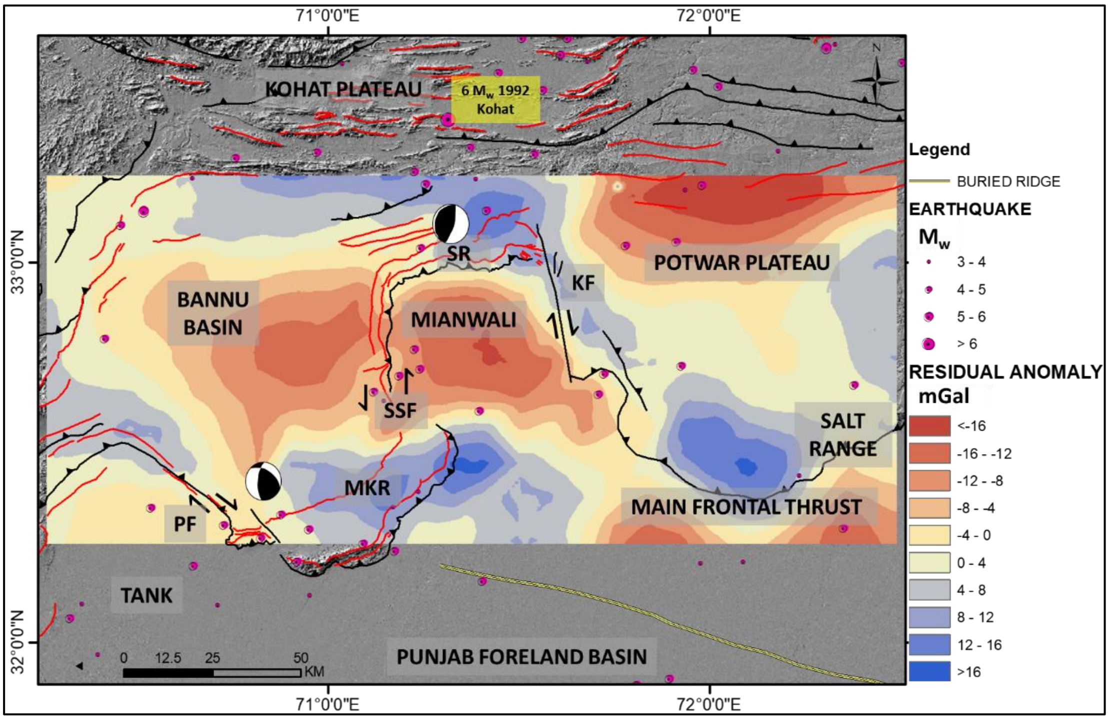

Figure 2.2. The residual gravity anomaly map of the western Himalaya's Main Frontal Thrust. The inferred Sargodha Ridge (yellow line) extended northwest underneath the Himalaya orogeny (after Din, 2007; Farah et al., 1977; Monalisa et al., 2005). Additionally, the seismicity map from 1900 until present-day obtained from United State Geological Survey (USGS) website is also overlaid. KF: Kalabagh Fault; SR: Surghar Range; SSF: Southern Surghar Range; MKR: Marwat-Khisor Ranges; PF: Pezu Fault. Black-white balls are Focal Mechanism Solution.

2.2.4 Seismicity

The seismicity across Himalaya orogen dominantly resulted from the Eurasian-Indian plates convergence that occurred since Eocene time. Most of the earthquakes are triggered on the MFT making the region as the highest rate of seismicity. Catastrophic earthquakes included the 7.5 M_w 1905 Kangra, the 8.1 M_w 1934 Bihar, the 8.6 M_w 1950 Assam and the 7.6 M_w 2005 Kashmir (Bilham, 2004; Turner et al., 2013). Half of the Eurasian-Indian plates convergence is distributed across its central division which is currently converging at rate ranging from 17.8 to 20.5 mm/year (Ader e t al., 2012). The convergence rate increases towards the eastern Himalaya but reduces slightly towards its western division (DeMets et al., 1990).

In the western Himalaya, the latest manifestation of catastrophic surface rupture event is the 7.6 M_w Kashmir earthquake that struck the northern Pakistan on 8th of October 2005. Over 80,000 casualties including 19,000 children are reported. Approximately 138,000 were injured and over 3.5 million rendered homeless (EERI Special Earthquake Report, Feb 2006). The seismicity level gradually reduced south into the Potwar Plateau region which is postulated to be attributed to the presence of ductile salt detachment. Salt lubricated the gliding plane between the basement rock and the overburden layer which eased the propagation of the Potwar Plateau. Moreover, thick accumulation of salt in the western Potwar Plateau can also act as natural buffer that absorbed the post-shock of the Kashmir earthquake (Khan et al., 2008). The Bannu Basin region appeared to be seismically inactive that might indicate the presence of ductile detachment. Contrarily, high magnitude earthquakes are concentrated in the least propagated Kohat Plateau which is postulated to be attributed to the lack of ductile basal detachment that locked its propagation. The latest catastrophic seismic event is the 6 M_w 1992 Kohat earthquake which displaced as much as 80km^2 of the Kohat Plateau (Satyabala et al., 2012). As a young and actively deforming structure, several low magnitude earthquakes were reported on the TIR. Focal mechanism solution (FMS) studies showed that the TIR is a complex geological structure with multi-tectonic activities inclusive of thrusting, transpression and normal faulting (Monalisa et al., 2005).

2.2.5 Salt Tectonic

The presence of salt formation had greatly influenced the tectonic activities of western Himalaya's MFT in accommodating the Himalaya orogeny. As stated on its name, salt tectonic is prominent in the Salt Range. Thick salt formation was exposed in the western Salt Range and gradually diminished in the eastern division (Sameeni, 2009). Sandbox modelling of Salt Range showed that the part of FAT belt gliding over thicker ductile detachment will propagate further than the part over thinner detachment. Moreover, a transpressional zone was formed at where a sudden change in thickness of detachment occurred. The Kalabagh strike-slip Fault demarcated the western Salt Range from the Surghar Range that marked the depositional limit of salt formation, indicating that the formation may be absent in the Surghar Range. The lateral variation in detachment thickness led to the formation of map-view curvature along the Salt Range. (Cotton and Koyi, 2000).

Khan et al. (2012) conducted remote geological mapping using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data integrated with seismic information to reinterpret the structure of Kalabagh Fault. Principal component analysis image processing is used for mapping the lithology. The integration of both surface and subsurface information subdivided the Kalabagh Fault into two segments having variation in tectonic activities. The northern segment represents a strike-slip zone associated with salt diapirism that caused uplift deformation of the fault. The southern segment represents the lateral ramp of MFT where oblique thrusting occurred over the salt basal detachment and emplaced older formation over the Siwalik Group of Punjab Foreland. Potwar Plateau-Salt Range propagated southward more than the Kohat Plateau-Surghar Range induced by the loosening effect of salt. The Kalabagh Fault marks the transfer zone that adapted the differential thrusting due to lateral variation in detachment horizon between the Kohat and Potwar Plateaus.

Ghazi et al. (2014) extracted the structural features from Google Earth images of Salt Range to highlight the effect of tectonic process on topography. The Salt Range consisted of the western, the central and the eastern divisions bounded to the west and east by the Kalabagh and Jhelum Faults, respectively. The Salt Range is dominated with compressional (thrusting and folding), transform (strike-slip) and extensional (normal fault) deformations. The anticlines in eastern Salt Range are tight, overturn, coupled with blind thrust, salt-filled core and formed triangle zones and pop-up structure. The central Salt Range is made up of minor folds grew parallel to the range front, high angle faults, salt diapir and strike-slip zones. Most folds are concentric with shortening become more intense southward and to the eastern division. The western Salt Range is dominantly comprised of salt diapir structures which are localized along high-angle faults. The presence of thick salt developed less folds in the western Salt Range compared to the eastern and central divisions.

The density of salt does not change with increasing burial depth which made the formation remains less dense than the surrounding rocks which induced an upward migration (buoyancy) and created diapir structure. Salt is also highly ductile which made the formation to deform laterally when compressed and acted as detachment horizon. In the Potwwar Plateau-Salt Range region, the behavior of salt either as detachment or diapir structure depends on the mechanical strength of overburden layer. Generally, thin overburden layer is less compacted and weaker compared to thick overburden layer. Salt tends to flow upward and formed diapir in the Salt Range where thin overburden present. Contrarily, thick overburden in Potwar Plateau caused salt to deform laterally and acted as detachment horizon (Abir et al., 2015).

Ghani et al. (2018) created a 3D model of the structural development of FAT belts in the Kohat and Potwar Plateaus constrained with geophysical and well data. Following the current knowledge of salt tectonics, the Potwar Plateau-Salt Range is modelled to be overlaying a ductile basal detachment (salt) while the Kohat Plateau-Surghar Range overlain a brittle basal detachment. The lateral variation in mechanical strength of basal detachment caused the Potwar region to propagate more into the

Punjab Foreland while restraining the propagation of Kohat region. Additionally, the model suggests an Eocene secondary detachment horizon for the Kohat Plateau. The surface structures of Kohat evolved as the roof thrust sequence above the Eocene secondary detachment. Paleocene sedimentary platform is tectonically shortened into north-dipping duplexes developed in between the secondary and main basal detachment which explained the complex structural style of Kohat Plateau. The dextral Kalabagh Fault that marks the transition zone where the ductile detachment of Potwar Plateau became more brittle. The frontal thrust of Kohat-Potwar Plateaus (Surghar and Salt Ranges) inherited a degree of map-view curvature which resulted from the variation in basal detachment's strength. The origin of the map-view curvature could also be attributed to the irregularities of pre-Himalaya basement normal fault ramp if both the Kohat and Potwar Plateaus overlain the same basal detachment (Figure 2.3).

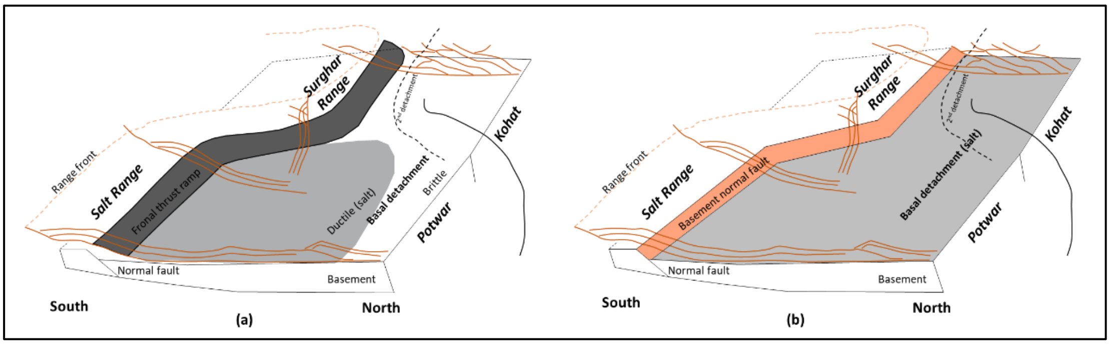

Figure 2.3. The tectonic setting of the Kohat and Potwar Plateaus that controlled the formation of map-view curvature of Surghar-Salt Ranges due to (a) difference strength of basal detachment and (b) irregularities of pre-existing basement normal fault (Ghani et al., 2018).

Based on the tectonic model, this suggests that the high gravity anomaly (Figure 2.2) relative to the Salt Range could be related to the pre-Himalayan basement normal fault ramp, which resulted from lithospheric flexure due to the loading of Himalayas. The same tectonic settings could be interpreted for the Marwat-Khisor Ranges due to similarity in the gravity profile.

Abir et al. (2017) reinterpreted 2D seismic and well profiles of Bannu Basin region to assess its deformation style and tectonics in relation to the entire northern Pakistan's FAT belts. Generally, the seismic profiles shows that Bannu depression lacks internal deformation. The Cambrian-Eocene sedimentary platform maintained constant thickness in both along- and across-strike directions. The surrounding Trans Indus Range seemed to be the only contractional structures in the Bannu Basin region. Range region. Additionally, salt layer was drilled at the central Marwat Anticline while salt structures were interpreted at both ends of Marwat Anticline. Comparatively, the across-strike structural style of Bannu Basin-Khisor Range is similar to the western Potwar Plateau-Salt Range. Thus, the Precambrian Salt Range Formation could also be the main basal detachment of the Marwat-Khisor Ranges and might underlain the Bannu depression's deposits which explained its lack of internal deformation.

2.2.6 Active Tectonic Studies

Following the 2005 Kashmir earthquake, a Global Positioning System (GPS) geodesy network was grounded to monitor the post-seismic deformation pattern and crustal velocity of the western Sub Himalaya, Pakistan. It is observed that the central Potwar Plateau had shifted southward at approximately 3 mm/year relative to the Indian plate. The measured rate is much lower than the 10-15 mm/year inferred from the geological studies (Khan et al., 2008).

Chen and Khan (2009) extracted the drainage pattern and density of the western Himalaya's MFT using 90m spatial resolution Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) to assess the effect of tectonic processes on topography. The MFT has low drainage density compared to the Sub Himalaya zone. The irregular flow in rose diagram plot of the MFT indicated a short, underdeveloped drainage pattern which is inferred as rapid uplift process of the thrust front.

Chen and Khan (2010) conducted 2-pass Differential Interferometry Synthetic Aperture Radar (DInSAR) observation using two European Remote Sensing Satellite (ERS) images to monitor the current slip rate and direction of the Kalabagh Fault. A cumulative Line-of-Sight (LOS) surface shift of ± 40 mm is measured from 28 November 1992 to 20 April 1999 (approximately 6.4 years). The measured shift is much lower than the 7-10 mm/year rate suggested by previous works. In the northern segment, the current deformation is concentrated in the splay faults of the main Kalabagh Fault. The right lateral strike-slip motion dies out where the Kalabagh Fault merged with the Surghar Thrust. In the southern segment, insignificant displacement is measured in the western Salt Range where the thrust front is postulated to be gliding over thick salt detachment (Chen and Khan, 2010).

Satyabala et al. (2012) also used InSAR to investigate the rare 1992 seismic event occurred in the Kohat Plateau. InSAR results showed that the earthquake had deformed 80 km^2 patch of the Earth's surface. Both InSAR and seismic data agreed that the basal detachment located 8km depth had ruptured seismically and triggered the 6 M_w earthquake. For such event to occur, the deformed patch must store great pre-seismic stress, yet InSAR failed to search for such deformation (e.g., low magnitude earthquake). It is inferred that a weak detachment must exist beneath the Kohat Plateau which allowed the thrust to slip aseismically and stressed the 1992 rupture zone. Seemingly, the 1992 Kohat earthquake was triggered on part of detachment with increased friction where detachment may had evacuated in the cores of anticlines. The propagation of Kohat's thrust sheet is modelled as caterpillar-like motion combining aseismic and seismic deformation.

Jouanne et al. (2014) monitored the active tectonic activities of the Potwar Plateau-Salt Range using GPS. The central Potwar Plateau had been shifting at 5 mm/year relative to the Punjab Foreland, which is consistent with the previously measured rate. Contrarily, the western Potwar Plateau-Salt Range including the Kalabagh Fault where salt was greatly exposed had appeared to be insignificantly deformed. It is inferred that the western division experienced episodic fault creeping. The other explanation could be that the parts of basal detachment are salt-free that may had been evacuated in the core of anticlines, thereby, increasing the friction and locked its propagation into the foreland area.

Abir et al. (2015) executed Small Baseline Subset (SBAS) InSAR using 10 (Phased Array type L-band Synthetic Aperture Radar) PALSAR data to study the present-day deformation pattern of the western Potwar Plateau-Salt Range. Figure 2.4 shows the InSAR deformation map dated from 7th January 2007 to 2nd March 2010, showing inconsistent uplifting rate. InSAR identifies two significant uplift zones with deformation rate up to 15 mm/year. Zone A is interpreted as a dextral transpression zone where the strike-slip Kalabagh Fault collided with the thrust ramp of pre-Himalayas basement fault beneath the Salt Range. In addition, Zone A coincides with the Sakesar Mountain peak, which is very probable for tectonic uplifting to occur. Contrarily, Zone B is surrounded with exposed salt and located near the active Warcha Salt Mine. This uplift event of Zone B is interpreted as salt diapirism, influenced by active transpression and compression. Due to low buoyancy of salt and thinning of overburden layer of the Salt Range, the salt tends to flow upward through the overburden and uplifted the western Salt Range, which was successfully measured using InSAR. Although InSAR only measure surface deformation, this shows that InSAR able to detect subsurface event (salt tectonic). Therefore, InSAR can be applied to measure the same effect in area dominated with salt tectonic.

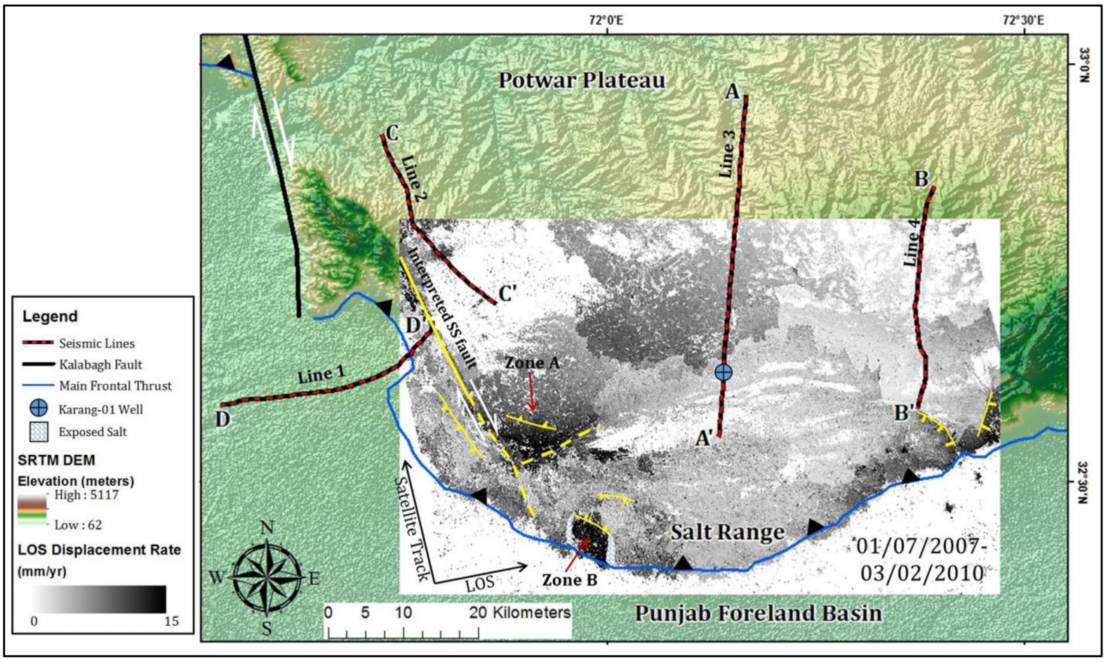

Figure 2.4. The InSAR deformation map of the western Potwar Plateau-Salt Range using SBAS InSAR technique (after Abir et al., 2015).

2.2.7 Map-view Curve of TIR

Klootwijk et al. (1986) conducted a paleomagnetic studies of the early Tertiary and older formations in the western Himalaya's MFT to assess the kinematics of the map-view curvature. Two magnetic signatures are predicted, (1) magnetic declinations and do not correlate with the changes in structural trend lines, and (2) magnetic declinations follow the changes in structural trend lines. The results showed that the magnetic declinations of the Salt Range do correlate with the structural trend lines. This indicated that the Salt Range was an initially linear FAT belt that rotated counter-clockwise around the Hazara Arc relative to the Indian Plate. It is suggested that the Surghar Range was obstructed by a concealed structural high that extend from the Sargodha High. Consequently, the Surghar Range did not rotate and shift southward as much as the Salt Range, thereby, led to the formation of map-view curvature.

Sajjad et al. (2008) reinterpreted the paleomagnetic results of the Surghar Range to reassess the origin of map-view curvature in TIR. Limited yet significant data showed that the magnetic declinations do not correlate with the structural trend lines of the Surghar Range implying the TIR as a primary, non-rotational FAT belt. It is suggested that the current map-view curvature reflected the lateral irregularities of the pre-existed basement normal fault ramp that formed due to the lithospheric flexure. Strain partitioning around the sharp bend in between Surghar and Makarwal Anticlines may accommodate the east-west and north-south induced compressions which resulted in the multi-vergence of the TIR. The thrusting over the ramp of Surghar Range began 1 million years after the Salt Range was thrusted. The thrusting of Manzai Range occurred simultaneously with the Surghar Range. The final stage included the southeast thrusting along the Pezu and Marwat Fault to form the current map-view curvature. This implied that the Khisor Range is older than the Marwat Range, supported by the fact that the Khisor Range was offset by the Kundal Fault while the Marwat Range remained unaffected.

Alam et al. (2015) conducted field works in western Khisor Range to create a structural model of the Marwat-Khisor Ranges. Two outcrops located in Bilot and Paniala are chosen to map the surface structural style of the range. It is inferred that the Marwat-Khisor Ranges represent thin-skinned deformation FAT belts associated with Precambrian basal detachment. Marwat Anticline was an initially low amplitude forced fold that thrusted over a blind ramp and evolved into fault-bend fold. Later, it was followed by thrusting over another thrust ramp originated directly from the basal detachment that emerged as the partially emergent Khisor Thrust and formed the fault-bend Khisor Anticlinorium. This implied the Khisor Range as the latest deformation stage and appeared younger than the Marwat Range.

Bannert (2014) studied the structural style near the sharp bends in the TIR to assess the forces responsible for the southeast propagation of the Marwat-Khisor