TECTONIC DEVELOPMENT OF THE POTWAR PLATEAU AND THE SALTRANGE (NW HIMALAYAS, PAKISTAN)

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TECTONIC DEVELOPMENT OF THE POTWAR PLATEAU AND THE SALTRANGE (NW HIMALAYAS, PAKISTAN)

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ABSTRACT

TECTONIC DEVELOPMENT OF POTWAR PLATEAU AND THE SALTRANGE (NW HIMALAYAS, PAKISTAN)

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Collision and indentation of the Indian Plate into the Eurasian Plate gave way to the development of Himalaya Orogen since early Eocene (around 50 Ma ago). The most recent products of the Himalayan orogeny is expressed by the development of Potwar Plateu and the Saltrange in W Himalayas, which are the main topic of this thesis. In order to unravel present architecture, evolution, and deformation styles of the Potwar Plateau and the Saltrange we have conducted paleomagnetism, fault kinematics, seismic interpretation and cross-section blancing tehniques.

For paleomagnetism more than 1000 samples are collected at 86 different locations spanning from Oligocene to Pliocene sedimentary units to determine vertical axis rotations. Temporal constrains of vertical axis rotations are determined by using magnetostratigraphy. The results have shown that the study area has experienced 10 to 30 degrees of counterclockwise rotations in two different episodes.

For understanding the structural development of the study area, paleostress inversion technique is used based on fault slip data collected from the mesoscopic faults developed in the region while Anisotropy of Magnetic Susceptibility (AMS) study was conducted on the collected paleomagnetic samples. These kinematic results show two major deformation phases. During first phase, the horizontal component of major principal stress axis ($\sigma1$) was subhorizontal and oriented NNE-SSW and switched to NW-SE during the second phase of deformation. During these phases minor stress axes were sub vertical. The major principal stress directions are almost parallel to the intermediate AMS (K2) axes, which collectively indicate compression and shortening.

In order to understand 3D architecture of the study area (20) 2D seismic sections that makes up 400 kms line length are interpreted. The interpreted sections are used as balanced cross-sections and restored to determine differential shortening amounts in Potwar and the Saltrange. The restored sections indicated that only 18% of Indian Plate convergence is taken up as shortening in Potwar and the Saltrange, the remaining 82 % convergence is not reflected in the form of shortening possibly due to tectonic glide over salt, also taken up by major thrust faults in the region.

Keywords: the Potwar Plateau, the Saltrange, paleomagnetism, magnetostratigraphy, paleostress inversion, Anisotropic Magnetic Susceptbility (AMS), cross-section restoration.

ÖZ

POTWAR PLATEAU VE SALTRANGE'İN TEKTONİK GELİŞİMİ (KB HİMALAYALAR, PAKİSTAN)

Qayyum, Abdul
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Ekim 2018, 113 sayfa

Hint Levhasının Avrasya Levhasına yakınsaması, yaklaşık 50 milyon yıl önce Himalayaların oluşmasına sebep verdi. En son Himalaya orojenisi, KB Himalaya'larda Potvar Platosu ve the Saltrange'in gelişimi olarak ifade edilir ve bu tezin konusunu oluşturur. Bu bağlamda, Potvar Platosu ve Saltrange'in günümüzdeki mimarisi ve evrimi yanında bölgenin deformasyon sitilini ortaya koymak için paleomanyetizma, fay kinematiği, sismik yorumlama ve enine kesit dengeleme yöntemleri kullanılmıştır.

Düşey eksen rotasyonlarını belirlemek için Oligosen'den Pliyosene kadar olan dönemi temsil eden çökellerden 86 farklı noktadan 1000'den fazla plaomanyetizma amaçlı örnek derlenmiş olup bu rotasyonların zamansal sınırlarının belirlenmesi için manyetostratigrafik yöntem kullanılmıştır. Elde edilen sonuçlar çalışılan alanın iki farklı zaman diliminde 10° ile 30° saatin tersi yönde döndüğünü göstermektedir.

Bölgenin yapısal gelişiminin anlaşılması için derlenen paleomanyetik örnekler üzerinde Anizotropik Manyetik Süseptibilite (AMS) çalışmaları yapılmış aynı zamanda bölgedeki fay çizikleri kullanılarak paleostres inversiyon tekniği kullanılmıştır. Kinematik çalışmalar bölgenin iki farklı deformasyon evresinden geçtiğini göstermektedir. İlk deformasyon evresinde asal gerilme ekseni ($\sigma1$) yataya yakın olup KKD-GGB yönünde olup sonraki evrede ise KB-GD yönüne dönmüştür. Elde edilen bu yönler ortaç AMS eksenlerine paralel olup beklendiği şekilde aynı sıkışma ve kısalma deformasyon stiline işaret etmektedir.

Çalışılan alanın 3B mimarisinin ortaya konulması ve bölgede meydana gelen kısalmanın miktarının belirlenmesi için 20 adet 2 boyutlu (2B) toplam boyu 400 km’ye ulaşan sismik kesit yorumlanmıştır. Yorumlanan bu kesitler dengelenmiş enine kesitlerin oluşturulmasında kullanılmış daha sonra bu kestiler çalışma alanında meydana gelen diferansiyel kısalmanın belirlenmesi için deformasyon öncesi hallerine restore edilmiştir. Elde edilen sonuçlar potvar ve Saltrange’de Hint plakasının yakınsama oranının sadece %18'ini karşıladığını göstermektedir. Geriye kalan %82’lik yakınsama muhtemelen tuz üzerindeki kayma ve bölgedeki diğer önemli bindirme faylarıyla karşılanmaktadır.

Anahtar Kelimeler: Potvar Platosu, Saltrange,Paleomanyetizma,Manyetostratigrafi, Paleostres dönüşümü, AMS, Enine Kesit Restorasyonu

To My parents

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CHAPTER 1

INTRODUCTION

Ongoing Indian and Eurasian plate collision since Eocene resulted in Himalayan ranges comprising series of south verging fold-and-thrust belts developed over Indian craton (Powal et al, 1973). The Indian Plate moves at a rate of 38 mm/year northwards into the Eurasian Plate making Indian NW front an tectonically active region (Bilham, 2006). Orogenic belts that involve salts are typically wider than their non-salt equivalents. Frontal fold and thrust belt of Himalayan Orogeny is still active and relatively broad in NW (the Saltrange) as compared to Indian Himalayas (Seebar and Armbrusten 1979. Indian convergence developed large north-dipping thrust sheets in north west Himalayas, namely Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) in order to compensate on-going shortening and crustal thickening (Butler et al., 1987). These thrusts demarcates different episodes of Himalayan Orogeny and make these geologically distinct. Foreland fold and thrust belt between Main Boundary Thrust and the Saltrange Thrust located far from the vicinity of the Himalayan orogeny which underwent the most recent phase of deformation (Dahlen et al., 1984; Davis and Engelder, 1985). The the Saltrange fold and thrust belt and the Potwar Plateau are the recent most expressions of Himalayan Orogeny. The Potwar Plateau and the Saltrange are detached along the infra-Cambrian evaporates and developed thin-skinned tectonics (Burbank and Beck, 1989; Butler et al., 1987; Jaume and Lillie, 1988; Lillie. R, 1986). The effective slide of the overburden rocks along sole thrust suggests the weak nature of the detachment horizon, which allows the translation of overburden sediments further with minimal resistance (Davis and Engelder, 1985). Overall rotation of greater India is counterclockwise since 80 Ma to present day (Powal et al, 1973). However, only 2° of clockwise rotation is observed since last 10 Ma (Copley et al., 2010; Torsvik et al., 2012).

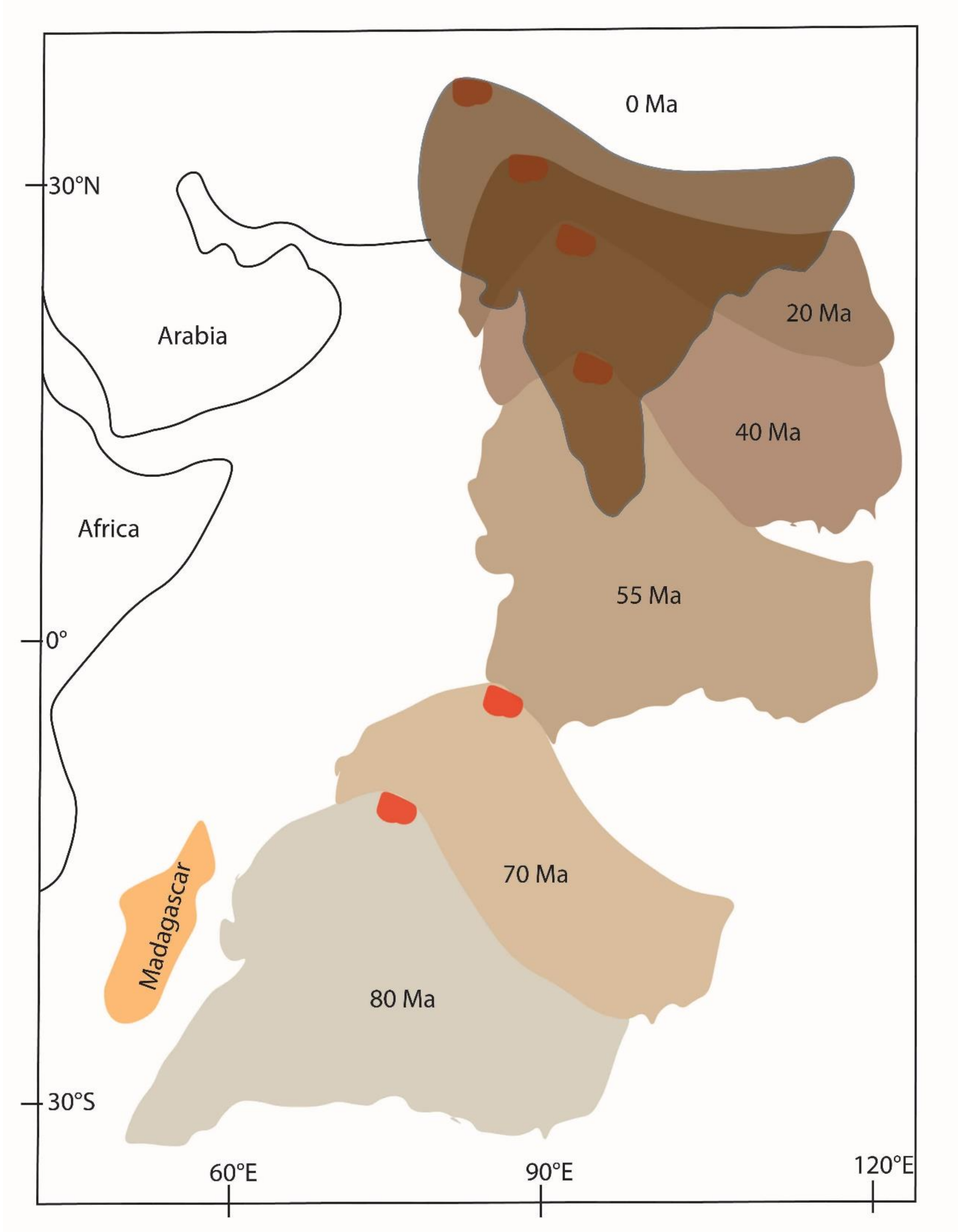


Figure 1. 1 Positions of Greater India from 80 Ma to present day with respect to Africa, Madagascar and Arabia fixed in their present postion (Modified from Powal et al, 1973). The Potwar Plateau and the Saltrange are shown in red over Greater India.

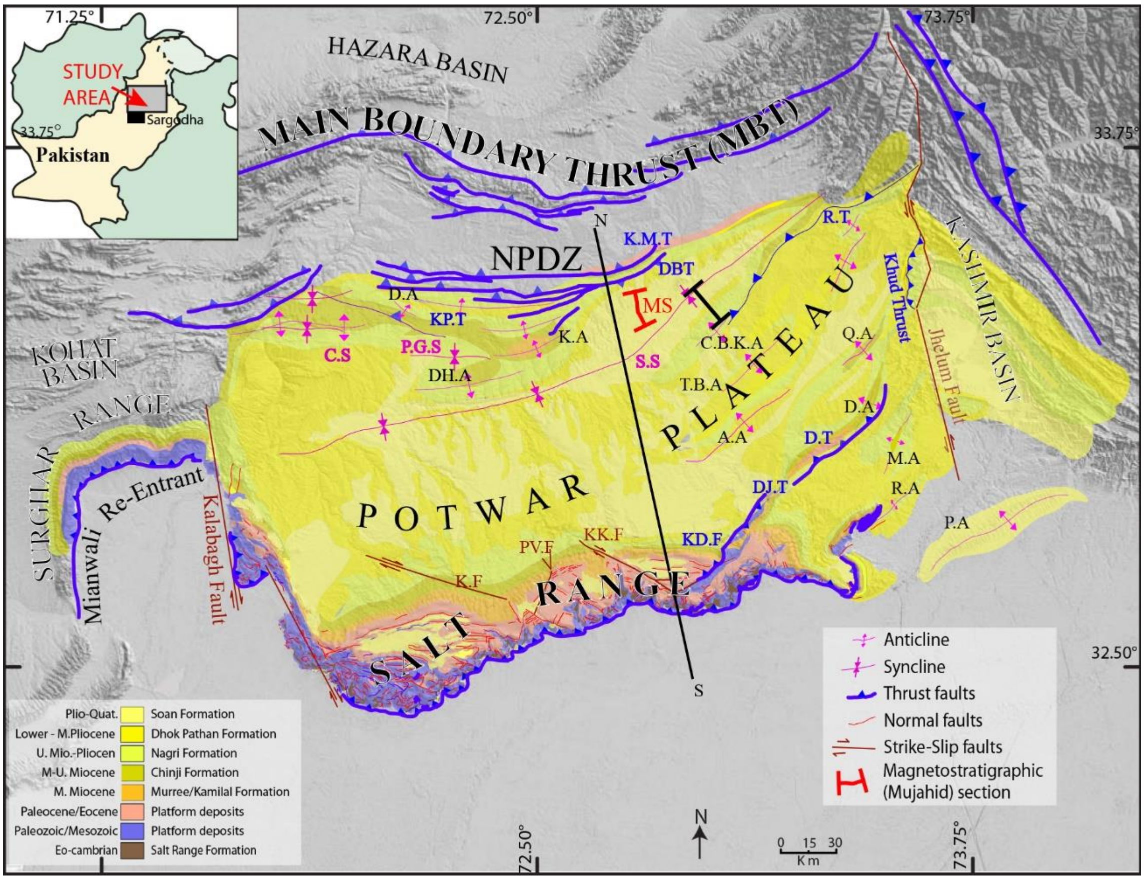


Figure 1. 2 Geological map of the Potwar Plateau and the Saltrange (modified from Gee 1989).

AA: Aadhi anticline, CBKA: Chak Beli Khan Anticline, DA: Domeli Anticline, DT: Domeli Thrust, DJT: Dill Jabba Thrust, DBT: Dhurnal Back Thrust, DHA Dhullian Anticline, KF: Kenhetti Faut, KDJF: Krangal Dill Jabba Fault, KKF: Kallar Kahar fault, KMT: Khair-e-Murat Thrust, KT: Kanet Thrust, KP.T: Kharpa Thrust, MS: Mujahid Section, NPDZ: North Potwar Deformed Zone, MA: Mehesian Anticline, MT: Mianwala Thrust, PA: Pabbi Anticline, PVF: Pail Vesnal Fault, QA: Qazian Anticline, RT: Riwat Thrust, SS:Soan Syncline, TBA: Tanwin Bian Anticline.

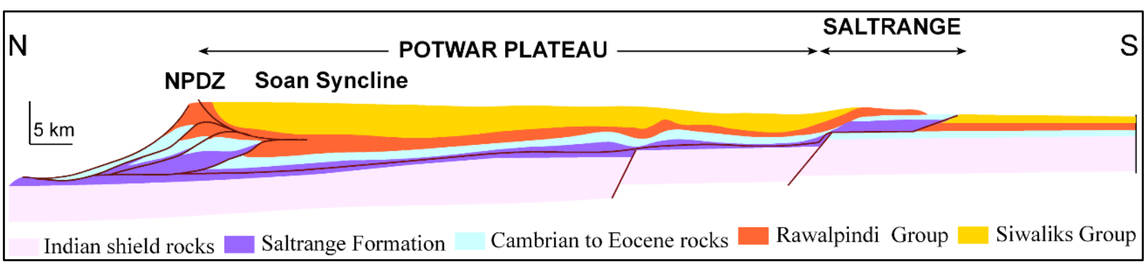


Figure 1. 3 Generalized cross-section of the Potwar Plateau and the Saltrange tectonic wedge (adopted from Lillie 1987).

1.1 Stratigraphy

Indian shield basement comprises metamorphosed Precambrian rocks exposed 80 km south of the Saltrange within the Indian Shield. In a well 280 km south of the Saltrange, which penetrated 900 m of the Saltrange Formation (Kirana Group) that overlies Precambrian Indian shield rocks are of late Proterozoic age.

Eo-Cambrian saltrange Formation serves as decollement layer. Non halite evapouritic facies were interbedded with salt originally, however igneous inclusions in salt are the material that are plucked from the strata below, known as Khewrite, might be plucked from substrate beneath the salt due to inter haline currents (Hudec and Jackson, 2007). Three members of Saltrange Formation are; Billianwala salt member, Bhanderkas gypsum member and Sahwal marl member. Saltrange Formation is overlain by clastics and dolomites of Cambrian, which are further unconformably overlain by Nilawhan group of early Permian in the eastern the Saltrange. Upper Permian Zaluch group is missing in the eastern Saltrange and well developed in the western Saltrange. Triassic, Jurassic and Cretaceous are absent from the eastern Saltrange. Paleocene formations Hangu, Lockhart and Patala are present both in eastern and western Saltrange. Eocene is well developed throughout the Saltrange and the Potwar Plateau and limestones of Sakesar and Chorgali formations are the hydrocarbon reservoirs in the Potwar Plateau. Eocene marks end of marine deposition and it is unconformably overlain by continental clastics of Rawalpindi Group (Murree & Kamlial Formations) of late Oligocene & Miocene age. The Siwaliks Group containing Chinji, Nagri and Dhok Pathan formations overlies Rawalpindi Group. Soan, Lei formations and Kalabagh conglomerates are the most recent clastic deposits shed from the Himalayan Orogeny. Soan Formation unconformably overlies Dhok Pathan Formation (Figure 1.4).

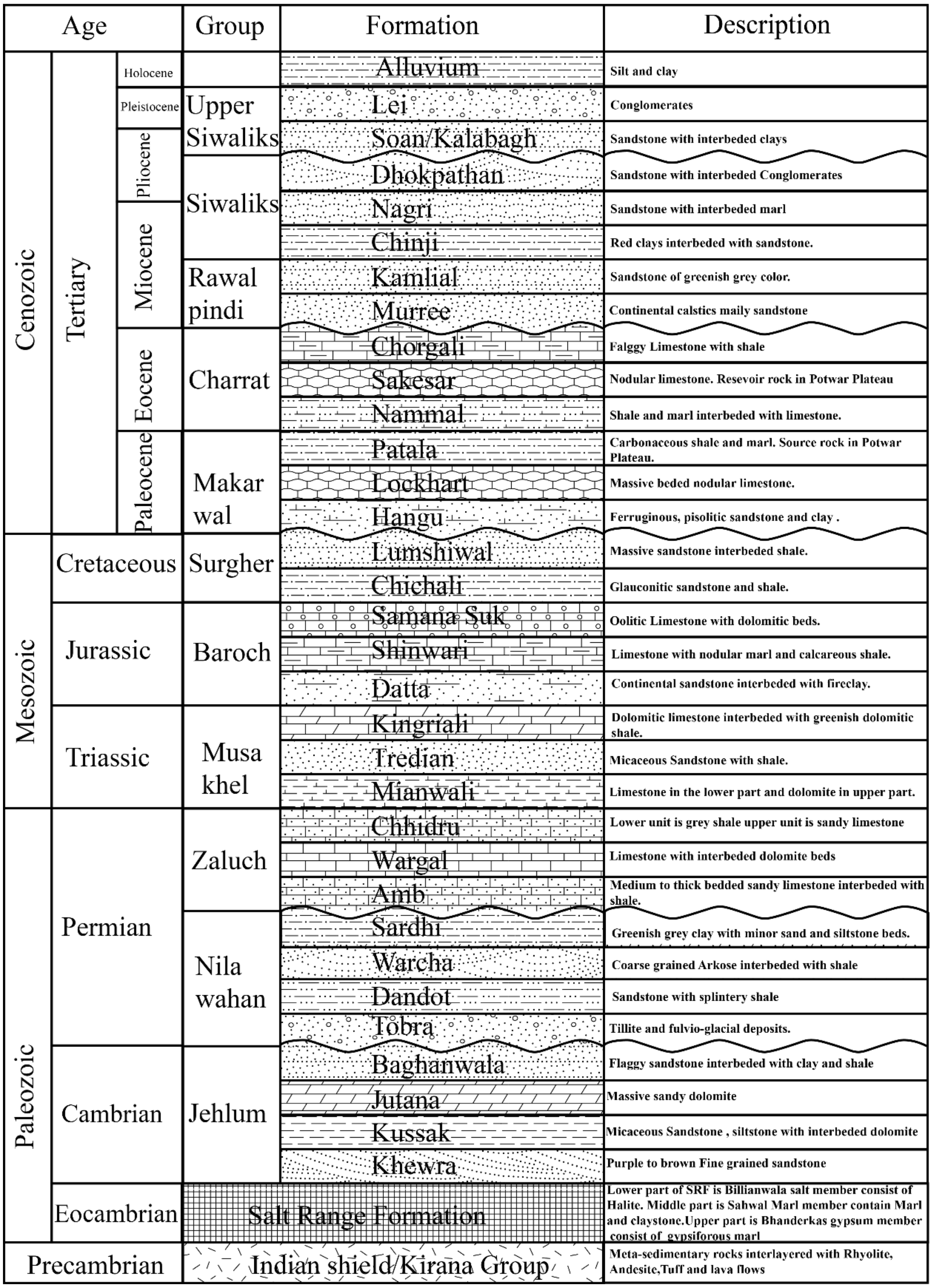


Figure 1. 4 Lithostratigraphic units exposed in and around the Potwar Plateau and the Saltrange (Modified from Gee, 1989).

1.2 Structural Divisions

The Himalayan NW frontal thrust system in the Potwar Plateau and the Saltrange is divided based on their structural characteristics and deformation styles into three parts. These include: (1) North Potwar Deformation Zone (NPDZ), which is characterized by footwall deformation of Main Boundary Thrust (MBT) prior to the development of the Potwar Plateau and deposition of Siwaliks (Figure 1.2). (2) Soan Syncline that include the youngest strata on top of the Potwar Plateau and (3) the Saltrange, a thrust belt in front of the Potwar Plateau (Cotton and Koyi, 2000) (Figure 1.2). Development of the tectonic wedge and its southward migration (at the footwall of MBT) results in the redistribution of salt from Saltrange Formation modifies deformation style in the Potwar Plateau (Jaswal et al., 1997), the Saltrange (Baker et al., 1988; Qayyum, 1991), and the eastern part of the Saltrange (Aamir and Siddiqui, 2006; Drewes, 1995; Gee, 1980; Pennock et al., 1989).

1.3 Tectonic Settings

Development of tectonic wedge due to shortening within the Potwar Plateau caused southward migration of the salt resulted in the development of the Saltrange high (Lillie, 1987). Further migration was blocked by normal fault steps within the basement that gave way to the ramping up and exhumation of the Saltrange Formation and deformation of overlying strata (Baker et al., 1988).

The basin infill includes Miocene to recent molasse sediments while thrusting exposed even older rocks. Phanerozoic clastics and carbonate sediments thrust over younger sediments. Distribution of the syn-tectonic deposits (Rawalpindi and Siwalik groups) provids narrow geochronological constraints on the timing and rate of deformation, Rawalpindi Group is however related to the initial stage of development of the Main Boundary Thrust (MBT) within the North Potwar deformation zone (NPDZ). Deformation in the Potwar Plateau and the Saltrange has started in the Late Miocene-Early Pliocene and continued until Recent. Previous paleomagnetic and magnetostratigraphic studies provide time frames for the tectonic events in the Saltrange and the Potwar Plateau (Burbank et al., 1996; Burbank and Beck, 1989; Johnson et al., 1986; Opdykes et al., 1979).

1.3.1 North Potwar Deformed Zone (NPDZ)

North Potwar Deformed Zone runs from MBT in the north to Khair e Murat Thrust in the south which is characterized by the imbricate duplex formed in the foot wall of the MBT (Treloar et al.,1992; Opdykes et al., 1979). Early Miocene sediments underwent horizontal shortening with the development of imbricate stacks (Jaswal et al., 1997) (Figure 1.3).

Although structures of the NPDZ show parallelism along strike but it is intensely deformed as compared to the Potwar Plateau. Eastern NPDZ is characterized by a buried thrust front under the Dhurnal Back Thrust; developes a triangle zone close to the northern limb of Soan Syncline whereas western NPDZ is characterized by emergent thrust front (Jaswal et al., 1997). Eastern segment of the NPDZ depicts the stacking mechanism of blind thrust under the passive roof thrust, which develop a triangle zone and syncline to the south of NPDZ (Banks and Warburton, 1986). In contrast, western NPDZ exhibits an emergent thrust front that developed faulted folds separated by wide synclines these faulted fold entrapped most of the petroleum in NPDZ.

1.3.2 Soan Syncline

Soan Syncline is present at the center of the Potwar Plateau. It is an asymmetrical syncline with almost vertical limb in the north (Dhurnal Back Thrust) while southern limb is gently dipping and terminates along Riwat Thrust (Gill, 1951). To the south of the syncline shortening is accommodated by the salt-cored anticline; (Aadhi) northern limb beds are terminated against sub-horizontal Soan Formation. Palemagnetic and radiometric dating suggest that the oldest post unconformable strata is of 3.7 Ma in age and the youngest pre-unconformable strata of the Dhok Pathan Pathan Formation is 5.1 Ma (Johnson et al., 1985). Soan Syncline formed due to the development of the secondary decollement at the upper level. The presence of salt weld below the Soan Syncline developed the depression in the center from where the Soan River flows. Subsurface structure of the Soan Syncline is however not as simple as surface expression. Northern limb is steeply dipping, the development of the Dhurnal Back Thrust with the progressive deformation eroded and deposited pile of sediments in the center of the Soan syncline, which seals the thrust as the sediments are deposited after the thrusting. Here, the oldest strata involved in thrusting is the Dhok Pathan

Formation, which brackets thrusting event post Dhok Pathan and pre-Soan Formation age (Early Pliocene). The southern limb is marked by the Riwat Thrust which is developed above the basement step.

1.3.4 Southern Potwar Plateau

Southern Potwar Plateau comprises area from the southern limb of the Soan Syncline (Riwat Thrust) to the Saltrange and is characterized by the development of broad syncline formed because of the salt removal where whole syncline sagged to develop the stratigraphic weld, or salt is completely squeezed out. The eastern and western margins of the Potwar Plateau are marked by the Jhelum sinistral fault to the east and the Kalabagh dextral fault to the west (Figure 1.2).

1.3.5 The Saltrange

The Saltrange is a positive area infront of the Potwar Plateau. It demarcates the southernmost Himalayan thrust front. Towards the east, the blind thrusts become dominant where the tip of the thrusts buried below the Pabbi anticline. The eastern Saltrange is dominated by a series of folds developed due to fault propagation folding. Along the southern border of the Saltrange the Himalayan Frontal Thrust becomes emergent along which salt is exhumed. Western Potwar Plateau and the Saltrange are characterized by the development of fault bend folds. Intial development of thrusting started about 5 M.yr ago and marked by the lack of rotation in the Soan Formation (Opdykes, N. D., johnson, 1979). The biostratigraphic data from the previous workers suggest that the deformation at the eastern and the western Saltrange are contemporaneous and took place sometimes between 6.3 M.yr and 4.5 M.yr (Burbank and Beck, 1989; Burbank et al., 1996).

1.4 Objectives of This Research.

The pervious workers consider the Potwae Plateau and the Saltrange as consistent zone as being a part of the northwestern Himalayan fornt (Burbank and Beck, 1989; Lillie, 1987; Opdyke et al., 1982; Opdykes, N. D., johnson, 1979; Pennock et al., 1989; Tauxe and Opdykes, 1982; Yeats and Thakur, 2008). However, certain factors develops the considerable difference in the structural style within the Potwar Plateau and the Saltrange. These factors are;1) Thickness and distribution of the decollement layer 2) Differential slip along the boundary faults of the Potwar Plateau and the Saltrange. The Potwar Plateau and the Saltrange is divided into sub domain based upon the consistent results of the analysis performed in the present study and the coherent structural style observed in the filed as well as in the subsurface.

The overall objective of this research is to determine the different stage of the tectonic development of the Potwar Plateau and the Saltrange. This overall objective is achieved by achieving following sub-objectives.

To determine Vertical axis rotation and its different episodes in the Potwar plateau and the Saltrange. In the case of the multiple episodes of rotations, age constrains of the rotation episodes must be determined in order to understand the rotational evolution of the Potwar Plateau and the Saltrange.

To determine the kinematic and structural development of the Potwar plateau and the Saltrange.

To determine the variation of the structural style along the tectonic transport direction and lateral changes from east to the west of the Potwar plateau and the Saltrange.

To determine the shortening rate and rete of deformation migration and its comparison to the regional tectonics.

1.5 Approach Taken

Present thesis integrates the various geological and geophysical data sets. Field data set and field observation serves as the base of the present study that involves the characterization of the faults and the involved stratigraphy, stratigraphic relationships and the observed changes within stratigraphy and their tectonic relationship. Moreover, these filed observations are extended to develop the subsurface section by using seismic profiles and various well log data sets. Subsurface section are restored to determine the amount of shortening within the Potwar Plateau and the Saltrange. Rotational deformation about vertical axes is determined by using the paleomagnetic studies that result in the sense and amounts of rotation in different parts the Potwar and the Saltrange.

1.6 Organization of Thesis

This thesis contains 5 chapters. First chapter consist of introduction to the study area, which serves as basis for the rest of the chapters. Chapter 2 consist of paleomagnetic results from sedimentary infill of Potwar Plateau Plateau and Salt range in order to determine Vertical axis rotation and their age constrains. Chapter 3 consist of kinematic and structural development of Powar Plateau and Saltrange carried out using the Plaeostress inversion and AMS studies and their comparison. Moreover, the temporal relationship of resultant deformation phases is established using filed and seismic data. Chapter 4 combines all the surface data and results obtained in chapter 2 and 3 to construct the Blanced cross section using Seismic data, well data, Geological maps and data obtained during field excursions. These balanced sections are restored to the pre-deformaiton state and compared with each other in order to establish a relationship between the deformation style and its lateral variations. Chapter 5 comprises of comparison of all the obtained results and their relationship with each other along with Tectonic and geological implication of results and their interdependency. Moreover, regional implications of the determined results are discussed in this chapter.

CHAPTER 2

ROTATIONAL EVOLUTION IN NW-HIMALAYAN FRONT, POTWAR PLATEAU AND SALTRANGE, PAKISTAN

2.1 Introduction

Miocene to recent deposits have the records of Himalayan Orogeny in the NW Himalayan front. This region is tectonically active and Indian-Eurasian plates have converged up to 3600 ± 35 km since 52 My (van Hinsbergen et al., 2012) with an average rate of 45 mm/year (Bilham, 2006). It is expressed by a sequence of south-verging thrusts over the Indian Craton. The Saltrange and the Potwar Plateau are the expressions of NW Himalayan front that developed over a salt decollement on which the rocks above salt to ride over and thrust against Punjab plains (Crawford, 1974; Seeber et al., 1981; Jaume and Lillie, 1988). Presence of normal faults in the units above the decollement horizon are the results of local extension developed due to escape of salt towards frontal thrust (Baker et al., 1988).

The eastern margin of the Potwar Plateau is marked by the Jhelum strike-slip fault and Hazara Kashmir syntaxis, a syntaxial bend developed because fold and thrust belt modify its trend to less broader thrust sheet creating relatively narrow zone of thrusting and higher tapper angle in India (Davis and Engelder, 1985). It suggests lateral thinning of the salt layer from west to east (Pennock et al., 1989). Transpressive right-lateral strike-slip fault marks the western margin of the Saltrange and the Potwar Plateau (Gee, 1989) known as Kalabagh Fault, which developed as lateral ramp as a response to variably distributed salt thickness (Cotton and Koyi, 2000). Presence of salt in the substrate and the absence of major earthquakes along the Kalabagh Fault imply that motion along this fault is mostly taken upby an aseismic creep (Khan et al., 2012). Northern boundary of the Potwar Plateau is marked by the MBT of Himalayas and deformation in its footwall is marked by the NPDZ (Figure 2.1).

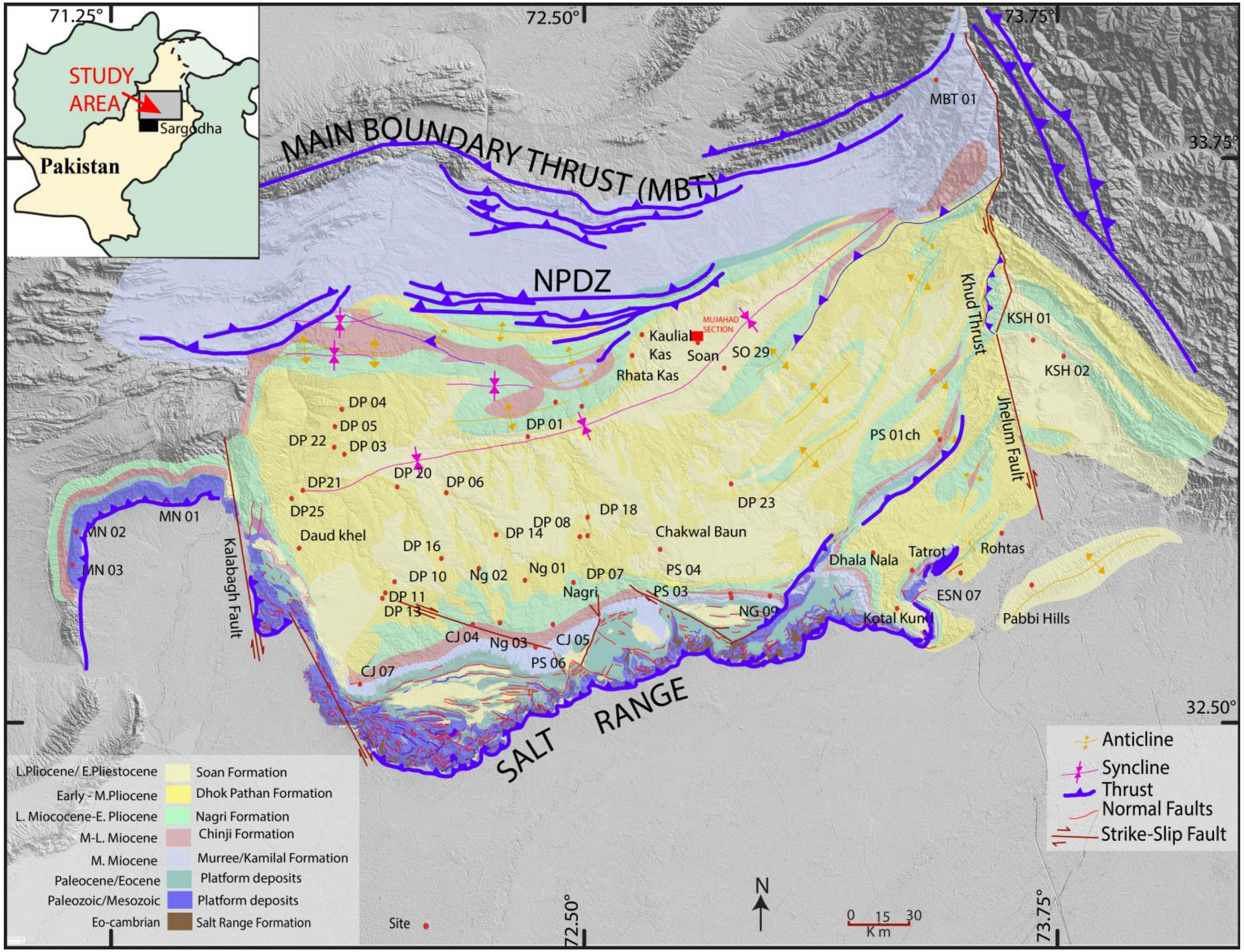


Figure 2. 1. Geological map of the Saltrange and the Potwar Plateau with Paleomagnetic sampling sites.

The Himalayan frontal thrust system can be divided, based on the different characteristics of deformation style, into three parts. NPDZ, Soan Syncline and, the Potwar Plateau and the Saltrange (Cotton and Koyi, 2000). NPDZ is characterized by an imbricate duplex formed in the foot wall of the MBT (Jaswal et al., 1997). Soan Syncline is present in the middle of the Potwar Plateau, it is an asymmetrical syncline with almost vertical limb in the north while southern limb is gently dipping and terminates along Riwat Thrust (RT) (Figure 2.1). Soan Formation (Late Pliocene-Pleistocene) is present in the core of the Soan Syncline overlies the older units by angular unconformity. The Saltrange ramped over a north dipping basement normal fault hence further migration was interrupted and the salt and its roof strata ramped to the surface (Baker et al., 1988).

Basin infill of the Potwar Plateau comprise Miocene to recent molasses deposited on Precambrian to Oligocene clastics and carbonates. Regional distribution of the syn-tectonic units (Rawalpindi Group and Siwalik Group) provides precise geochronological constraint on the timing and rate of deformation.

Previous paleomagnetic studies that provide temporal constraints on the tectonic events in certain locations of the Saltrange and the Potwar Plateau include Burbank et al. (1996); Burbank and Beck (1989), Johnson et al. (1986), Johnson et al. (1986), Opdyke et al. (1982), Tauxe and Opdyke (1982). Our work combine newly collected data from the Miocene to Pliocene molasses deposits exposed in unexplored parts of the Potwar Plateau and the Saltrange. We also collected data from the surrounding syntaxes and re-entrants of the Potwar Plateau and the Saltrange in order to test if these areas results from oroclinal bending. Additionally, a magnetostratigraphic analysis of the Soan Formation in its type section is carried out to provide high precision age constrain on the deformation events.

2.2. Methodology

2.2.1. Sampling

Two different sampling techniques were performed. Sampling for determination of vertical axis rotations in different parts of the Potwar Plateau was performed in 56 sites. For this purpose in general 10 to 15 samples from each site were collected, totalling 871 samples. Sampling for magnetostratigraphic analysis was carried at out from the Soan Formation. The sampling at the lowermost part of the Soan formation started at Mujahad village (Figure 2.6). Then, we followed a traverse perpendicular to the strike of the Soan Formation. From each level, at least 3 samples were collected. The position of each sample site was recorded with a GPS. 140 samples were collected from 28 levels in order to date 862 m thick section.

Samples are collected using both gasoline powered and battery powered drill machine. Battery powered drill machine is preferred for more fragile and less compact sediments. Samples were collected mainly from red mudstones. In the absence of fine sediments, samples were collected from sandy mudstones and/or muddy sandstones. Sample orientations are measured using magnetic and sun compass. All the sampling measurements are corrected for present day declination according to IGRF (International Geomagnetic Reference Field) which is 2° E in the study area. Samples were carefully numbered and packed in aluminium foils and transported to Utrecht University for the analysis.

2.2.2 Paleomagnetic Analysis

Samples were cut into 2.5 cm cube, each site is divided in two equal number of samples and demagnetized both by thermal and alternating field (AF method) in a succeeding demagnetization steps. For thermal Demagnetization, magnetically shielded oven is used with the demagnetization steps ranging from 20° to 50° C up to 680° C. After each demagnetization step, NRM (Natural Remnant Magnetization) is measured for each sample in 2G Enterprises horizontal DC-SQUID magnetometer. Alternating field demagnetization is carried out in robotized 2G Enterprises horizontal DC-SQUID magnetometer with in-line AF demagnetization and ARM/IRM acquisition with the demagnetization steps from 5 to 20 mT up to maximum 80 mT.

Magnetic carrier minerals are determined by thermomagnetic runs using ultrasensitive horizontal translation Curie balance (Mullender et al., 1993). Rock sample is powdered and placed in the glass container. The quartz wool blocks the nose of the container in order to keep the sample intact. Maximum 70 mgs of the powdered sample is used for the analysis. Temperature is raised successively up to 700°C with heating and cooling rate of 10°C. Instrument has a sensitivity of 5 × 10¯9 Am2. Magnetic carrier minerals for each formation is determined and utilized while interpreting the demagnetization diagrams (Figure 2.2)

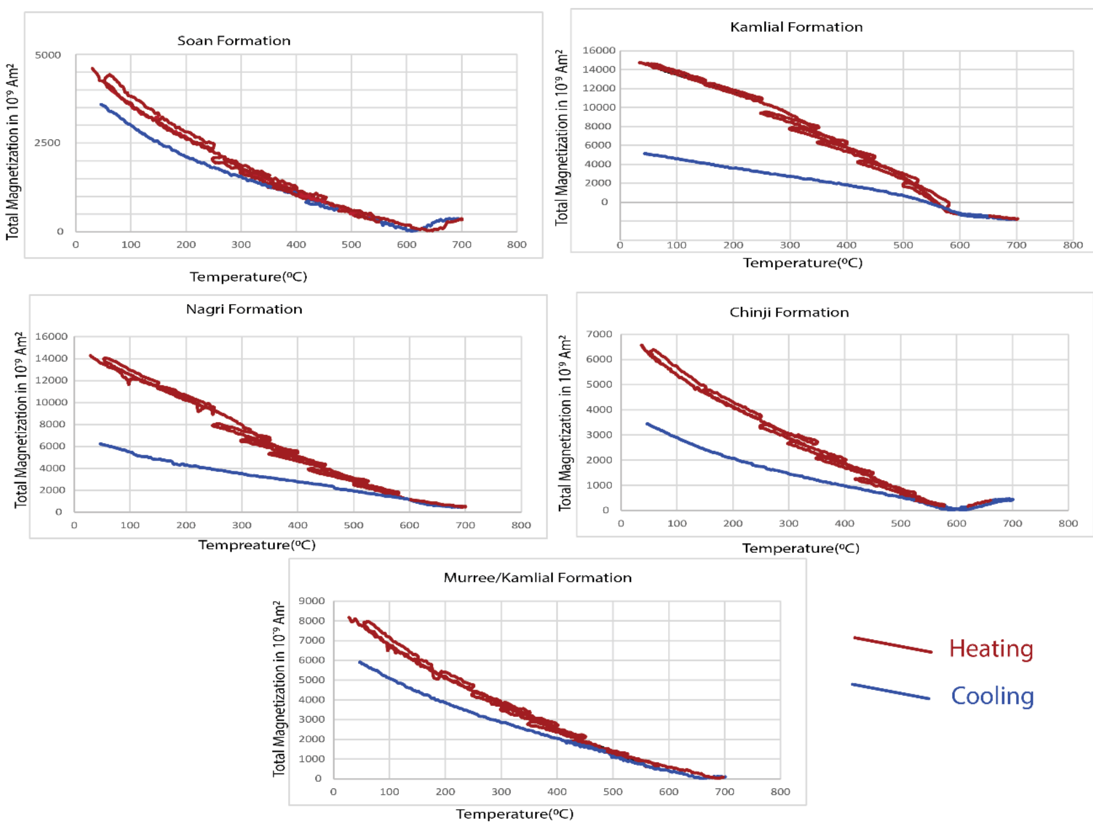


Figure 2. 2. Curie balance results of samples collected from various formations. Heating (Red curve) and cooling (Blue) curves are plotted against temperature and Total Magnetization.

Orthogonal vector diagrams are used to determine Natural Remnant Magnetism (NRM) (Zijderveld, 1967). Successive demagnetization steps (generally five or more) were considered to determine the CHRM directions, using eigenvector approach (Kirschvink, 1980), else samples with the partial over-print are resolved using great circle approach (McFadden and McElhinny, 1988) (Figure 2.3).

Due to the fact that paleomagnetic direction are induced by the secular variation of the earth's magnetic field are ellipsoid at equator and circular at poles, (Tauxe and Kent, 2004). Site mean for each sampling site is determined along with virtual geomagnetic pole (VGP). Corresponding error in inclination (ΔI_x) and declination (ΔD_x) is also determined following Butler (1992). Cut-off value of 45° is used to assess VGP distributions are attributed to paleosecular variations within N-dependent reliability envelope. A reversal test is also carried out in order to evaluate in case two distributions have a common true mean (McFadden and McElhinny, 1988).

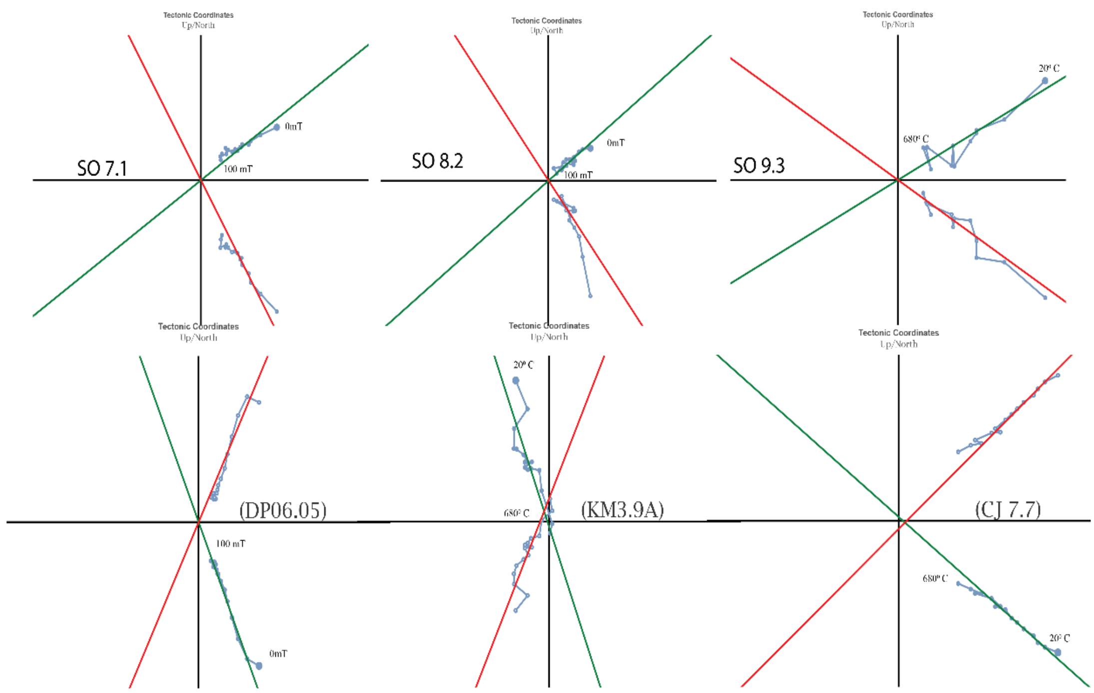


Figure 2. 3. Examples of orthogonal vector diagrams are shown in tectonic coordinates.

For all analyzed specimens 16 successive demagnetization steps up to 680° C are applied. These steps start at 50 °C and goes up with 30°-50°C increments. For AF, starting from 5 mT, 15 successive demagnetization with 5-10 mT increments are applied up to 80 mT. Natural Remnant Magnetism (NRM) for each sample is measured after each demagnetization step. Samples are pre-heated up to 150° C before AF run in order to get rid of secondary present day field component or viscous component in the case of thermal initial demagnetization steps are not considered.
Demagnetization of samples from each Formation (Miocene-Palistocene) indicates that magnetic carrier minerals are mostly either magnetite or hematite as evident from thermomagnetic runs using Curie balance (Figure 2.2).

2.3 Analysis of Vertical Axis Rotations

The paleomagnetic results are analyzed according to their spatial characteristics. In addition to our results, reliable data from the literature are also combined with our results. First, all data are grouped according to which tectonic domain they belong. These domains are; 1) The Potwar Plateau and the Saltrange and 2) neighbouring domains (Figure 2.4).

2.3.1. The Potwar Plateau and the Saltrange (PPS) Domain

The results in the PPS (Figure 2.4) revealed that there are a number of sub domains of consistent rotations. Using these coherent rotations, the PPS is divided into supposedly semi-rigid sub domains (Figure 2.5). In addition to the analysis of individual site, we have also determined a common rotation amount for each sub domain by gathering all the sites within a sub domain. The common results are considered to represent an average rotation amount of the sub domain (Figure 2.5). From west to east, the results of each sub domain are presented below.

The Nammal sub domain is the western most lock in the study area. It contains three sites. One of the sites shows a reverse polarity while the other two sites have normal polarity. The results of the Kamlial Formation is -33.1°±6.5 (Middle Miocene) while younger rocks of the Dhok Pathan Formation (Early-Middle Pliocene) reveals 12.6°±4.2° CCW of rotation. Dhaud khel site is adopted form Opdyke et al. (1982); it shows 17.8° of CCW rotation. Since the ages of the samples are not known in Dhaud khel site, it is not included in the rotation age calculations.

Combined analysis of the three sites, after converting the reverse polarities to normal, indicate that the Nammal Sub domain underwent a counter-clockwise (CCW) rotation of 21.9°±5°.

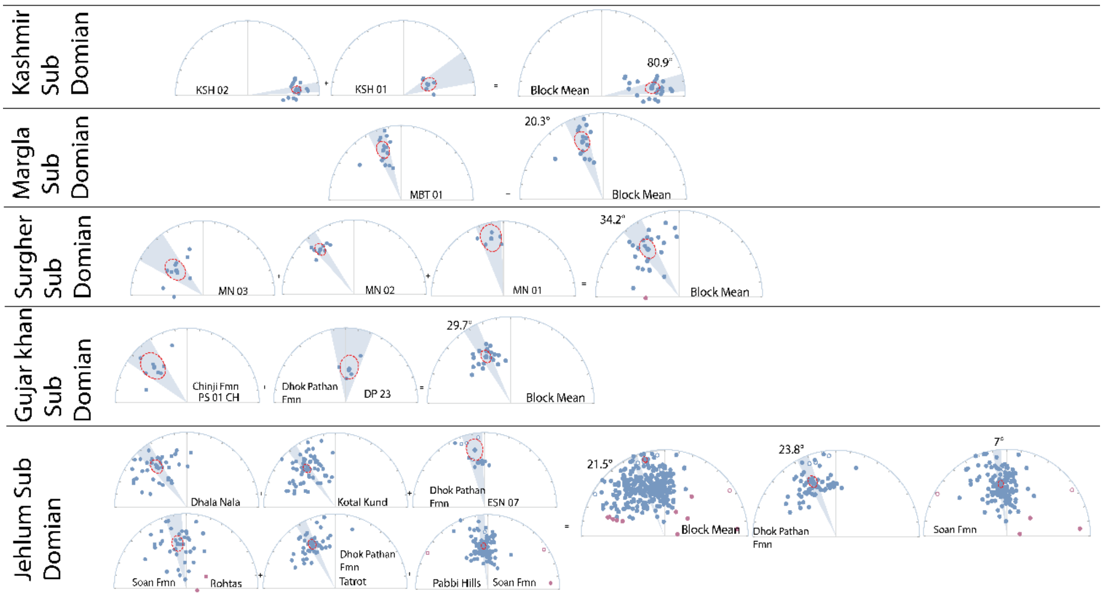


Figure 2. 4. Characteristics remnant magnetization diagrams (ChRM) of each site, combined to develop a sub domain of similar vertical axis rotations.

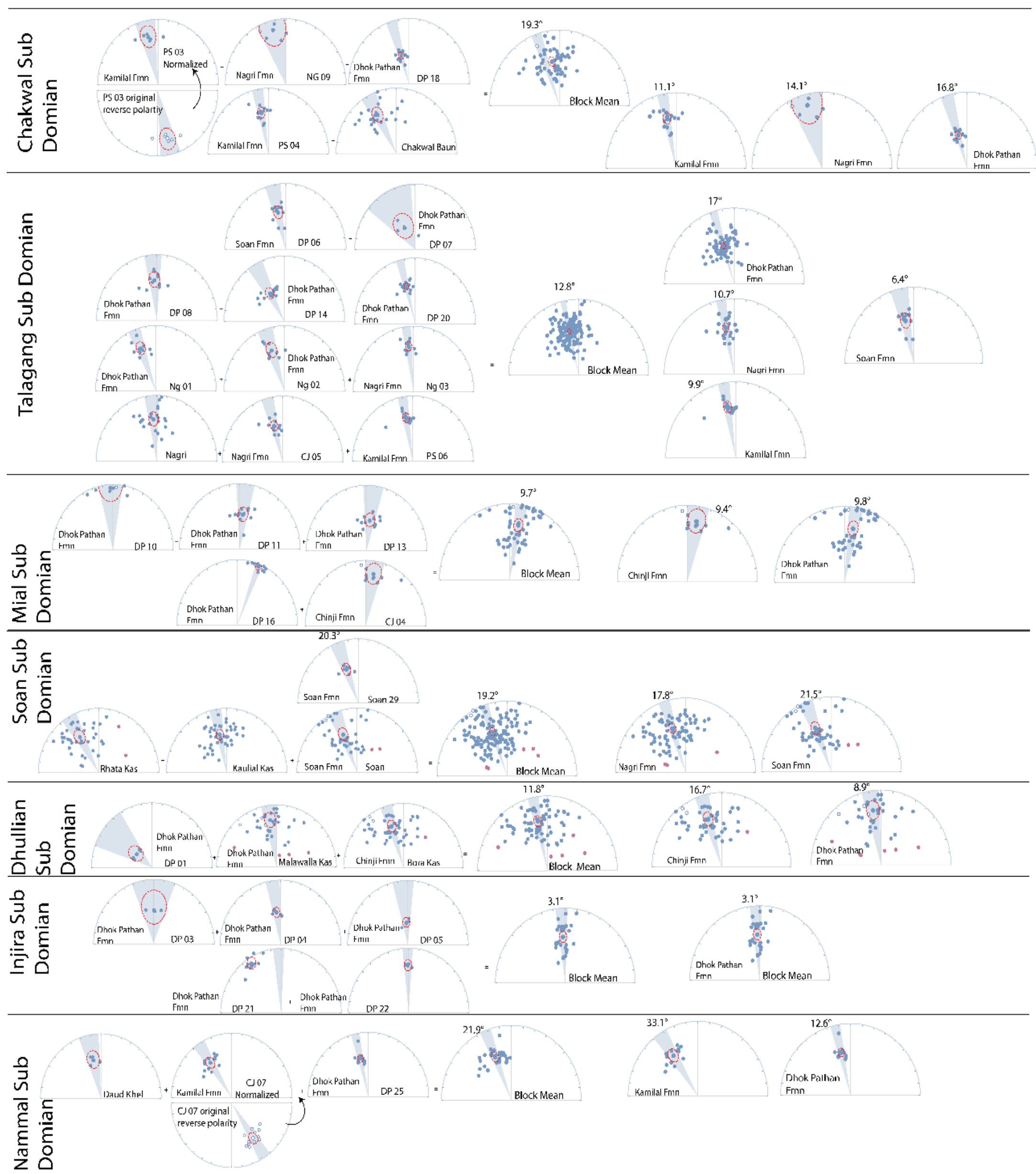


Figure 2. 4 (continued)

Table 2. 1 Plaeomagnetic results of each sub domain and episodes of rotations.

Name	mDec	mInc	k	α95	K	A95	A95min	A95max	ΔDx	ΔIx	λ
Nammal Sub Domian	338.1	38.2	39.8	4.3	36.9	4.5	3.1	9.8	4.8	6.4	21.5
Injira Sub Domain	356.9	38.5	21.7	5.9	32.8	4.7	3.1	9.8	5.1	6.7	21.7
Dhullian Sub Domain	345.9	31.2	11.1	5	14.2	4.3	2.1	5.2	4.5	6.9	16.9
Mial Sub Domain	9.7	27.6	10.9	6.3	17.3	4.9	2.5	6.8	5.1	8.2	14.7
Talagang Sub Domain	347.2	39.3	27.9	2.3	28.9	2.3	1.7	3.7	2.4	3.2	22.3
Chakwal Sub Domain	340.7	36.4	17.4	4.5	21.1	4.1	2.3	6.2	4.4	6	20.3
Soan Sub Domain	338.5	38.1	11.3	6.5	15.2	5.5	2.6	7.3	5.9	7.9	21.4
Gujar khan Sub Domain	330.3	44.8	10.5	13.4	8.7	14.9	4.3	16.3	16.7	18.7	26.4
Jehlum Sub Domain	338.5	36.1	13.8	2.3	15.3	2.2	1.3	2.4	2.4	3.3	20.1
Surghar Sub Domain	325.8	34.3	17.1	7.4	17.8	7.2	3.4	11.1	7.6	11	18.8
Kashmir Sub Domain	80.9	39.2	26.2	5.9	29.3	5.6	3.4	11.1	6	7.8	22.2
Margalla Sub Domain	339.7	29.7	21.9	8.7	35.8	6.7	4.2	15.6	7	11	15.9
First episode of Rotation	338.7	37.3	17.1	1.9	18	1.8	1.2	2.1	2	2.7	20.9
Second episode of Rotation	352.6	39.9	19.2	2.8	23.7	2.5	1.7	3.7	2.8	3.5	22.7

(mDec) is mean declination, mInc is mean inclination, (k): estimate of the precision parameter determined from the ChRM directions, (a95): cone of confidence determined from the mean ChRM directions for in situ and tilt corrected data , K : precision parameter determined from the mean virtual geomagnetic pole directions (VGPs), (A95): cone of confidence determined from the mean VGP direction, A95min / (A95max): minimum / (maximum) value of the A95 for the given dataset. , (Dx) / (Ix): errors in declination / (inclination) determined from the A95 of the poles, (λ): paleolatitude.

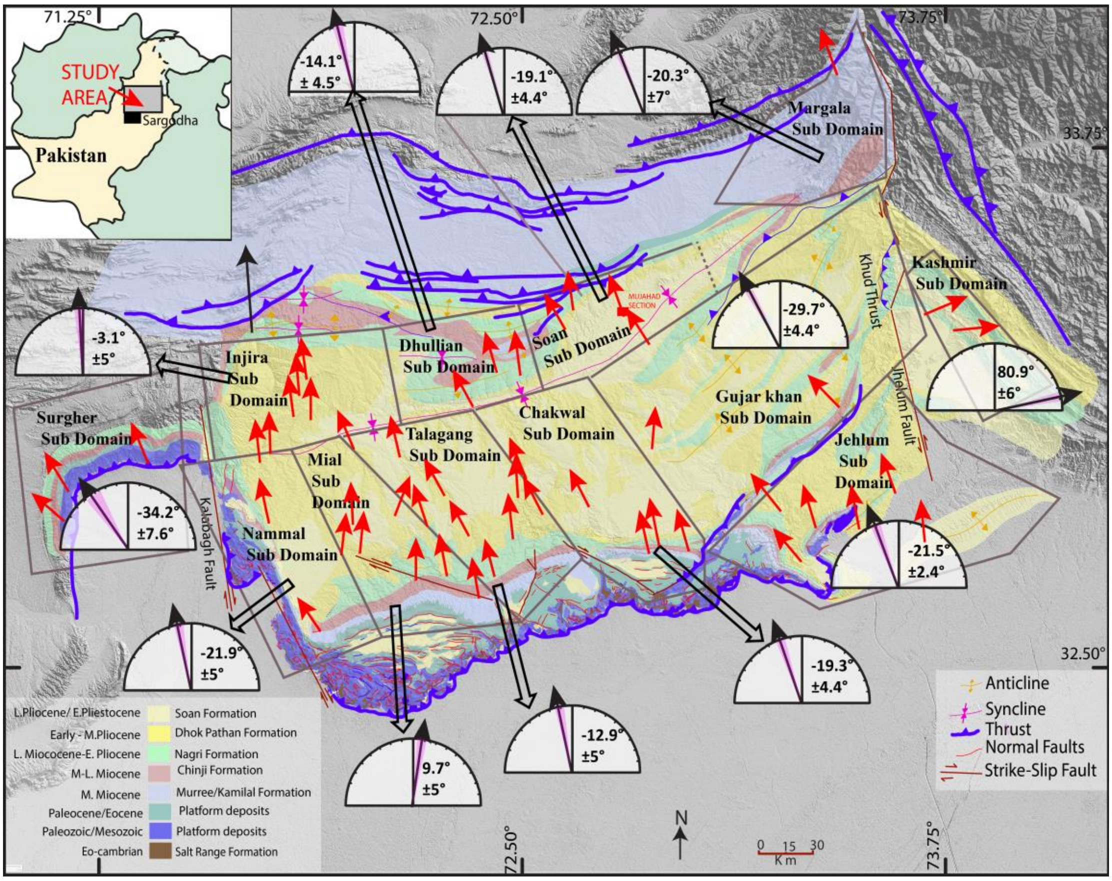


Figure 2. 5. Rotation vectors (red arrows), Sub domain boundaries and mean rotation vectors for each sub domain is illustrated over geological map of the study area.

Injira sub domain is western-most sub domain in the study area to north of Nammal sub domain. It contains five sites from Dhok Pathan Formation (Early-Middle Pliocene);all of samples revealed normal polarity and most of the samples shows CCW rotation. Mean declination of all samples suggests that Injira sub domain underwent counter clockwise rotation of -3.1°±5°.

Dhullian Sub domain is adjacent sub domain with Injira sub domain it contains 3 sites in total. Two site adopted from the literature (Tauxe and Opdykes, 1982) and one site is sampled during the present study. All samples contain normal polarity and most samples shows CCW rotation. Mean declination of all samples shows that Dhullian sub domain underwent counter-clockwise rotation of -14.1°± 4.5°. Two formation were sampled from the Dhullian sub domain. Chinji Formation (Middle-late Miocene) shows -16.7°±6° of vertical axis rotations while Dhok Pathan Formation (Early-Middle Pliocene) shows -8.9°±7.3° vertical axis rotations.

Mial sub domain contains five sites. All of the sites show normal polarity. Most samples are consistant with CW rotations. Averaging all samples suggests that Mial sub domain underwent a clockwise rotation of 9.7°±5°. This is the only sub domain, which suggests net clockwise rotation. Dhok Pathan Formation underwent 9.8±6° and Chinji Formation underwent 9.4±9° of clockwise rotation (Figure 2.4).

Talagang sub domain contains twelve sites. Eleven sites are collected during the present study and Nagri site is from literature (Opdyke et al., 1982). All the samples have normal polarity and most reveals CCW rotations. Mean declination of all samples suggests that Talagang sub domain underwent counter-clockwise rotation of -12.9°±5°. Kamlial Formation (Middle Miocene) underwent CCW rotation of -9.9°±4°, younger unit Nagri Formation (Late Miocene-Early Pliocene), underwent CCW rotation of -7.6°±4.2°, Dhok Pathan Formation (Early-Middle Pliocene), shows CCW rotation of -17°±3.3° and Soan Formation (late Pliocene-Early Pleistocene), shows CCW rotation of -6.4° ±7.5°. Literature site Nagri is not used as calculation of rotation ages due to lack of sample age (Figure 2.4).

Chakwal sub domain consists of five sites. Four sites are collected durring the present study Chakwal-Baun and is from literature (Opdyke et al., 1982). All samples have normal polarity and most samples shows CCW rotations. Mean declination of all the samples suggests that Chakwal sub domain underwent counter-clockwise rotation of -19.3°±4.4°. Samples from the Kamlial Formation (middle Miocene) has gone through CCW vertical axis rotation of -11.1°±4.7° whereas Nagri Formation (Late Miocene - Early Pliocene) went through CCW rotation of -14.1°±14.4°. Dhok Pathan Formation (Early-Middle Pliocene) which went through CCW rotation of -16.8 °±4.8°. Chakwal/Bhaun is not included in rotation age calculations as it also contains samples from both Dhok Pathan and Soan formations (Figures 2.4 and 2.5).

Soan Sub domain is the northeastern sub domain in the study area and it consists of four sites. Two sites are adopted from the literature (Tauxe and Opdykes, 1982) and two sites are sampled during present study in Mujahad village. Samples contains both normal and reverse polarities. Mean declination of all samples suggests that Soan sub domain underwent counter-clockwise rotation of -19.1°±4.4°. Two locations from litrature (Tauxe and Opdykes, 1982) are from the Nagri Formation and reveals -

17.8°±4.9° of CCW rotation. Site taken from the Soan Formation (Late Pliocene) shows -21.5°±5.9° CCW rotation (Figures 2.4 and 2.5).

Gujar khan sub domain is the eastern most sub domain in the study area and consists of two sites. Both sites shows normal polarity. Mean declination of all samples suggests that Gujar khan sub domain underwent CCW rotation of -29.7°±4.4°. Samples are from the Chinji Formation (Middle-Late Miocene) which reveals 43.9°±12.7° of CCW rotation whereas Dhok Pathan Formation (Early-Middle Pliocene), shows 4.8°±17.2° of CW rotations (Figures 2.4 and 2.5).

Jhelum sub domain in the south eastern sub domain in the study area which consists of six sites; five are adopted from the literature (Opdyke et al., 1982). Most samples have normal polarity and reveals CCW rotations. Mean declination of all samples suggests that Jhelum sub domain underwent counterclockwise rotation of -21.5°± 2.4°.Samples from the Dhok Pathan Formation(Early -Middle Pliocene) shows -23.8°± 4.3° CCW rotation and while Soan Formation(Late Pliocene) exhibits -7°± 2.9° CCW rotation (Figures 2.4 and 2.5).

2.3.2 Neighbouring Domains

The paleomagnetic domains outside the Potwar Plateau and the Saltrange include Surgher Range, Kashmir and Margala sub domains.

Surgher sub domain is located west of the study area; three sites were collected in the Surgher sub domain and all samples have normal polarity. Mean declination indicates that Surgher Range underwent counter-clockwise rotation of -34.2°± 7.6° (Figures 2.4 and 2.5).

Kashmir sub domain is located east of study area, and contains two sites. Both sites show normal polarity and most samples indicate clockwise rotation. Mean declination of all samples suggests that Kashmir sub domain has underwent 80.9°± 6° of clockwise rotation.

Margala sub domain is located in the north east of study area includes one site. All samples show normal polarity and CCW rotations. Mean declination of all samples suggests that Margala sub domain underwent CCW rotation of -20.3°± 7° (Figures 2.4 and 2.5).

2.3.3 Magnetostratigraphy.

Magnetostratigraphical study was carried out for the Soan Formation, which is the youngest deposits within the Potwar Plateau. This is important to obtain a better age control on dating the youngest deformation events.

Samples are collected from 28 levels of the Soan Formation at the northern flank of the Soan Syncline. The total thickness of the sampled section is 870 m (Figure 2.6), which implies an average sampling interval of 31m.

The results of magnetostratigraphic analysis are depicted in Figure 2.7 where Declination vs Inclination is plotted according to sampled horizons Normal polarity levels are indicated with black and reverse polarities as white. The horizons with uncertain polarities are shown in grey.

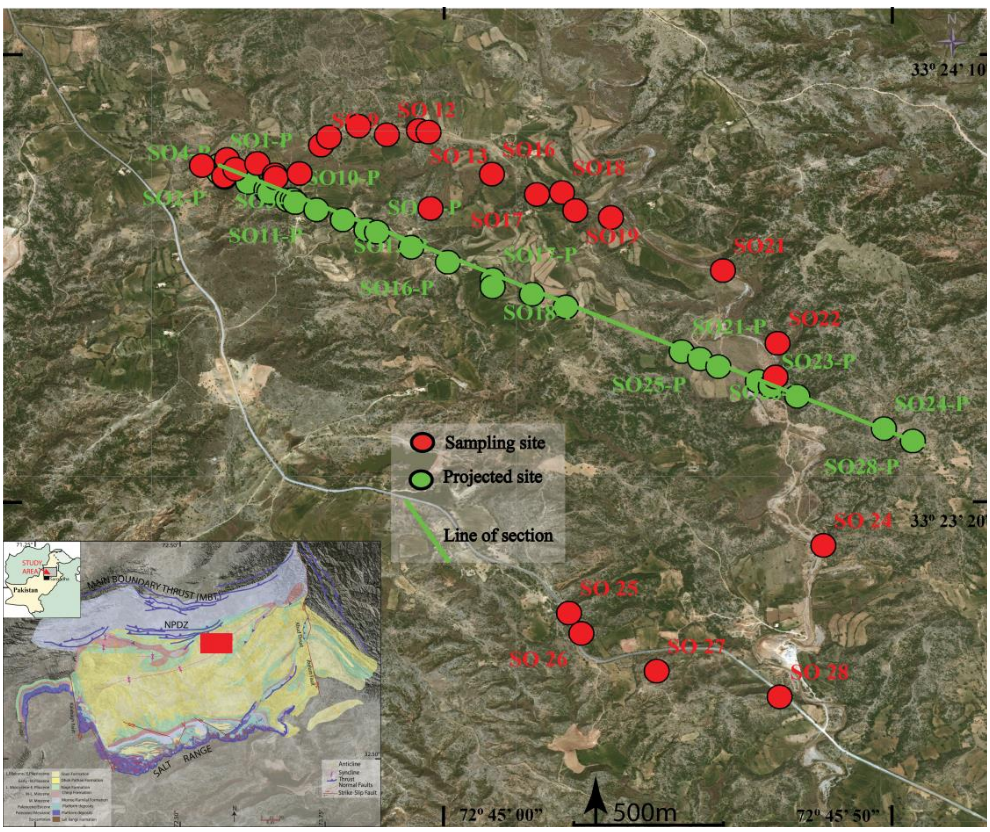


Figure 2. 6. a) Inset map showing the study area. b) Locations of magnetostratigraphic sampling sites. The positions of each site is projected to a straight line using the strikes of beds at each site.

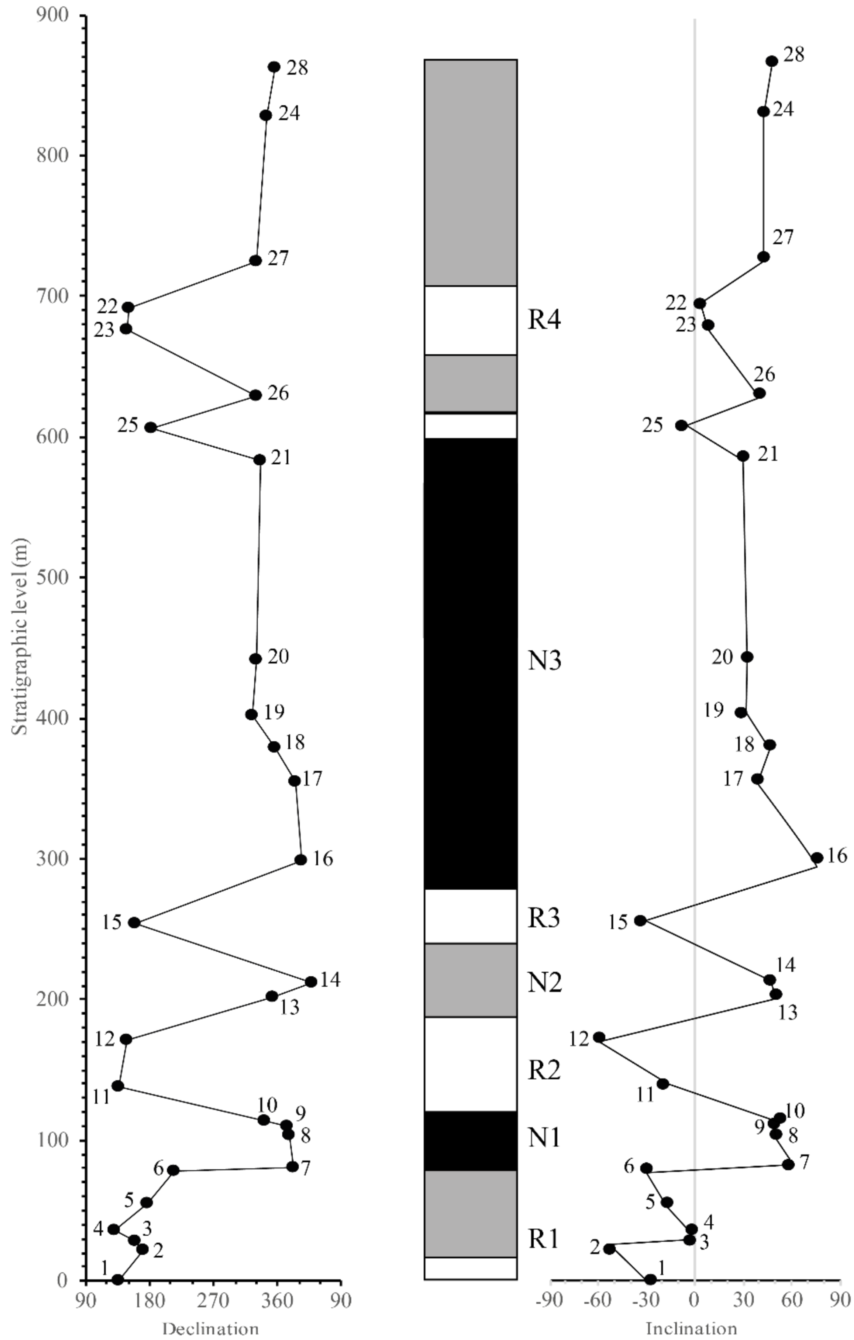


Figure 2. 7 Results of magnetostratigraphic analysis of the Soan Formation. Black levels are normal, white levels as reverse and grey levels indicate uncertain polarities.

2.4. Discussions

2.4.1 Vertical Axis Rotations

The Potwar Plateau and the Saltrange (PPS) are divided based on amount of rotations into various sub domains however overall rotation in the PPS is counter-clockwise (Figure2.12). Strikes against declination of the beds are plotted on the samples from the Potwar Plateau and Kashmir basin are also plotted on the samples. Results suggests that declination is changing with a change in strike: this fulfills the criteria to pass the orocline test (Pastor-Galán et al., 2017) (Figure 2.8).

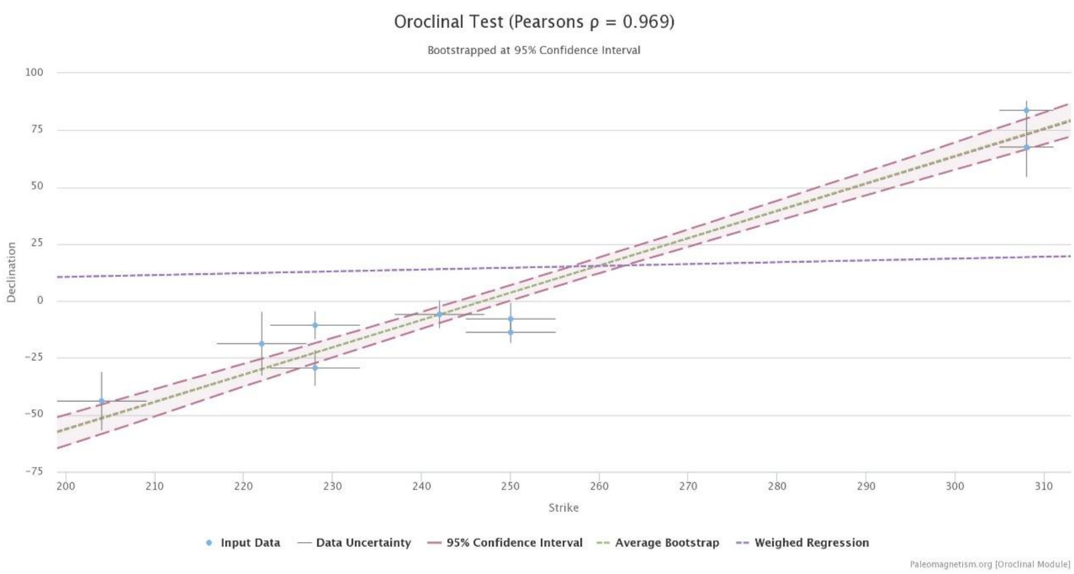


Figure 2. 8. Orocline test of the sites around the Potwar Plateau and in the Kashmir basin explaining how magnetic declination is changing with the change in strike.

Compaction in sediments causes the inclinations in the magnetic minerals to become shallow. We preformed the bootstrap on our sample in the Potwar Plateau and results suggests that inclination is around 48.5°. Expected inclination in the Potwar Plateau and the Saltrange is 51.5° that is fairly close to the bootstrapped results (Figure2.9)

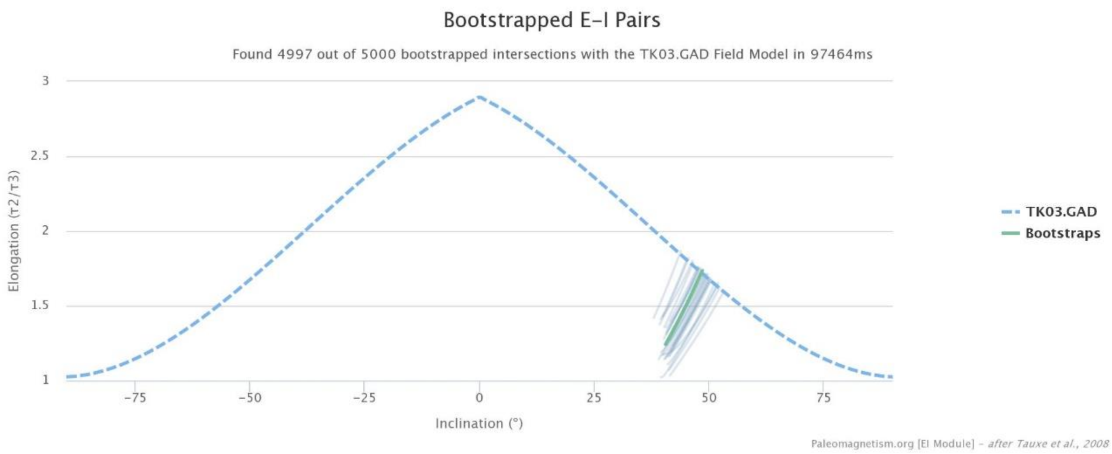


Figure 2. 9. Bootstrapped inclination of all samples in the Potwar Plateau. The resultant inclination is 48.5°.

Based on the analysis of each sub domain, two episodes of rotations are observed in the Potwar Plateau and the Saltrange. First episode is CCW rotation and has started in Middle Pliocene (Dhok Pathan Formation). Second episode is CCW rotation and has started in Pleistocene and continued until Present. First episode of rotation is recognized by the 10°-30° of CCW rotations and second episode 0°-7° of CCW. Second episode of rotations in Soan sub domain is well pronounced due to out of sequence reactivation of thrusts.

First episode of CCW rotation continued until the initiation of ramping along the Saltrange. Second episode of CCW rotation probably started after the Saltrange development (late Pliocene to Pleistocene).

According to Coulomb's fracture criteria, conjugate faults develop at ~30° from major principle stress axis (σ1) and mostly not stable during the deformation (Freund, 1970; Sylvester, 1988), their deformed state is V-shaped conjugate strike-slip faults as described by Yin and Taylor. (2011) . Two sets of V-shaped conjugate strike-slip faults , having a comparable slips initiated at the same time at an angle ~30° from the major principle stress axis (σ1) (Yin and Taylor, 2011) and continued unidirectional stress tend to rotate conjugate set of faults away from major principle stress axis in opposite directions (Garfunkel and Ron, 1985). Later stage regional vertical axis rotations develop their present day orientation of faults. (Dewey et al., 1989; Freund, 1970; McKenzie and Jackson, 1986)

Two sets of V-shaped conjugate strike-slip faults are identified in the Saltrange. First set consists of Kenhatti Fault and Pail-Vasnal Fault they are present between Mial and Talagang sub domains. Second set consist of Kalarkahar Fault and Krangal- Diljabba Fault (previously known as Krangal Diljabba thrust), and occure between Chakwal and Gujar khan sub domains (Figure 2.10). Ideally, if conjugate set of faults are initiated at the same time at almost same angle with comparable slips then they must also have comparable amount of rotation in opposite directions, which is the case in Kenhatti /Pail-Vasnal (Tapponnier and Molnar, 1976). V-shaped conjugate strike-slip faults occure between Mial and Talagang sub domains. Mial sub domain underwent CW vertical axis rotation of 9.7°± 5° and Talagang sub domain underwent CCW vertical axis rotation -12.9°±5°. On the other hand, in case of Kalarkahar /Krangal-Diljabba V-shaped strike-slip faults within the Chakwal Sub domain does not follow opposite direction of vertical axis rotation relationship. This is due to differential slip histories between different fault sets. First episode of regional CCW vertical axis rotations has resulted in net CCW rotation in the Chakwal sub domain.

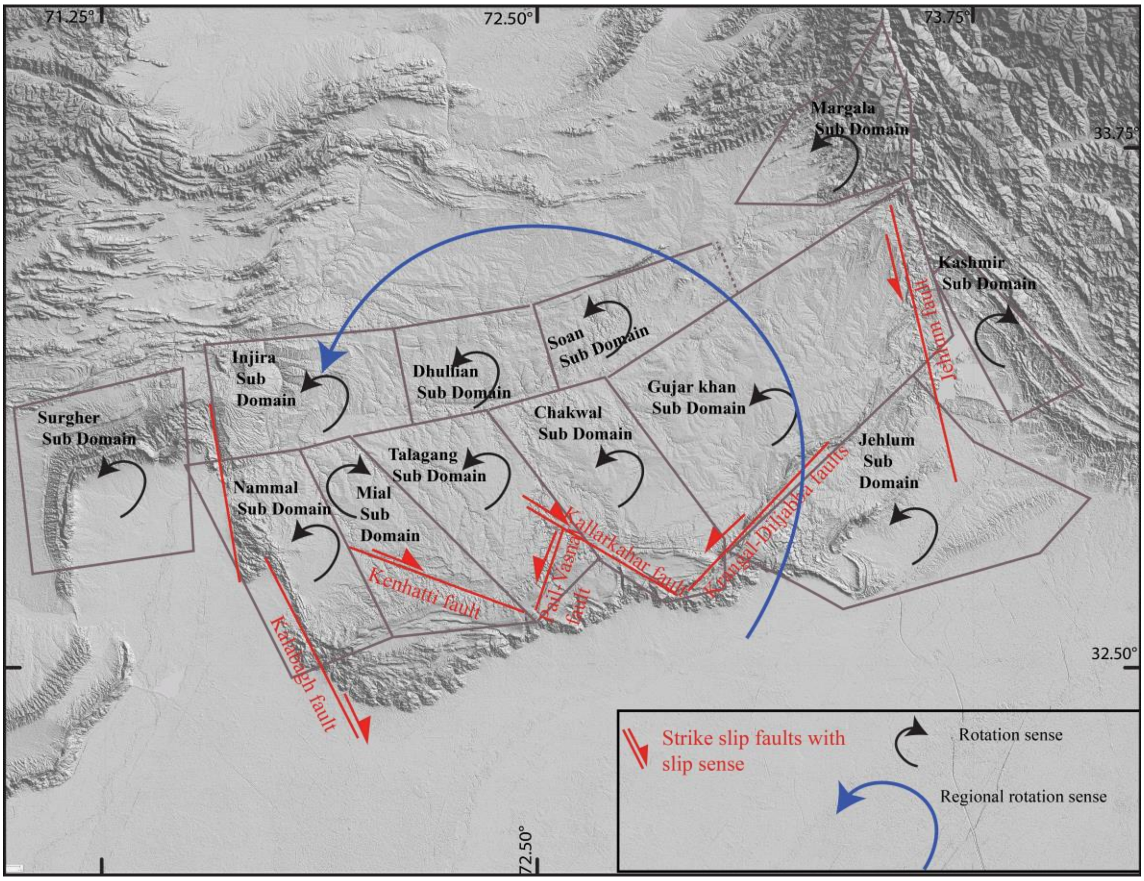


Figure 2. 10. Roatations in each sub domain and regional rotations.

A seismic slip along the Kalabagh Fault against relatively more brittle slip along the Jhelum Fault (Jouanne, 2014) developed a left-lateral shear zone in the Potwar Plateau and the Saltrange. This left-lateral shear zone, causes dominant CCW rotation in Middle Pliocene (Dhok Pathan Formation) during first phase of vertical axis rotations. These Middle Pliocene rotations resulted as CCW net rotations in the Potwar Plateau and the Saltrange. Except for the Mial sub domain which gives CW net rotations as rotation is accommodated as slip along Pail Vesnal and Kenhatti Fault developing net CW rotations in Mial sub domain due to different mechanical strength along each conjugate faults.

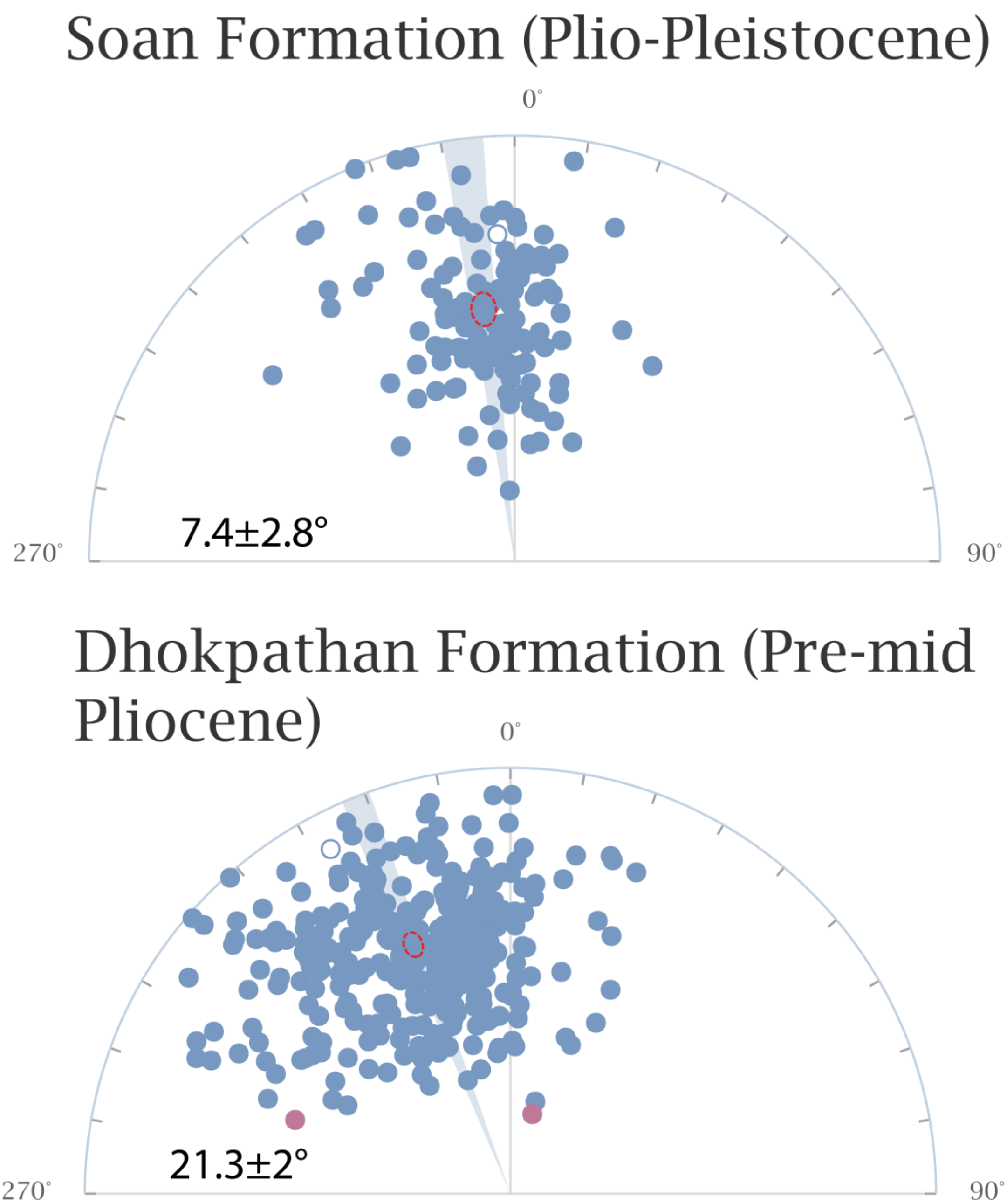


Figure 2. 11. Comparison of the first and the second episode of vertical axis rotations in the Potwar Plateau and the Saltrange. (Red hollow is mean CHRM, Red filled circles are rejected data points).

Jhelum sinistral fault developed as receding transition of ductile substrate into brittle Substrate towards east. While Kalabagh Fault developed due to abrupt lateral change in substrate from ductile in the Potwar Plateau and relatively brittle in Surgher range developing a Lateral ramp. First stage CCW rotation dominates and resulted as net CCW rotation in the Potwar Plateau and the Saltrange. Creation of tectonic wedge in the Potwar Plateau increased differential gravitational loading over the salt substrate resulting in migration of salt towards relatively stable region (south) in a squeezed way. Further migration is stopped by a basement step present below the Saltrange creating a closed system for a salt. At this point V-shaped conjugate set of faults develop along with the creating of initial suture along the Saltrange but exhumation of salt along the Saltrange was not initiated. First stage of rotation is associated with regional CCW vertical axis rotations when a left lateral shear zone developed between east and west due to differential slip over salt. These first stage Regional CCW rotations took place after (Early-Middle Pliocene) when Dhok Pathan Formation underwent CCW rotation and before end of Pliocene compared to second stage Soan Formation, which underwent very little rotation (Figure 2.12). We sampled Soan Formation for magnetostratigraphic studies in order to constrain the age first and second episode of rotations and its associated development of structures.

2.4.2. Magnetostratigraphy

Interpreted Magnetostratigraphic section of Soan Formation can be interpreted into two different possible scenarios in order to match paleomagnetic polarity time scale. Paleontological records and stratigraphic evidences suggests that the age of the Soan Formation is Late Pliocene-Early Pleistocene. This suggests that the total time span for the intiatian of Saon Formation deposition is around 3.5 My.

Correlation of our results with the geomagnetic polarity time scale (Hilgen et al. 2002) suggest that two possible scenarios can explain our data. In the first scenario all the grey areas in the R4 section and N2 are considered as reverse polarity while grey level in N1 are considered as normal polarity (Figure 2.13). In the second scenario N2 is considered as normal polarity and R4 is considered as reverse polarity.

Using this information our section is matched with the Geomagnetic Polarity Time Scale (Hilgen et al. 2002). Sedimentation rate for Saon Formation ranges between 29 to 86 cm/Kyr (Figure 2.13). Maximum sedimentation rate observed in Dhok Pathan Formation is 79 cm\kyr (Johnson et al., 1985). Interpreted magnetostratigraphic section presented in this study (Figure 2.12). Normal interval N3 have time span between 320 to 951 Kyrs. Only normal chron known of such length is C2An. 1n that is top Gauss. Below Gauss if N2 of our interpreted section is considered as normal, it will fit between Kaena and Mammoth chron, which is our option 2. The whole section would fit to Gauss (C2An) chron.

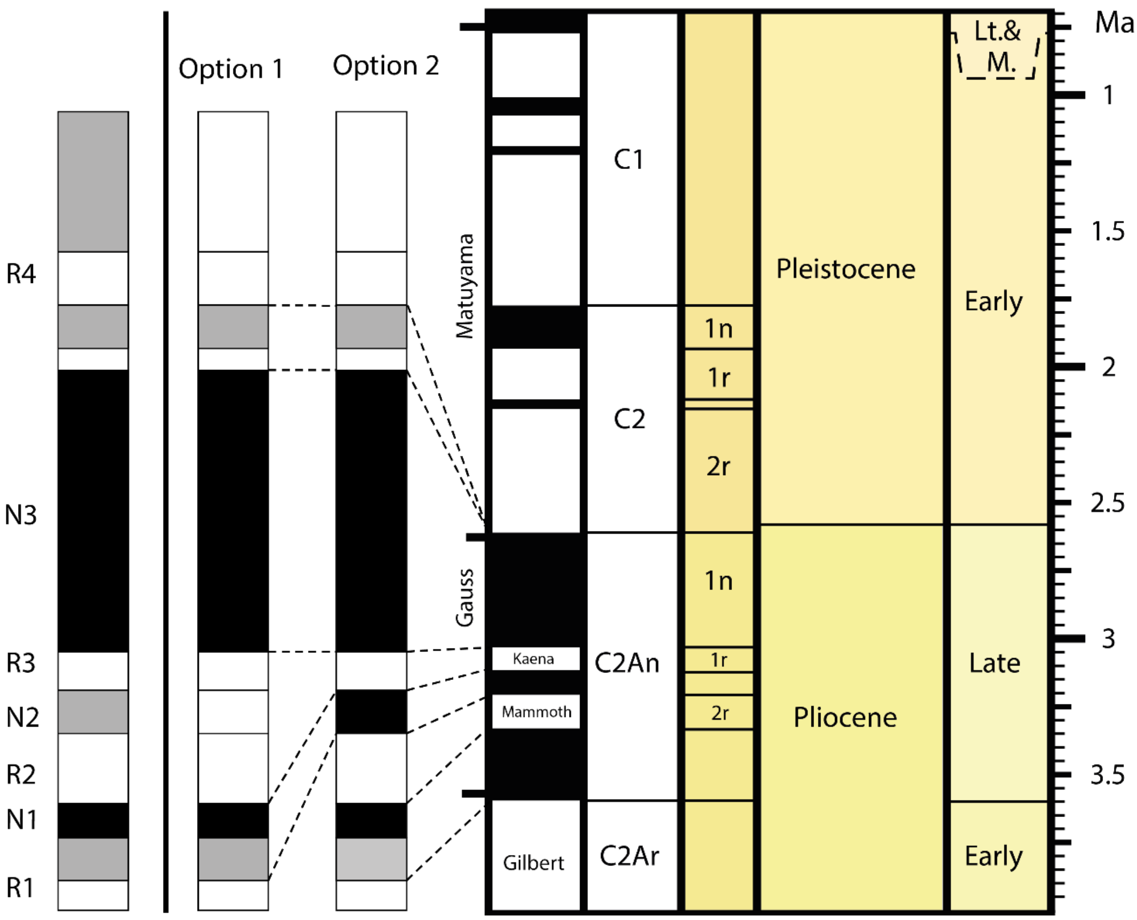


Figure 2. 12. Developed magnetic polarity chart along with two options for the possible correlation with magnetic time scale.

If it is considered as normal (option 1 & option 2) sedimentation rate will enormously increase which will not fit even with maximum sedimentation rate of Dhok Pathan Formation (Johnson et al., 1985). So the best fitting scenario determined as scenario 2 that gives us the maximum age of Soan Formation as 3.7 M.yrs.

Sedimentation rate is plotted against all two scenarios, which also resulted in the approval of scenario 2. Sedimentation rates for scenario 1 is not fitting with the thickness of Soan Formation. Only possibility to fit the sedimentation rate for scenario 1 is to increase it up to 190 cm/kyr for Gauss which is highly improbable. Our results indicate the sedimentation rate of around 40 cm/kyr at 3.5 Ma and observed increase in sedimentation rate in Gauss is 75 cm/kyr (Figure 2.13).

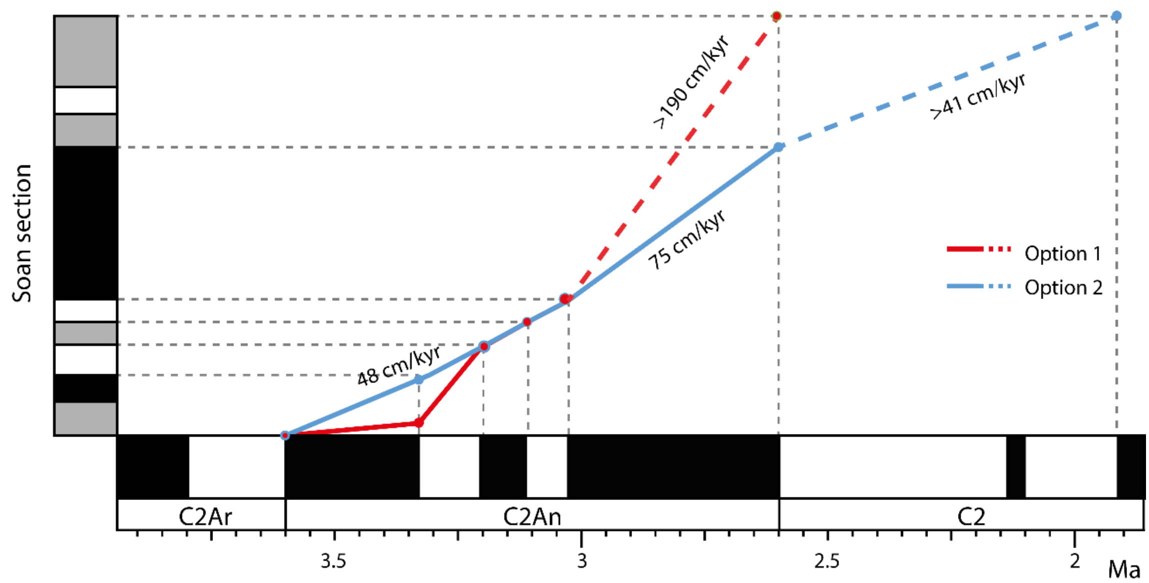


Figure 2. 13. Developed magnetic polarity chart of Soan Formation against the magnetic time scale.

The oldest part of Soan Formation is aged as 3.7 Ma and oldest part of Dhok Pathan Formation is Early Pliocene. Presence of major amount of rotation in Dhok Pathan Formation and absence of major vertical axis rotation in Soan Formation in the Potwar Plateau and the Saltrange (except for the out of sequence reactivation in Soan sub domain), suggests that thrusting of the Saltrange occurred before 3.7 Ma (Age of Soan Formation) and after 5.1 Ma (youngest age of Dhok Pathan Formation (Barndt et al., 1978; Johnson et al., 1985).

2.5 Conclusions

The Potwar Plateau and the Saltrange experienced major two episodes of vertical axis rotations. First episode of CCW rotations initiated at Early Pliocene and continued up to Middle Pliocene, which is the significant episode of rotation in the Potwar Plateau. Second episode of vertical axis rotation, which is CCW began at Late Pliocene (Figure 2.11)

Syntaxial bend present at the western margin of the Potwar Plateau and the Saltrange is Orocline and lateral ramp present at the western margin of the Potwar Plateau and the Saltrange developed due to already existing basement structure present at the frontal margin of Surgher range.

Oldest age of Soan Formation is found by the magnetostratigraphic technique is 3.7 M.yr and compression of vertical axis rotation between The Dhok Pathan Formation and the Soan Formation suggests that youngest possible age of the Saltrange thrust is 3.7 M.yr. Soan Formation demarcates the boundary between first and second vertical axis rotation episodes.

CHAPTER 3

KINAMATICS AND STRUCTURAL DEVELOPMENT OF THE POTWAR PLATEAU AND THE SALTRAGNE: A PALEOSTRESS INVERSION AND AMS STUDY

3.1 Introduction

The purpose of this study is unravel kinematic evolution of the Potwar Plateau during the Neogene. For this purpose, we have used paleostress inversion technique to decipher the paleostress history from the fault plane solutions.We used AMS technique (Ainstrophy of magnetic suceptability) for the areas where direct stress indicators (Fault planes) are absent. AMS is a technique that reveals favored adopted orientation of magnetic minerals under applied stress (Hrouda, 1982). It is thought that the magnetic minerals are re-oriented under stress after lithification process. AMS could also develop by means of other mechanism such as preferred orientation of sediments during deposition or magnetic flow etc. Therefore, care must be paid during sampling and make sure that the samples are not subject to sedimentation or cooling anisotropy, since the deformation in the study area is not intensive, we assume that there must be a correlation between stress and strain directions.

3.2 Geological settings

The Potwar Plateau and the Saltrange in NW Himalayas express present day deformation front of Himalayan orogeny (Figure 3.1). A detachment is developed over Indian shield in the Eo-cambrian evaporates of the Saltrange Formation of (Baker et al., 1988; Burbank and Beck, 1989; Butler et al., 1987; Lillie, 1987). Significant glide over the sole decollement permits translation of overburden sediments with nominal resistance (Davis and Engelder, 1985). Translation of sediments was blocked by the basement normal fault and salt and overburden sediments are ramped over the normal fault developing the Saltrange (Baker et al., 1988). Eastern and western margins of the Potwar Plateau and the Saltrange are respectively marked by the Jhelum and the

Kalabagh Fault which suggests differential thickness distribution of salt (Davis and Engelder, 1985; Seeber et al., 1981). Eastern margin is marked by the sinistral slip Jhelum fault (Baker et al., 1988; Butler et al., 1987; Jaume and Lillie, 1988) developed due to lateral thinning of evaporate layer towards east (Pennock et al., 1989). The Kalabagh Fault is a lateral ramp developed as a dextral slip fault suggesting absence of salt due to basement high (Cotton and Koyi, 2000). Northern margin of the Potwar Plateau is marked by the MBT (Main boundary thrust).

Himalayan orogeny developed a wedge in the Potwar Plateau which includes Miocene to Recent sediments (Gee, 1989). These units consist of Rawalpindi and Siwaliks Groups (Yeats et al., 1992). Allochthonous growth of salt developed out of sequence thrusting and reactivation of faults in the Potwar Plateau and the Saltrange. So the distribution of overlying sediments thickness and types of structures developed by the salt movement is of key importance to understand the structural development in the Potwar Plateau and the Saltrange, which is tectonically active based on the recent seismic activity and GPS velocities (Jadoon et al., 2014; Jouanne, 2014; Yeats et al., 1984).

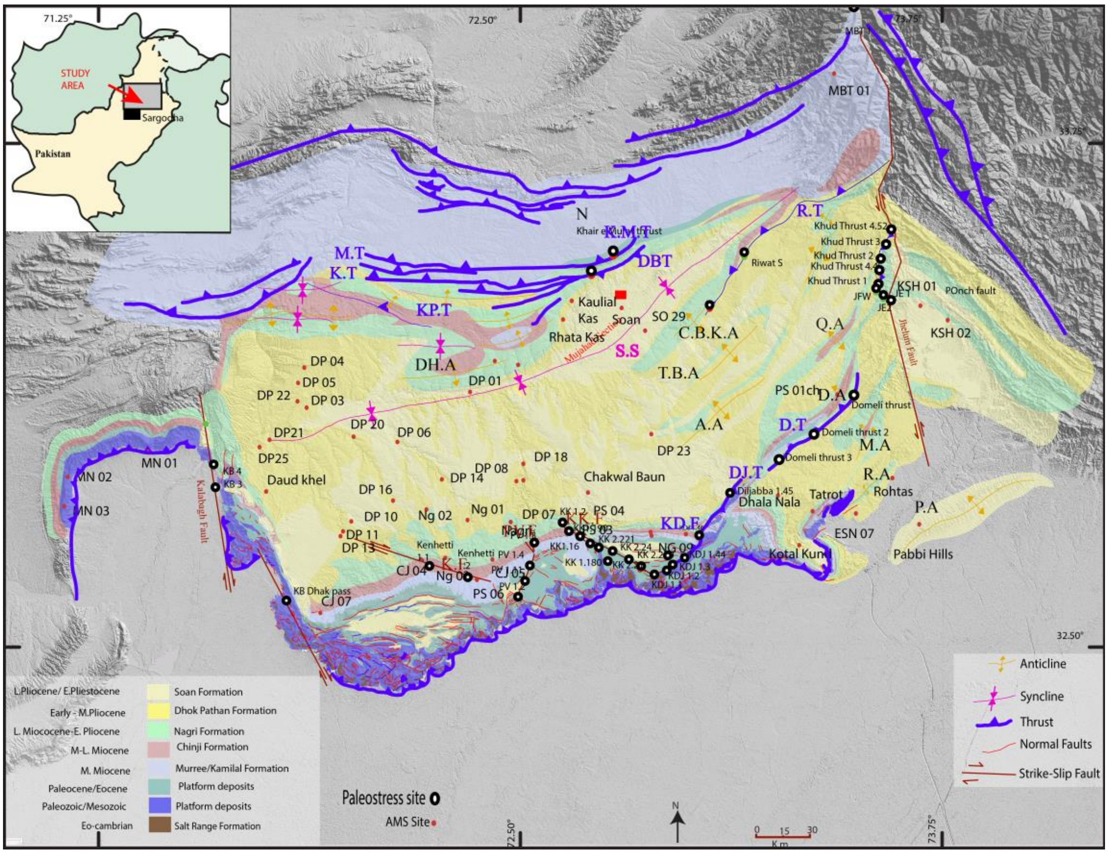


Figure 3. 1. Geological map of the Potwar Plateau and the Saltrange depicting paleostress sampling sites and AMS sampling sites.

AA: Aadhi anticline, CBKA: Chak Beli Khan Anticline, DA: Domeli Anticline, DT: Domeli Thrust, DJT: Dill Jabba Thrust, DBT: Dhurnal Back Thrust, DHA Dhullian Anticline, KF: Kenhetti Faut, KDF: Krangal Dill Jabba Fault, KKF: Kallar Kahar fault, KMT: Khair-e-Murat Thrust, KT: Kanet Thrust, KP.T: Kharpa Thrust, MS: Mujahid Section, NPDZ: North Potwar Deformed Zone, MA: Mehesian Anticline, MT: Mianwala Thrust, PA: Pabbi Anticline, PVF: Pail Vesnal Fault, QA: Qazian Anticline, RT: Riwat Thrust, SS:Soan Syncline, TBA: Tanwin Bian Anticline.

3.3 Methodology

We used paleostess analysis to determine the kinematic history of the Potwar and the Salt range. To reach this goal more than 1400 fault slip measurements from 41 different sites in the Potwar Plateau and the Saltrange are used. Sampling in a site was performed according to Kaymakci et al. (2000), which requires that all the data points in a site must be kept within about 50 m diameter in order to maintain the structural homogeneity (Hancock, 1985). Otherwise, the measurement locations which farther than 50 m diameter are classified as separate sites (Figure 3.1). For each reading, fault plane attitude, orientation of slickinside and movement sense and relative dating markers are measured in the field. Fault plane data is analyzed using Win-Tensor software (Delvaux and Sperner, 2003), which is based on the Angelier's reduced stress tensor concept (Angelier 1994). Output from Win-Tensor consist of Relative Magnitudes of Principle Stress (Φ1, Φ2, Φ3), their orientations and stress ratio ($R=(\sigma_2-\sigma_3/\ \sigma_1-\sigma_3)$ which ranges between 0 and 1 (Angelier, 1994).

We also applied Anisotropic Magnetic Susceptibility (AMS) technique in the study area. For this purpose, the same samples collected for vertical axis rotation and magnetostratigraphic purposes discussed in previous chapter were used. Most of the AMS measurements are performed in the central part of the Potwar Plateau where a few faults are developed (Figure 3.1). This region is slightly deformed and characterized mainly by open to broad folding and small-scale faults. This implies that amount of strain in this region is less and therefore we assumed that the AMS tensors are comparable to paleostress tensors.

The susceptibility tensors consist of principle susceptibilities ($K1 \geq K2 \geq K3$). During deformation maximum axis of susceptibility tensor (K1) expected to be parallel to the maximum extension direction (stretching direction) while minimum axis of susceptibility (K3) is almost always parallel to compaction direction in low to mildly deformed rocks (Duermeijer et al., 1998) and the intermediate axis is generally parallel to the major compression direction (Jelinek, 1981; Jelinek and Kropáček, 1978).

In the laboratory, the AMS values are determined in weak magnetic field by device known as Kappa Bridge. Resultant AMS fabric are then corrected for the bedding orientation and interpreted.

3.4 Field Observations

The Potwar and the Salt range is subdivided in to 9 different sub domains based on the structural style and stratigraphic relationships. The Potwar and the Salt range is delimited in the west and the east by the dextral Kalabagh and the sinistral Jehlum strike slip faults. In the southers part of the plateau two conjugate sets of strike slips faults are developed. Namely, these are the Kenhetti-Pail Vesnal and Kallarkahar-Krangal-Dill Jabba faults. A number of faults which have reactivated repeatedly are also developed and displaced the Potwar plateau and the Saltrange. These faults include Riwat Thrust and Dhurnal back Thrust. The youngest units that these faults deformed include Early Pliocene unitsand they are are unconformably overlain by the late Pliocene Soan Formation, which indicates that the activity of these faults lasted until late Pliocene. However, Soan Formation is also deformed and it is as expressed within the broad Soan Syncline, it is also displaced by faults especialy at the north and widespread mesoscopic faults with few tens of cm’s to meters off-set are developed within the Soan Formation. Thes deformation events are attributed to a new deformation phase that took place after the defposition of the Soan Formation by the late Pliocene. In Table 3.1. Field observations along each fault is listed.

Table 3.1 Showing faults observed in the field and their possible age of development.

Faults	**Youngest displaced Unit**	**Possible age range**
Kalabagh Fault	Kalabagh conglomerates	Early Pliocene- Recent
Jehlum Fault	Soan Formation	Late Miocene-Recent
Kenhetti Fault	Dhokpathan Fm.	Early Pliocene-Pleistocene
Pail-Vesnal Fault	Nagri Formation	Early Pliocene
Kallar Kahar Fault	Nagri Formation	Early Pliocene
Karangal-Dill Jabba Fault	Soan Formation	Early Pliocene- Recent
Domeli Thrust	Soan Formation	Late Pliocene
Riwat Thrust	Soan Formation	Early Pliocene- Recent
Dhurnal Back Thrust	Soan Formation	Early Pliocene- Recent
Khair-e-Murat	Kamlial Formation	Late-Miocene
Khud Thrust	Soan Formation	Late Pliocene
MBT Thrust	Margala Hill Limestone	Oligocene-Early Miocene

3.5 Results

In order to compare paleotress data with the AMS results, the study area is divided into coherent sub domains (Figure 3.2) as discussed previously. Since AMS data corresponds to strain, the general trends of paleostress configurations for each sub domain are compared with the average AMS results.

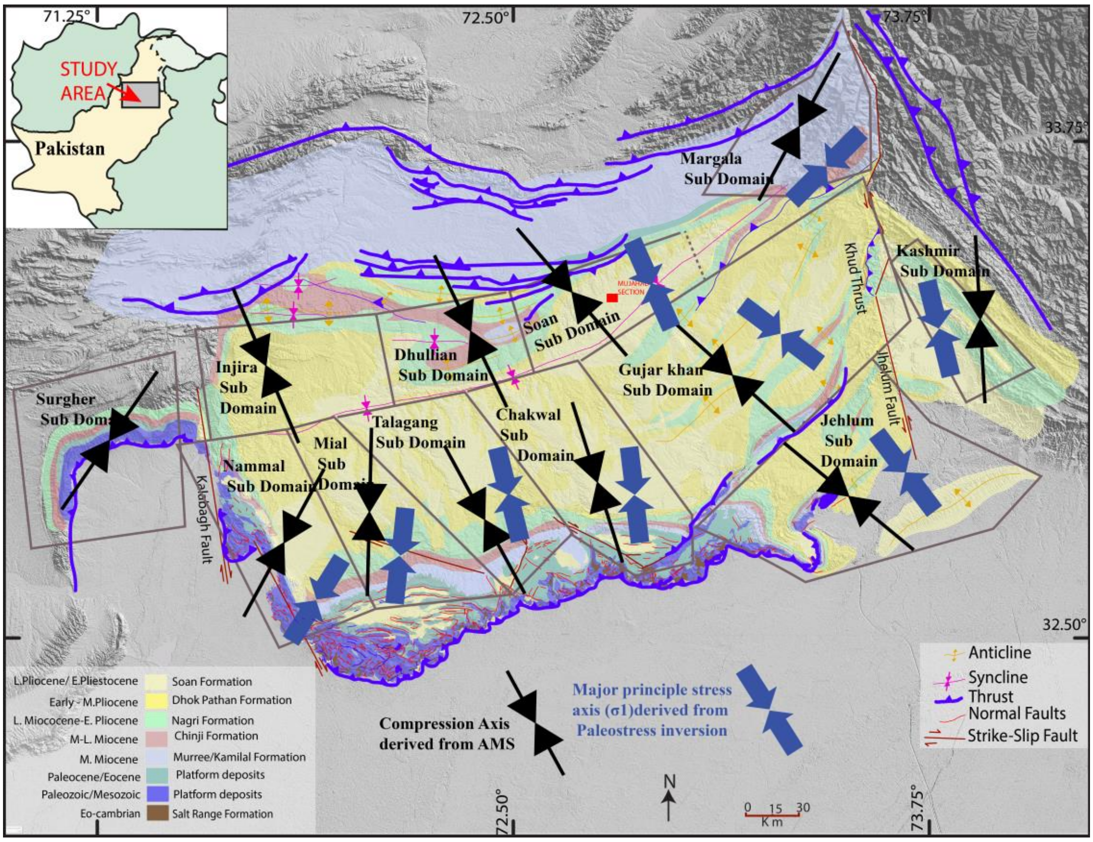


Figure 3.2 Comparison of paleostrass inversion results with Ams results represented on Geological map of the Potwar Plateau and the Saltrange.

3.5.1 Nammal Sub Domain

Nammal Sub domain contain fault plane readings form Kalabagh fault. Paleostress orientations related to Nammal Sub domain indicates NE-SW directed compression and NW-SE directed extension while intermediate stress is subvertical.

AMS results of Nammal Sub domain are as follows K1: 295°N/06°, K2: 025°N/05°, K3: 145°N/82°, (Figure 3.3 and Table 3.2). These results indicate that AMS results in Nammal Sub domain are conformable with the paleostress configurations (Figure 3.3 and Table3.2)

3.5.2 Mial Sub Domain.

Mial sub domain contains Kenhetti Fault. Plaeostress inversion results suggest that compression axis in Mial Sub domain is NNE-SSW and ESE-WNE directed extension axis. (Table 3.3 and Figure 3.3).

AMS results from Mail Sub domain are follows, K3, compaction axis is vertical, K2: 015°N/3, K1: 105°N/4° (Figure 3.3 and Table 3.2). These results indicate WNW-ESE directed extension and NNE-SSW compression.

3.5.3 Talagang Sub Domain

Pail-Vesnal Fault is present in the Talagang Sub domain. Fault plane data from Talagang Sub domain is measured at four different locations. Paleostress inversion results shows NNW-SSE directed compression axis (Table3.2 and Figure 3.3)

AMS results from adjoining Talagang Sub domain suggests that K3, compaction axis is vertical K2: 336°N/4° and sub-horizontal extension axis K1; 66°N/1° that suggests ENE-WSW directed extension and NNW-SSE directed compression (Figure 3.3 and Table 3.2).

Mial and Talagang Sub domains contains Kenhetti & Pail Vesnal Fault which are conjugate set of faults. Combined paleostress inversion results of Mial and Talagang Sub domains indicate ENE-WSE directed extension and NNW-SSE directed compression as shown in Table3.2 and Figure 3.3. Combined AMS results from Mial and Talagang Sub domain are conformable with paleostresss configurations.

3.5.4 Chakwal Sub Domain.

KallarKhar Fault and KrangalDill Jabba faults are present in Chakwal Sub domain. Fault plane measurement form Chakwal Sub domain was collected form 14 different sites. Paleostress inversion results shows general trend of compression is NNW-SSE and extension direction is ENE-WSW. Data is collected from Eocene (Sakesar Limestone) and Murree & Kamlial Formation (Middle Miocene age). (Table 3.2 and Figure 3.3)

AMS results from Chakwal Block shows that K2: 334°N/7° with vertical compaction axis K3 and with sub-horizontal extension axis K1: 065°N/4° which suggests ENE-WSW directed extension axis and NNW- SSW directed compaction (Table 3.2 and Figure 3.3). Tatral Fault is developed as normal faults Perpendicular to $\sigma1$ of Chakwal Sub domain. (Table3.2 and Figure 3.3).

3.5.5 Gujar Khan Sub Domain

Jehlum Fault and Khud thrust are present in Gujar Kahn sub domain. Paleostress inversion results from the Gujar Khan Sub domain suggest that NW-SE directed σ1 in Gujar Khan Sub domain.

AMS results from Gujar Khan Sub domain suggests that K2: 345°N/35°, with vertical compaction axis K3 and extension axis K1: 230°N/31°, which suggests ENE-SWS extension axis and NNW-SSE compaction and (Table3.2 and Figure 3.3).

3.5.6 Jehlum Sub Domain

Domeli Thrust is present in Jehlum Sub domain. Fault plane reading are collected from three different locations (DT, DT 1.31, D2). Results from paleostress inversion shows NW-SE direction compression and as represented in Figure 3.3 and Table 3.2. Data is collected from Chinji Formation (Middle-late Miocene) and Nagri Formation (Late Miocene-Early Pliocene) (Table 3.2 and Figure 3.3).

AMS results from Jhelum Sub domain shows K2: 311°N/33°, with vertical compaction axis K3 and extension axis K1: 216°N/8° that is NE-SW directed extension axis and NW-SE directed compression axis (Table3.2 and Figure 3.3).

3.5.7 Soan Sub Domain

Raiwat Thrust Dhurnal Back Thrust and are present in Soan Sub domain. Dhurnal Back Thrust marks the northern boundary of of Soan syncline and Soan Sub domain. Paleostress inversion results from Soan Sub domain suggests NNW- SSE directed compression axis.

AMS results from Soan Sub domain suggests that K2: 138°N/01°, and vertical K3, and extension axis K1: 228°N/01°, which suggest NE-SW directed extension and NW-SE directed compression axis (Table 3.2 Figure 3.3).

3.5.8 Dhullian Sub Domain

Dhullian Sub domain is present at the west of Soan Sub domain. AMS results in Dhullian Sub domain suggests K2: 148°N/5°, with vertical compaction axis K3 and sub-horizontal extension axis K1: 056°N/19°, which suggests ENE-WSW directed extension and NNW-SSE directed compression axis (Table 3.2 Figure 3.3). No fault plane data is available in this Sub domain for the Plaeostress inversion.

3.5.9 Injira Sub Domain

Injira Sub domain marks the northwestern boundary of the Potwar Plateau. AMS results from Injira Sub domain suggests that K2:153°N/3°, vertical compaction axis K3, and extension axis K1: 062°N/3°, which suggests ENE-WSW directed extension and NNW-SSE directed compression axis (Table 3.2 Figure3.3). No fault plane data is available in this Sub domain for the Plaeostress inversion.

3.5.10 Surghar Sub Domain

Ams results from Surghar Sub domain are K2:051°N/32°, vertical compaction axis K3, and extension axis K1: 310°N/17°, Which suggests SE-NW directed extension axis and NE- SW directed compression axis (Table 3.2 and Figure 3.3).

3.5.11 Margala Sub Domain

It includes Main boundary thrust in the north of the Potwar Plateau and the Saltrange. Result of Paleostress inversion data collected from MBT suggest NE-SW directed compression axis (Table 3.2 and Figure 3.3).

AMS results from Margala Sub domain suggests that K2: 349°N/71°, vertical compaction axis K3, and extension axis K1: 148°N/17°. Here the position of K2 axis and K3 axis is switched which suggest higher degree of deformation (Table 3.2 and Figure 3.3).

3.5.12 Kashmir Sub Domain

Is located toward east of the Potwar Plateau in Kashmir basin. Ponch Thrust is included in the Kashmir Sub domain Results of paleostress inversion in Kashmir Sub domain suggests NNW-SSE compaction and vertical extension (Table 3.1 and Figure 3.2).

AMS results from adjacent Kashmir Sub domain suggest that K2: 198°N/13°, vertical compaction axis K3, and extension axis K1: 105°N/12° (Table3.2 Figure 3.3).

Table 3. 2 Ams results compared with the Paleostress inversion results

Sub Domain	**K1 (D/P)**	**K2 (D/P)**	**K3 (D/P)**	**σ1 (D/P)**	**σ2 (D/P)**	**σ3 (D/P)**	**R**
Nammal	295/06	025/05	154/82	212/05	092/80	303/09	0.44
Mial	105/04	015/03	251/85	005/12	218/76	097/08	0.45
Talagang	066/01	336/04	163/86	166/01	258/71	076/19	0.5
Chakwal	065/04	334/07	183/82	353/0	263/34	084/56	0.18
Jehlum	216/08	311/33	114/59	150/13	243/10	010/73	0.74
Gujar Khan	230/31	345/35	110/39	127/10	218/06	342/78	0.21
Soan	228/01	138/01	090/17	335/05	244/07	101/82	0.68
Dhullian	056/19	148/05	253/70				
Injira	063/03	153/03	286/85		No Data		
Surghar	310/17	51/32	196/52				
Margala	148/17	349/71	240/06	055/22	159/31	295/51	0.53
Kashmir	105/12	198/13	335/72	168/05	258/04	027/83	0.83
Mial+Talagang	074/03	344/03	212/86	354/10	256/40	095/48	0.28
Phase 1	238/11	330/10	102/75	192/12	289/31	084/56	0.35
Phase 2	227/2	317/3	111/87	140/00	230/05	045/85	0.25

D. Direction, P: Plunge, R ((σ2−σ3)/σ1−σ3)):stress ratio. K1,K2,K3: susceptibility axes.

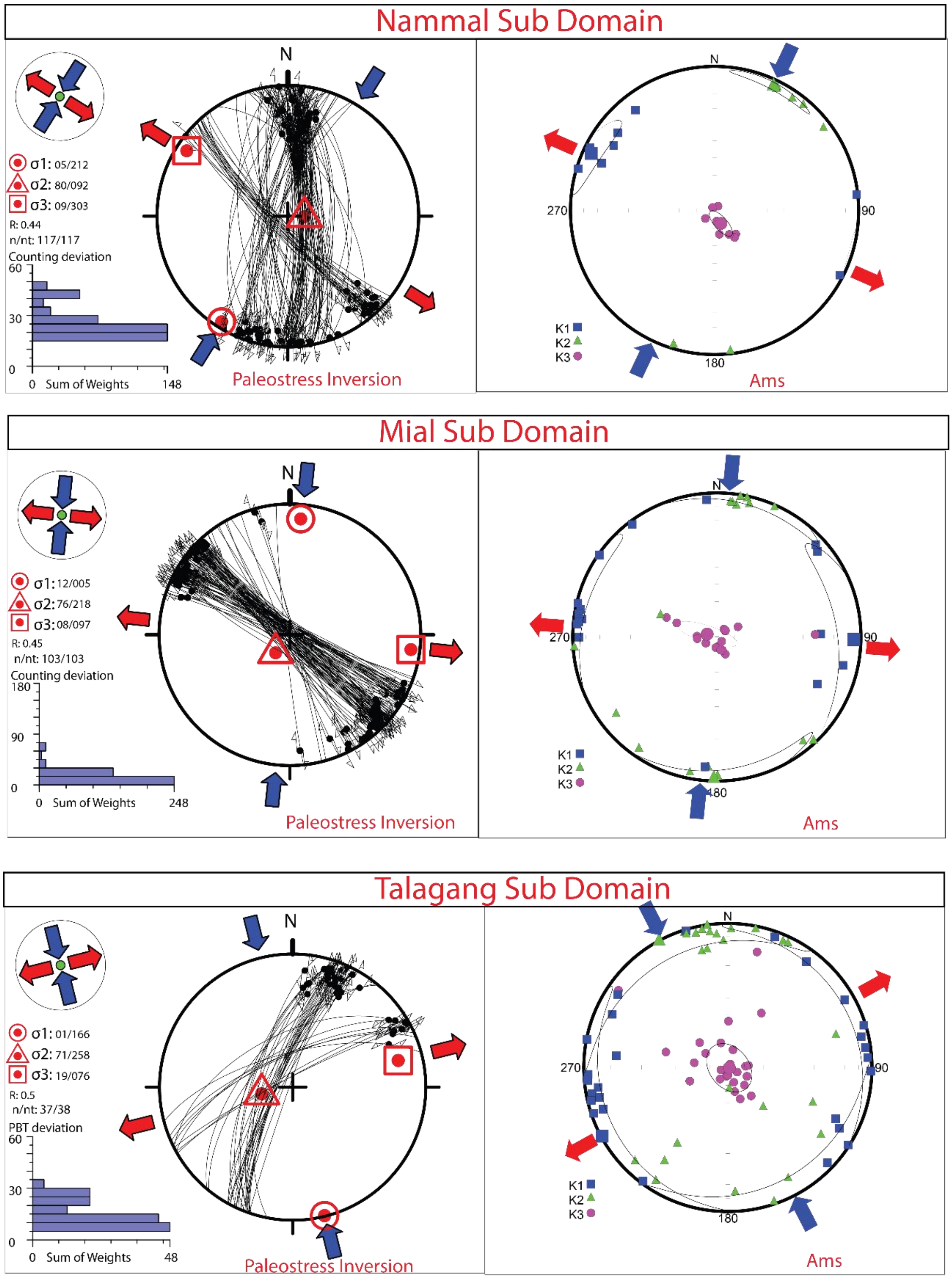


Figure 3.3 Stereographic projections of constructed paleostress configurations for each sub domain and Mean solution. (Equal area, lower hemisphere projection) compared with the AMS results of each sub domain (See Figure 3.2 for the locations of each sub domain).

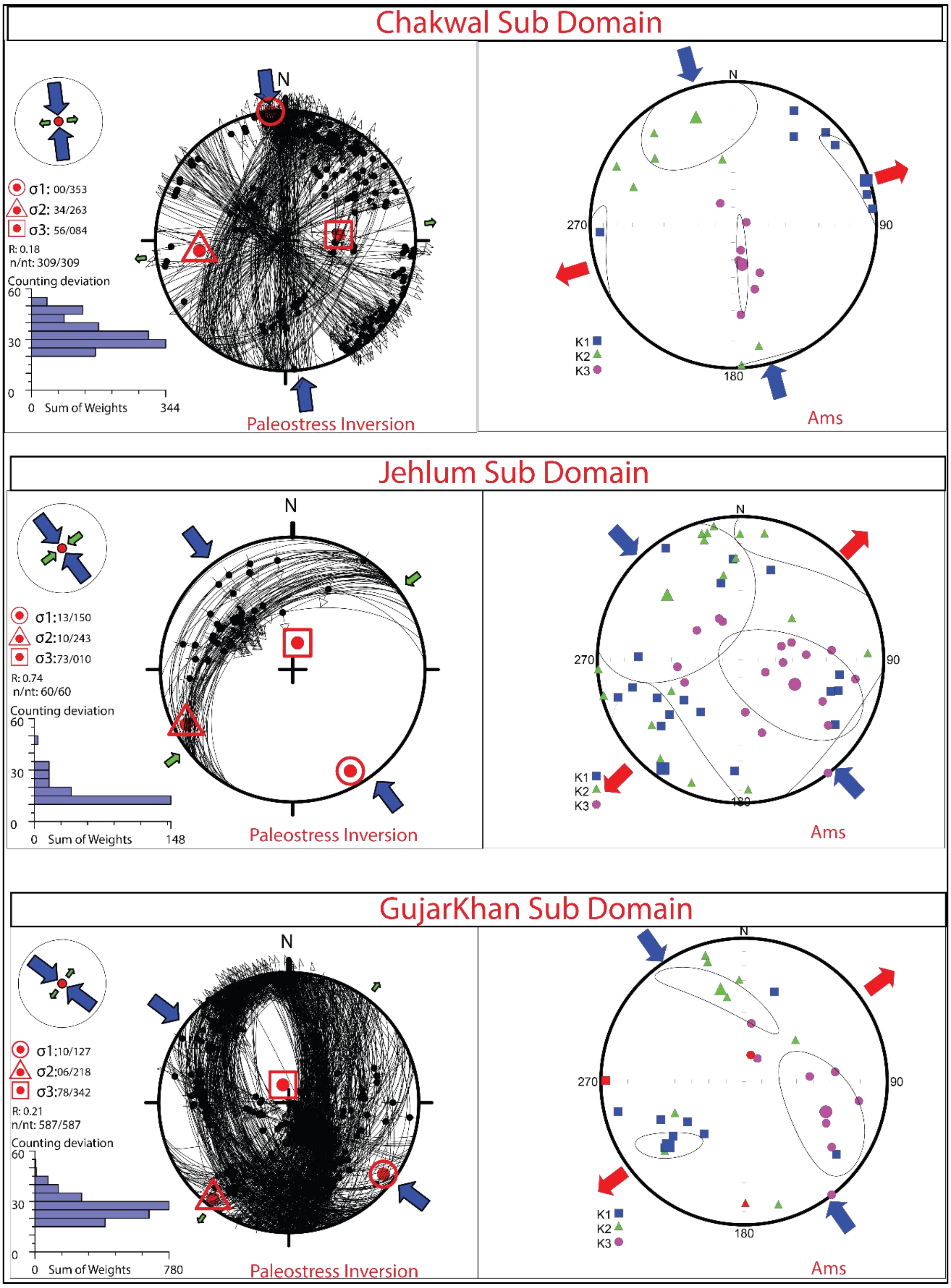
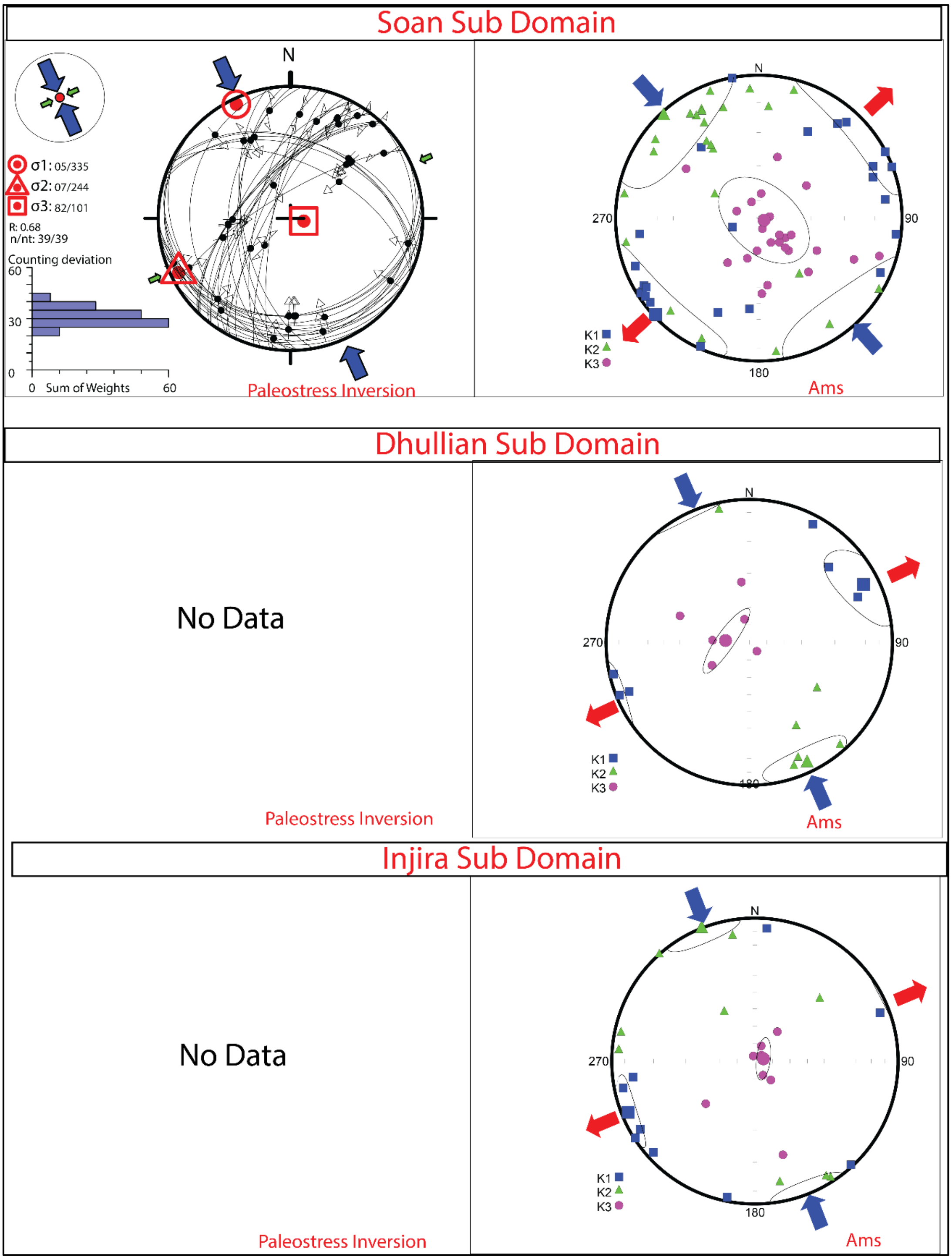


Figure 3.3 (Continued)



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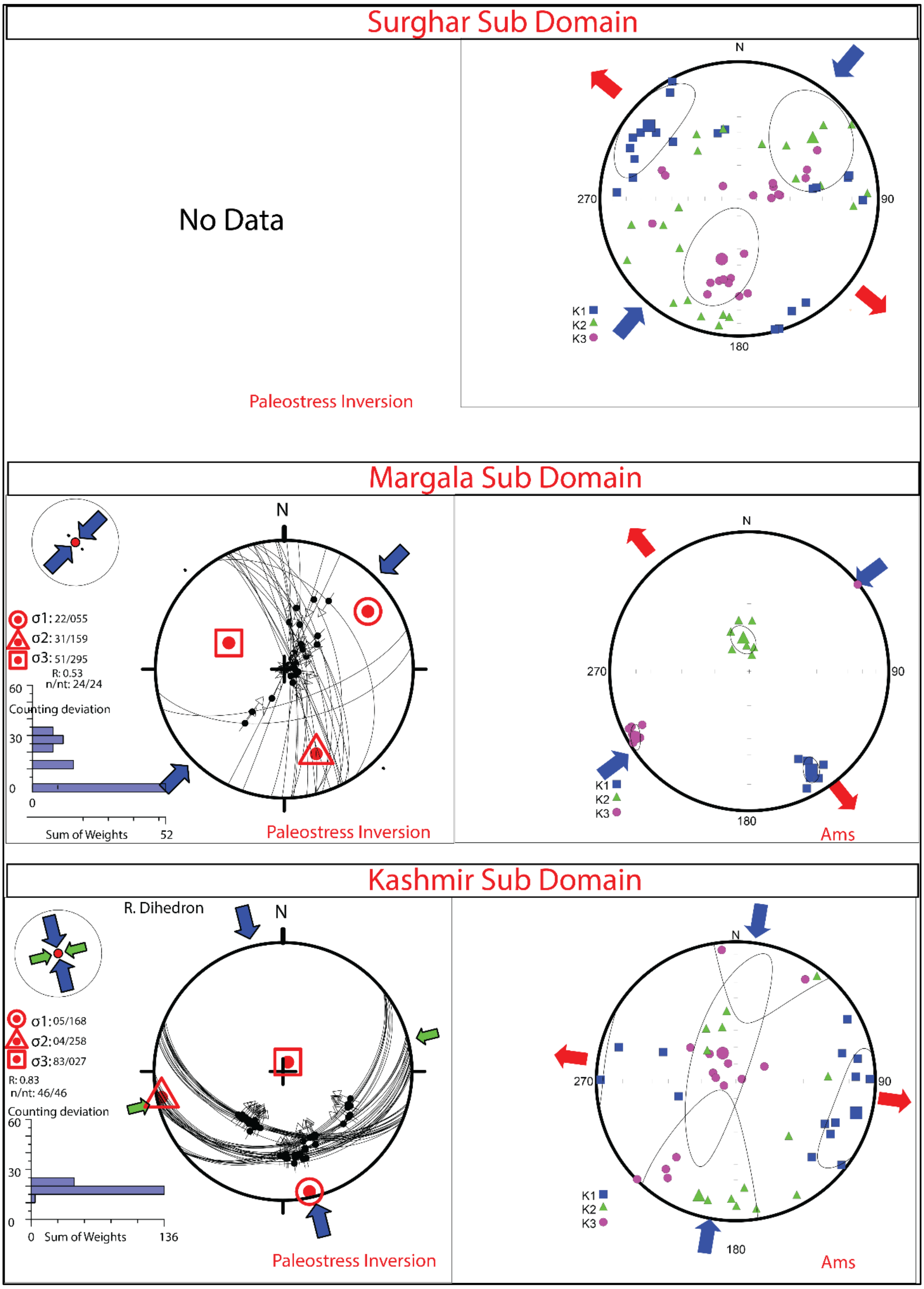

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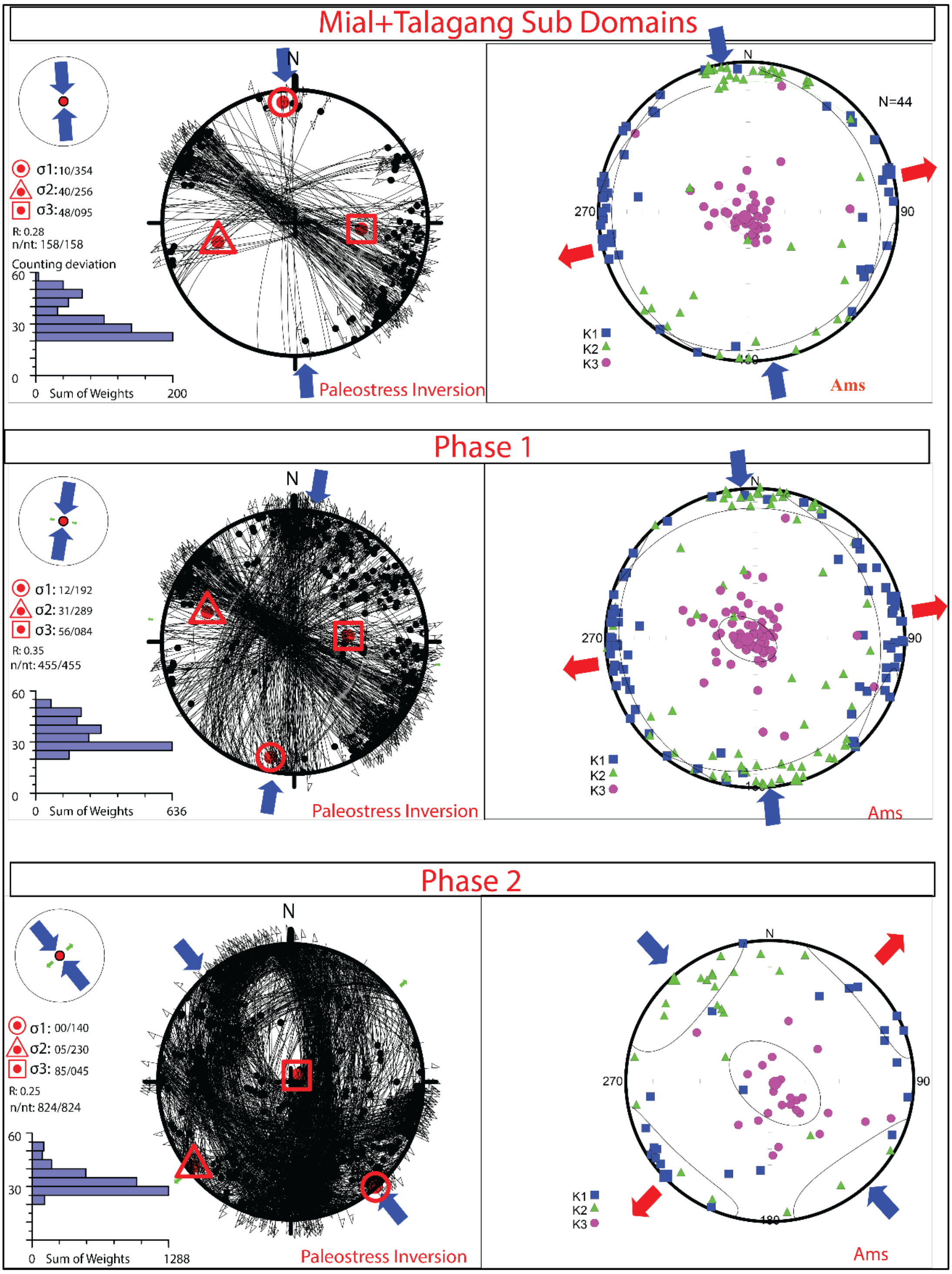

Figure 3.3. (Continued)

3.6 Discussions

3.6.1. Spatio-Temporal Relationships and Deformation Phases

Establishing temporal constrain in constructed stress configurations is a main concern in the paleostress inversion. Stratigraphic Ages of deformed rocks and cross cutting relationship provide the age of stress configurations (Angelier, 1994).

Soan Formation act as a seal to most of the structures in the Potwar Plateau. It makes difficult to observe and get data from buried faults and develop a temporal relation of the collected data from constructed stress orientations. Siwaliks are deposited as a result of the Himalayan wedge having high sedimentation rate (Tauxe and Opdykes, 1982) Siwaliks are coarse grained clastics interbedded with fine muds suggest these sediments underwent very less time for the compaction. Molasse deposits are not well in preserving the records of faulting, since loose sediments deform as moving sand not developing a fault plane and slickensides. Movement along a decollement developed underneath the Potwar Plateau and the Saltrange results in relatively less internal deformation in the sediments above decollement (Grelaud et al., 2002). All these constraints hinders development of a homogeneous spatial and temporal relationship of deformation everywhere, nevertheless available outcrops and faulted outcrops provided recognition of two major episodes of deformation in the region.

Temporal relationship of the faults is developed based on crosscutting relation and stratigraphy. Two phases of deformation are determined in the Potwar Plateau and the Saltrange. First phase of deformations is from Late Miocene to Late Pliocene in which Khair-e-Murat, KKF, KDJF, PV and Kenhetti Faults were developed. Data from these faults are combined to obtain a mean stress tensor for the first deformation phase. Results suggest that deformation started as a compressional regime in which compression axis is oriented NNE- SSW (Figure 3.3 and Table 3.2).

3.6.2 Phase 1

This deformation is characterized by the development of faults and folds. Possibly these faults are developed within the southwards sliding tectonic wedge of the Potwar Plateau was obstracted by a basement step, which lies in the footwall block within the Indian Shield, below the central part of the Saltrange discussed previously.

Younger units are not involved in the thrusting of Khair-e-Murat Thrsut, that suggest Khair e Murat thrust was not operational during the second deformation phase and deformation front has already been migrated southwards, by the end of first phase of deformation.

Soan Formation has sealed most of the structures in the Potwar Plateau and in the Saltrange that suggests deformation phase 1 predate the deposition of Soan Formation. However, faults that displaced the Soan Formation are assumed be active during the second phase of deformation and they are developed by the late Pliocene deformation and probabaly still active. Data from these faults are combined to construct mean orientation of principal stress axes. General trend of the compression in the second deformation phase is NW-SE (Figure 3.3 and Table 3.2) and has been active since late Pliocene.

Faults that have been active during second phase of deformation include the Saltrange Thrust, Kalabagh Fault, Jhelum Fault, Domeli Thrust, Dill Jabba Thrust, Riwat Thrust and Dhurnal Back Thrust.

3.6.2.1 Development and Characteristics of Faults in Phase 1

Two sets of conjugate faults are developed in the Saltrange. Kallar Kahar Fault (KKF) and Krangal-Dill Jabba Fault (KDJF) conjugate set is present in the eastern part of the Saltrange. V- shaped conjugate set of strike slip faults develop at an angle of 60°-75° from major principle stress axis (σ_1). Such obtuse fault sets, contrary to Coloumb-Mohr wedges, commonly develop in the geological record and they are developed contemporaneously with comparable slip amount depending upon the mechanical strength of each fault and mechanism by which regional rotations is accommodated (Yin and Taylor, 2011). Present geometries and characteristics of these faults fit the criteria defined by Yin et.al (2011). Angle between KKF and KDJF is 116° and paleostress data collected from KFF and KDJF (Chakwal Sub domain) are combined to develop a common stress tensor (Figure3.3 and Table 3.2). The results indicate that σ_1: 353°N/00° σ_2: 263°N/34° σ_3: 084°N/56°. Strike of the KKF is 302°N and KDJF is 58°N that means that the angle between the horizontal component of the σ_1 and KKF is 51° and 65° for KDJF.

KDJF is a sinistral slip fault and KKF is a dextral slip fault developed during the first deformation phase. During the second phase of deformation, KDJF reactivated as thrust. This is evidenced by results of the data collected from NE part of KDJF (KDJF 1.46 and Dill Jabba 1.45 sites, Please see the Appendix for the resolved tensors for each site). Change of the behavior of fault from strike slip (KDJF 1.46) to back thrust (Dill Jabba1.45) suggest KDJF developed as sinistral strike slip fault during phase one and reactivated as thrust during second phase.

Kenhetti (KF) and Pail-Vesnal (PVF) Faults are conjugate set of strike slip faults present in the western the Saltrange. Unlike Kallar Kahar Fault and Krangal-Dill jabba Fault, Kenhetti and Pail-Vesnal Faults have an angle of 85° from their intersection point. One of the fault develop at 30° from $\sigma 1$ and other fault develop at 60° from $\sigma 1$ (Tapponnier and Molnar, 1976). Fault plane data sets from Kenhetti and Pail-Vesnal Faults (Mial+Talagang Sub domains) is combined to develop a combined stress tensor (Figure 3.3 and Table 3.2) that suggests following results $\sigma 1$: 354°N/10°, $\sigma 2$: 256°N/40° and $\sigma 3$ 095°N/48°. Assuming our paleostress inversion results are correct orientation of Kenhetti and Pail-vesnal fault should be 294°N and 24°N or 324°N and 54°. Kenhetti Fault has strike of 295°N and Pail-vesnal fault has a strike of 20°N (Figure 3.3).

Khiar-e-Murat Thrust of North Potwar Deformed Zone is steep reverse fault. Oldest Formation involved in thrusting is Sakesar Limestone of Eocene age. Such a steep thrust is developed when entrapped allochthonous salt kept moving vertical in the subsurface. Soan Formation is not involved in the thrusting of Khair-e-Murat Thrust and its location in the North Potwar Plateau suggest that this reverse fault developed during the first phase of deformation.

Toward south of Khair-e-Murat Thrust, Dhurnal Back Thrust makes a triangle zone where outcrops of both thrusts intersect Kamlial Formation is brought against Sakesar Limestone of Eocene age. This triangle zone is developed just above the Dhurnal Popup structure (Chapter 4). Khair-e-Murat Thrust, Dhurnal Back Thrust and Riwat Thrust were initiated during the first stage of deformation, However, Dhurnal Back Thrust and Riwat Thrust remain active during the second phase of deformation.

3.6.3 Phase 2

Second phase of deformation started from Late Pliocene to present day and classified based on involvement of younger stratigraphy in the deformation, out of sequence faulting, rotated or reactivated faults.

Dhrunal Back Thrust and Riwat Thrust marks the northern and southern margin of Soan syncline respectively. Cross cutting relationship between Soan Formation and Dhok Pathan Fmn suggest that these thrust are active during Late Pliocene to early Pleistocene .Moreover, Soan Formation exhibits significant CCW rotation (Figure 2.4) suggests Riwat Thrust and Dhurnal is out of sequence thrust was active during second phase of deformation.

Kalabagh Fault is right lateral strike slip fault, which developed as lateral ramp. Two different trends of Kalabagh Fault are observed in the field. This change in strike of Kalabagh Fault develop a restraining bend along Kalabagh Fault. The Kalabagh conglomerates are stratigraphic equivalent of Soan Formation in western the Potwar Plateau. Close to northern tip of Kalabagh Fault, involvement of Kalabagh conglomerates in faulting suggests that The Kalabagh fault was active during the second phase of deformation.

Jhelum Fault is the eastern margin of the Potwar Plateau and the Saltrange. It is the strike slip fault with the sinistral sense of movement. Jhelum Fault is not restricted to the eastern margin of the Potwar Plateau and the Saltrange, truncation of MBT along Jhelum Fault suggest that Jhelum Fault extends up to eastern margin of Hazara basin in the north. Two different characteristics of the Jhelum Fault are recognized in the field. Southern part of the Jhelum Fault is a sinistral strike slip fault and northern part is a thrust. Change in the trend of Jhelum Fault developed a single restraining bend by creating a thrust known as Khud Thrust. Involvement of Soan Formation in the displacement of Jhelum Fault suggest that Jhelum Fault is active at the second phase of deformation.

Trend of the Domeli Thrust is similar with the KDJF, so it is also possible that it is continuation of KDJF that developed as strike slip in the first phase and reactivated as thrust during second phase of deformation.

3.6.4 AMS

AMS samples from Soan Formation are combined to develop susceptibility tensor for the second deformation phase. Results of the second deformation phase derived from susceptibility tensor are compression axis K2: 317°N/3°, K3: Vertical compaction axis, K1: 227°N/2° extension axis. Compression axis derived from AMS data is almost same as Paleostress inversion results for the phase 2. Only 3° of difference is observed between the resultant Paleostress inversion solutions and AMS results (Table 3.2 and Figure 3.3). However, AMS results combined for the Phase 1 are significantly different (28° apart) than Paleostress inversion results (Table 3.2 and Figure 3.3). This is because AMS is the strain experienced by the magnetic minerals in the rock, so the strain experienced by the magnetic minerals in the phase one of deformation is overprinted by the second phase of deformation. In the present scenario Phase one determined by the paleostress inversion resulted in NNE-SSW compression axis, and second phase of deformation determined by paleostress inversion as well as AMS resulted in NW-SE directed compression. Therefore, magnetic minerals in the rocks were overprinted by the deformation in the second phase. Results from AMS second phase of deformation are in between first phase results and second phase results. Hence, developing temporal relationship based on AMS results will reveal mostly orientations of the latest most deformation phase.

AMS results from most of the Sub domains shows σ1 in NNW-SSE except for the Mial and Nammal Sub domain. NNW-SSE σ1 are comparable with the second phase of deformation determined form Paleostress inversion results. (Table 3.2 and 3.3)

3.6.5 Tectonic implications

Structural development of the Potwar Plateau and the Saltrange occurred in two different deformational phases. First phase of deformation start at Late Miocene and continued up till early Pliocene with σ1 as NNE-SSW. Second phase of deformations starts at late Pliocene and continues to the present day with σ1 as NW-SE.

First stage is associated with the migration of deformation front towards south until migrating deformation front blocked by the basement step in the Indian shield, which acted as an indenter. It causes the initiation of faults and blockage of salt migration further towards the south. Indentation closed the system for the salt which is left with no where to move but to deform as an allochthones salt body. During the second phase, already developed folding in the Potwar Plateau enhanced by the allocthonous growth of salt, which developed faulting, salt cored popups and welded synclines which cause the reactivation of faults and out of sequence thrusting. After the indentation at the Saltrange salt started to ride normal step in the Indian shield, eventually developing the Saltrange and exhuming the salt to the surface. However, entrapped salt in the form of stratigraphic welds in the Potwar Plateau kept its growth so faults like Riwat Thrust, Dhurnal Back Thrust become out of sequence. Allocthonous growth of salt is the reason that thrusts measured in the field (Khair e Murat Thrust, Dhurnal Back Thrust, Riwat Thrust, Domeli Thrust) were having such a steep angle of dip (>70°). A seismic creep along the Kalabagh Fault (Jouanne, 2014) developed differential slip between the Kalabagh Fault and the Jhelum Fault (relatively more brittle as compared to Kalabagh Fault). It cause compression axis to move from NNE- SSW (phase 1) to NW- SE (Phase 2). Normal fault present in the Saltrange (e.g Tatral) are not considered as extension episode of deformation because these normal faults are created in compressive tectonic regime where ductile flow of salt created space problem and the strata above salt collapse under gravity. Evaporites from the Saltrange Formation are exposed along the Saltrange Thrust (SRT) fault plane reading from salt or any evapouties are not considered reliable to plastic nature of flow present along the Saltrange.

3.7 Conclusions

In the Potwar Plateau and Salrange two different phases of deformation are recognized. These two phases correspond to the time when deformation front reaches the Potwar Plateau and the Saltrange after the development of MBT.

First phase started from Late Miocene-Early Pliocene corresponds to compression with the NNE-SSW compression axis. This phase corresponds to the indentation tectonics of Indian shield with present day salt range, which caused early development of structures and faulting in the Potwar Plateau and the Saltrange.

Second phase of deformation started in Late Pliocene and continue to the present day. Second phase of deformation corresponds to the compression with NW- SE compression axis. Second phase of deformation is associated with Soan Formation deformation. Soan Formation sealed structures developed in the first phase and continued displacement along faults deformed Soan Formation during second phase of deformation.

CCW shift in major principle stress axis from NNE-SSW to NW-SE can be justified by the CCW vertical axis rotation present in the Potwar and the Saltrange (Chapter 2).

Comparison of AMS results with the plaeostress inversion results show consistent result and can be compared with each other as deformation in the Powtar and the Salt range is not intense.

CHAPTER 4

ARCHITECTURE AND RATE OF DEFORMATION IN THE POTWAR PLATEAU AND THE SALT RANGE

4.1 Introduction.

The Saltrange and the Potwar Plateau host the frontal fold-thrust belt and a sub basin of NW Himalayas. High-density contrast between crystalline Indian shield and Eo-Cambrian evaporites developed a detachment above the Indian shield (Crawford, 1974) which created an extended basin and fold/thrust belt with very narrow cross-sectional tapper as compared to the western Himalayan frontal thrust with high cross sectional tapper (Jaume and Lillie, 1988). At present, along the deformation front (the Saltrange) Eo-Cambrian decollement is exposed as the evaporites of the Saltrange Formation (SRF) and overlaying sequences override against its own syn-oroganic deposits (Yeats et al., 1984). Western extension of the Saltrange is terminated by a dextral lateral ramp called Kalabagh Fault and eastern margin is marked by the Jhelum Fault (Yeats and Lawrence,1984) developed to accommodate southwards sliding of the Potwar Plateau (Davis and Engelder, 1985). Northern margin is marked by the Main Boundary Thrust (MBT) and its associated foot wall deformation in North Potwar Deformed Zone (NPDZ) (Jaswal et al., 1997). Basement (Indian shield) is cut by normal faults (basement steps) as north dipping high angle basement steps are developed due to (1) extension related to Eo-Cambrian rifting of Indian shield which created a lagoonal environment for the deposition of SRF (Lillie. R, 1986) or (2) the Neogene flexural bending of the crust resulted from the vertical load of the Himalayas and Indian plate under thrusting (Duroy, 1986). Eo-cambrian Saltrange Formation is overlain by Cambrian-Eocene platform sequences, syn-Himalayan orogenic deposits known as Rawalpindi group (often known as lower Siwaliks) and Siwaliks (often known as Middle and Upper Siwaliks) overlies platform sequences.

Eastern Saltrange is dominated by a NE-SW trending tight anticlines separated by a broad synclines whereas the central and the western Saltranges are dominated by south-verging asymmetric folds trend E-W. They are resulted from a footwall ramp developed below the Saltrange Thrust. The subsurface is analyzed using combination of seismic reflection data, field observations and well logs in order to understand how the structures evolved. We focused mainly on the relationship between shortening amounts and vertical block rotations and development mechanisms of various structural styles developed due to differential shortening took place along the Saltrange and within the Potwar Plateau. In this regard, five different cross-sections, two main sections and two-aid sections in the Potwar Plateau, and one outside the Potwar Plateau were constructed. The outer cross-section was constructed transverse to the adjoining Kohat Basin in order to compare the deformation amount and styles within and outside the Potwar Plateau (Figure 4.1).

4.2 Methodology.

65 seismic lines and 20 wells are analyzed and interpreted for construction of cross-sections along the tectonic transport direction. As seismic data is acquired for petroleum exploration purpose, several seismic sections are combined to develop continuous cross-sections. Places where seismic data is not available, we used the field observations and previously published cross-sections. SMT Kingdom software (version 2016) was used for the seismic interpretations and interpreted seismic lines were imported to the Midland Valley Move software. Depth conversion of the seismic lines was performed by using interval velocities calculated from well logs. Results of depth converted-lines were verified by already published data. Basement (Indian shield) is identified as prominent reflector due to high-density contrast between SRF and crystalline rocks of Indian shield. Above the basement, SRF is recognized by discontinues translucent reflectors on the seismic lines. Sedimentary sequences above the salt (SRF) Cambrian to Eocene are recognized by the package of strong parallel, consistent reflectors having high to moderate amplitudes. Siwaliks were identified as partially consistent parallel reflectors having moderate amplitudes. 10% error margin was accounted for the shortening calculations considering the differences in the stratigraphic thickness, eroded thickness of units and procedural error.

Sections were restored in two steps, first marker beds (stratigraphic unit tops) were un-faulted and moved along the fault planes by using the method of “Fault parallel flow” in the MOVE software and heaves along the faults were calculated. After unfaulting procedure, 2d unfolding procedure was applied to the units of the sections. During unfolding procedure, “line length” method, which preserves the original lengths of tops and bottoms of the layers, was used.

4.3 Cross Sections

4.3.1 Eastren Potwar Plateau & the Saltrange

More than twenty seismic lines and several well tops information were utilized to deduce the structural style. However, only four seismic lines used to create 138 km long section AA` along tectonic transport direction in the eastern Potwar Plateau and the Saltrange. Interpretation of the subsurface data is done by considering characteristics of the faults, which were discussed in paleostress section (chapter-3), and vertical axis rotations defined in paleomagnetic results (chapter-2).

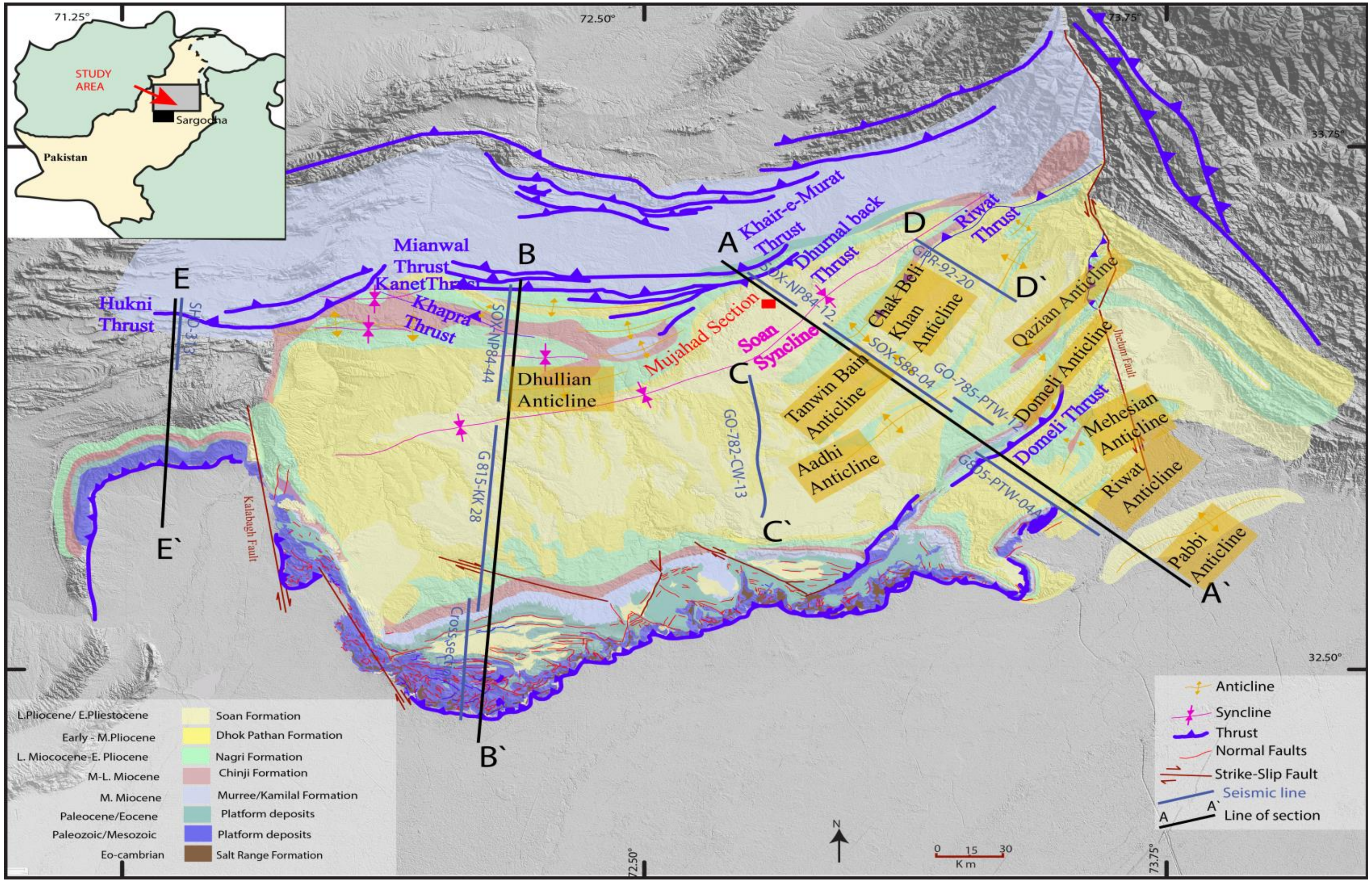

Figure 4.1 Positions of cross-sections and the seismic lines overlaid on the geological map of the study area.

4.3.2 Seismic Interpretation

Starting from north, Seismic line SOX-NP84-12, which covers the Dhurnal Back Thrust and Dhurnal popup structure as expressed in Figure 4.2. Basement is marked at 6km depth on the southern side of the seismic profile. However, towards north, a normal step cutting the basement increases depth to 6.7 km. Above the basement and below the Roof thrust sequence, the Dhurnal popup structure is marked which is a salt-cored popup and demarcated by tringle zones on each side. The surface expression of the Dhurnal popup structure is concealed by the Dhurnal Back Thrust identified by crosscutting pattern of the reflectors that are located at 2km depth and crops out towards north (Figure 4.2 and 4.6).

Dhurnal Back Thrust marks the northern boundary of the Soan syncline. Riwat Thrust marks the southern boundary of the Soan syncline, which is present on the seismic line SOX-S88-04 shown in Figure 4.3 and 4.6. Riwat Thrust is a roof thrust marked at the depth of 3 km on the northern margin of the seismic line SOX-S88-04. A fault propagation fold, developed along Riwat Thrust, is known as Chak Beli Khan Anticline. Basement is identified at the 6 km depth however, a basement normal step is identified exactly below Riwat Thrust. This basement step has an offset of about 700 m. To the south of Riwat Thrust, Tanwin Bain anticline developed as fault propagation fold- is observed. To the south of Tanwin bain Anticline, Aadhi salt-cored pop-up structure is developed. Above the Aadhi popup structure, folding is observed in Siwaliks (Figure 4.3, 4.6 and Appendix A2).

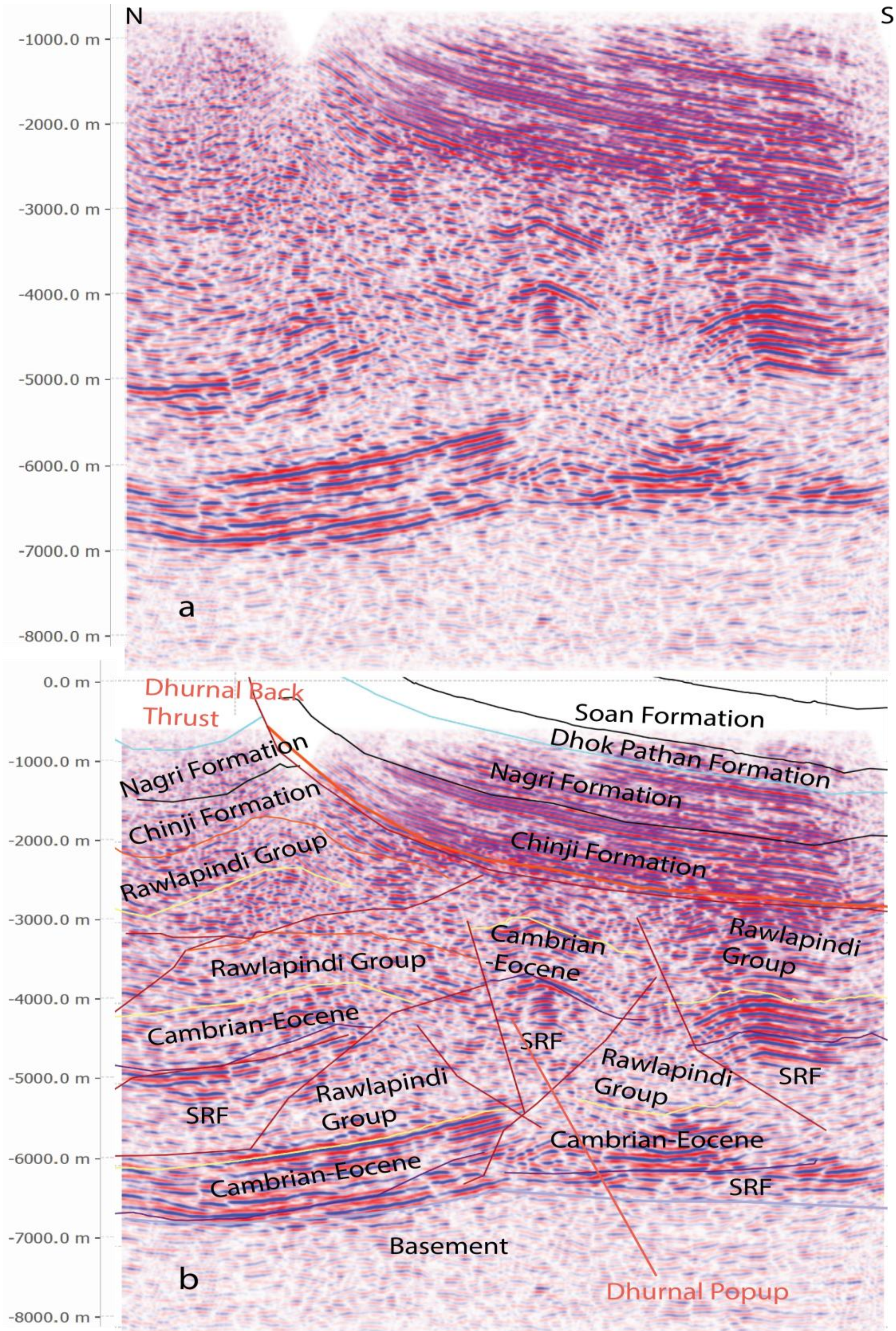

Figure 4.2 a) Un-interpreted and b) interpreted seismic section SOX-NP84-12 (SRF: Saltrange Formation).

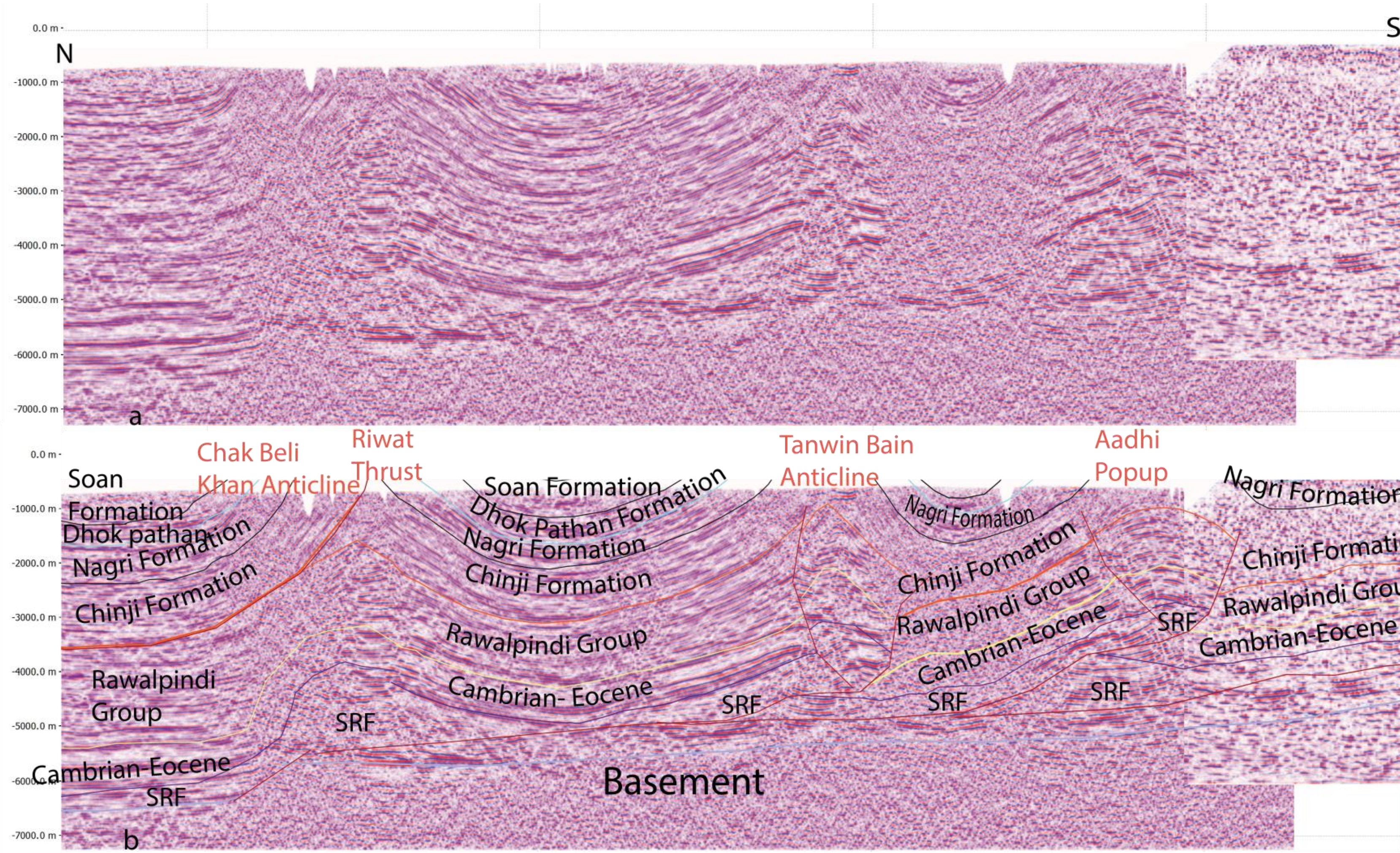

Figure 4.3 a) Un-interpreted and b) interpreted section SOX-S88-04 (SRF: Saltrange Formation).

To the south of Aadhi Popup structure, Qazian anticline is present on the seismic section GO-785-PTW-12 (Figure 4.4 and 4.6). Basement on this seismic line is identified at 5km depth. Qazian anticline is a salt-cored pop-up structure. Southern part of the seismic line contains is continuation of Domeli Thrust which is well observed on the seismic line “G805-PTW-04A” (Figure 4.5 and 4.6).

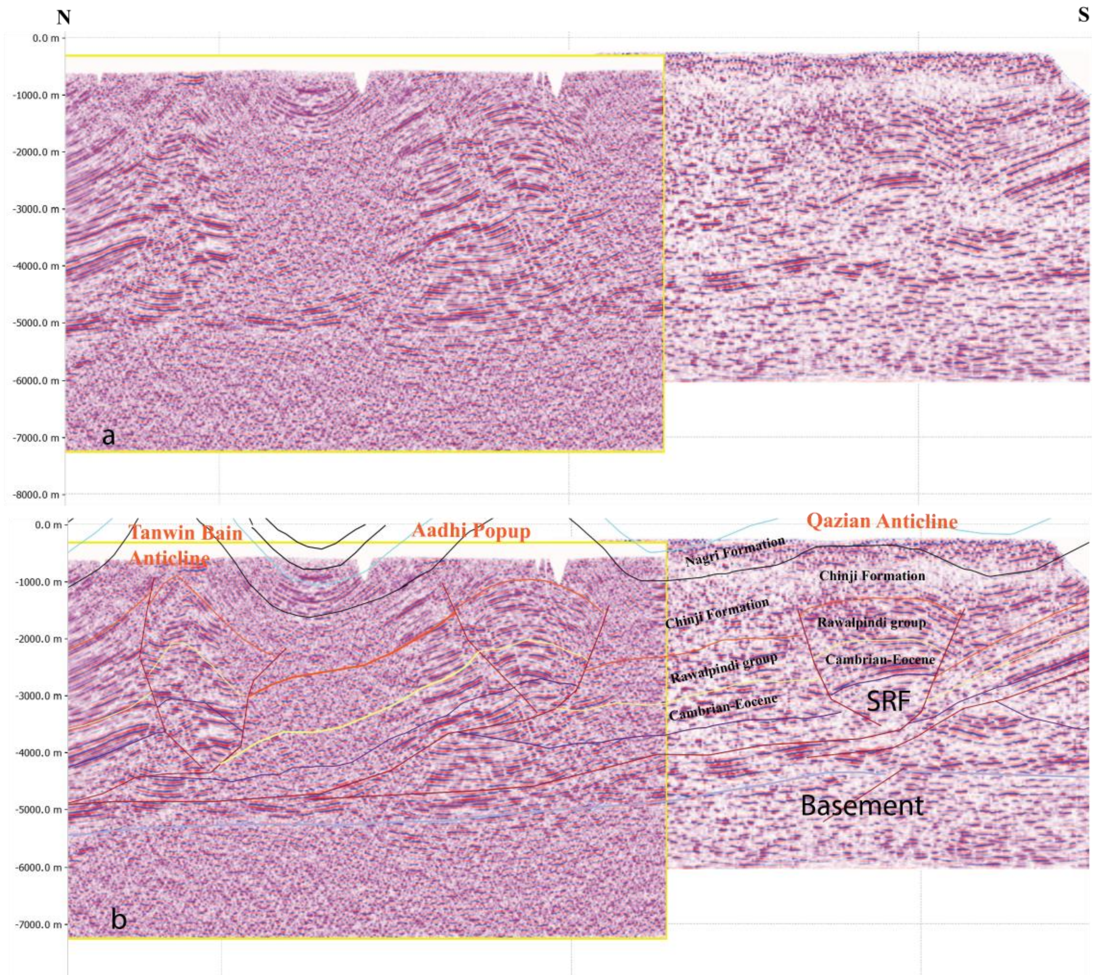

Figure 4.4 a) Un-interpreted and b) interpreted seismic section GO-785-PTW-12 (SRF: Saltrange Formation)

On seismic profile GO-785-PTW-12, basement is identified at 4.3 km depth at the northern margin of the seismic line where Domeli Thrust crops out at the surface. A significant decrease in the thickness of the Salt is observed at the south of Domeli Thrust. Mehesian structure developed to the south of Domeli Thrust and faulting is restricted by Miocene Rawalpindi Group. To the south of Mehesian structure, Rohtas anticline is developed on the hanging wall of Rohtas back thrust. Mehesian fore thrust and Rohtas Back Thrust creates a triangle zone. Pabbi anticline is located at the south of Rohtas anticline and it is the southernmost structure of the Saltrange (Figure 4.5 and 4.6).

4.3.4 Geological interpretation/Balanced Cross Section.

Dhurnal Back Thrust developed as passive roof thrust above the Dhurnal Pop-up structure. Dhurnal pop-up is followed by triangle zones on each side of the structure. Faulting at Dhurnal popups and adjoining triangle zones is restricted at the Murree and Kamlial Formations of Rawalpindi Group. A passive decollement surface at the top of Kamlial Formation that is the oldest unit displaced, is outcropped at Dhurnal Back Thrust. Middle Siwaliks (Chinji, Nagri, Dhok Pathan Fmn) exhibits same trend along the Dhurnal Back Thrust as the Kamlial Formation. Upper Siwaliks units (Soan Formation and Recent sediments) exposed in the Soan syncline exhibits angular relationship to Middle Siwaliks at the southern boundary of the Soan Formation. To the south, Riwat Thrust developed as the passive roof thrust and its associated fault propagation fold called Chak Beli Khan Anticline. Angular relation between middle Siwaliks and upper Siwaliks is observed both in the field as well as in the seismic section within Soan Syncline. Soan Formation observed in the Soan syncline is sub-horizontal (dipping 7° SE). Basement step is observed below the Riwat Thrust, which causes salt to ramp along this step (Figure 4.6).

To the south, Tanwin Bain Anticline is developed as fault propagation fold and faulting is restricted to the Murree and Kamlial fmns. Tanwin Bain Anticline and Chak Beli Khan Anticline are separated by the broad syncline, which include the sparsely distributed deposits of Upper Siwaliks (Soan Formation). Aadhi popup is developed to the south of Tanwin Bain Anticline that is a salt cored pop up. Middle and Upper Siwaliks are folded above Aadhi popup structure. Aadhi popup is developed in Middle Siwaliks and Rawalpindi group, upper Siwaliks are not observed in the filed on either limbs. To the south of Aadhi, Qazian anticline is developed as pop up. It is not very well exposed structure on surface and mostly cover under recent alluvium however, interpretations from the seismic section suggests that Qazian structure is restricted to the Middle Siwaliks (Figure 4.6). The south of Qazian structure, Domeli structure developed as faulted asymmetrical overturned anticline. The oldest stratigraphy exposed along Riwat structure is Eocene carbonates (Sakesar limestone).

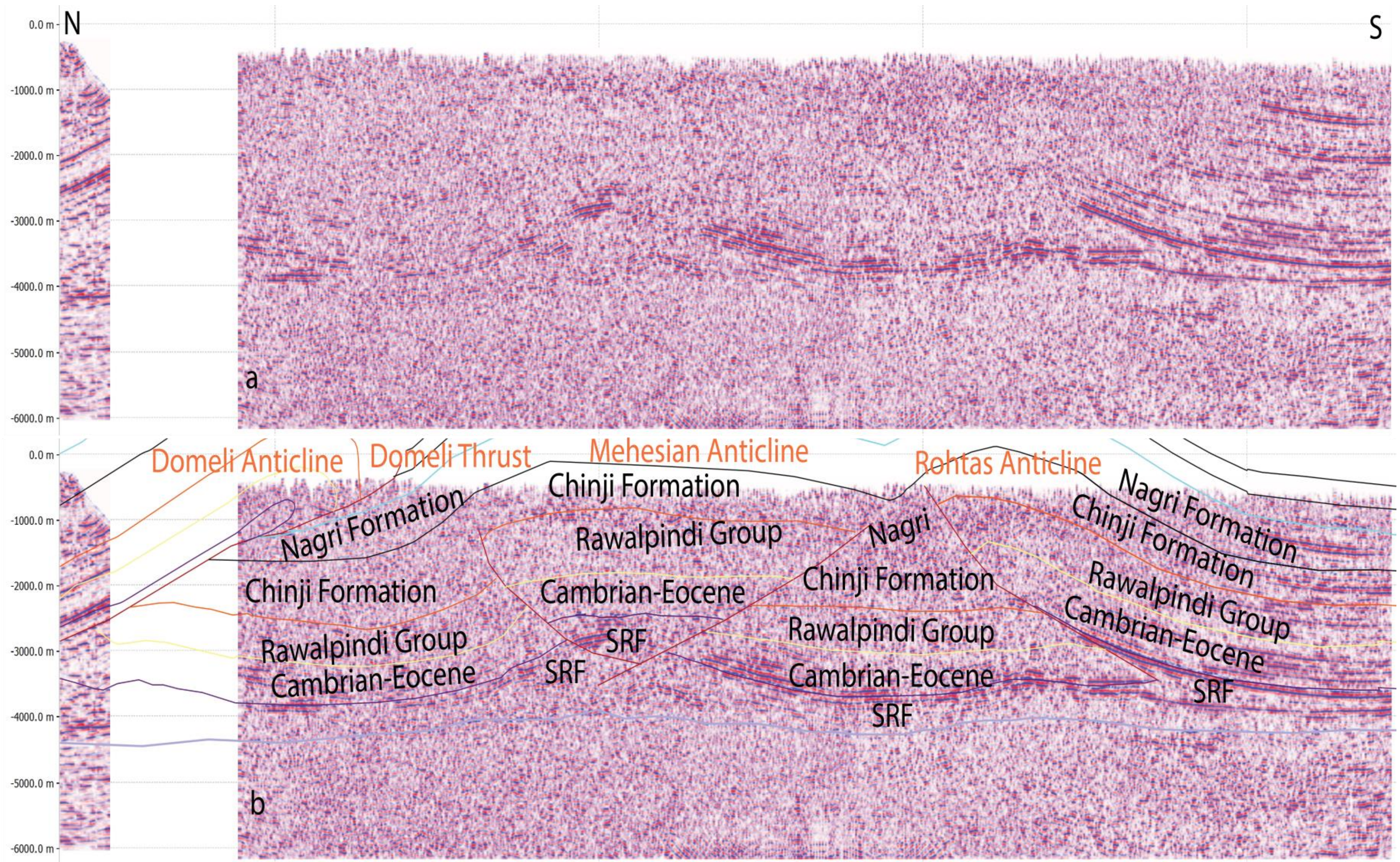

Figure 4.5 a) Un-interpreted and b) interpreted seismic section “G805-PTW-04A” (SRF: Saltrange Formation).

To the north of the Domeli Thrust debris accumulated in the syncline which are dated (Raynolds, 1980) in the north of Domeli Thrust are 2.5 Myr old which contain nummulitic nodules derived from Eocene. That suggest the youngest possible age for the development of Domeli Thrust is 2.5 M.yr (Figure 4.5).

To the south of Domeli, Mehesian anticline developed as fault propagation fold. Strata from Rawalpindi group is exposed in the core of Mehsian anticline. Middle and upper Upper Siwaliks sequence was observed on the flanks. To the south east of Mehesian, Rohtas anticline developed as fault propagation fold over back thrust. Between Mehesian and Rohtas structure a triangle zone is developed. Upper Siwaliks were observed in the filed as a surface expression of Rohtas structure. Strata in the crust of Rohtas structure are sampled (Raynolds and Johnson, 1985) and results suggest that the Rohtas structure is 1.4 M.yr old. To the south-east of Rohtas structure, Pabbi anticline developed as asymmetric anticline over a blind thrust, which displaced the older rocks. Surface expression of Pabbi anticline are upper Siwaliks. Sediments sampled from the Pabbi anticline are 0.4 M.yr old (Opdyke, 1979) (Figure 4.6).

4.3.5 Cross Section Restoration.

Shortening is estimated in Eastern Potwar Plateau by restoring Section AA`. Total length of the section is 137.9km. From the south, the Pabbi anticline accommodated 280m of shortening. Rohtas anticline developed on back thrust accommodated 3.9km of shortening. To the north of Rohtas anticline, Mehesian anticline accommodated 4.2 km of shortening. Domeli anticline and Dolmeli Thrust accommodated 7.5 km of shortening. Structures present in the north from Qazian to Tanwin Bain anticline accommodated combined 5.8 km of shortening. Chak Beli Khan Anticline and Riwat Thrust accommodated 2.8 km of shortening. Dhurnal Back Thrust accommodated 918m of shortening, below the Dhurnal Back Thrust Dhurnal pop up and triangle zones accommodated 3.8 km of shortening. In total whole section (measured at the top of Murree/Kamlial Fmn) underwent shortening of 29.7 km of shortening which is 21%. Siwaliks underwent maximum (Chinji Formation) 12.7 km of shortening, which is 9%. Due to ductile nature of salt restored on top of SRF gives maximum amount of shortening 41.8 km that is 30.3% but it is not considered as correct amount of shortening (Table 4.1).

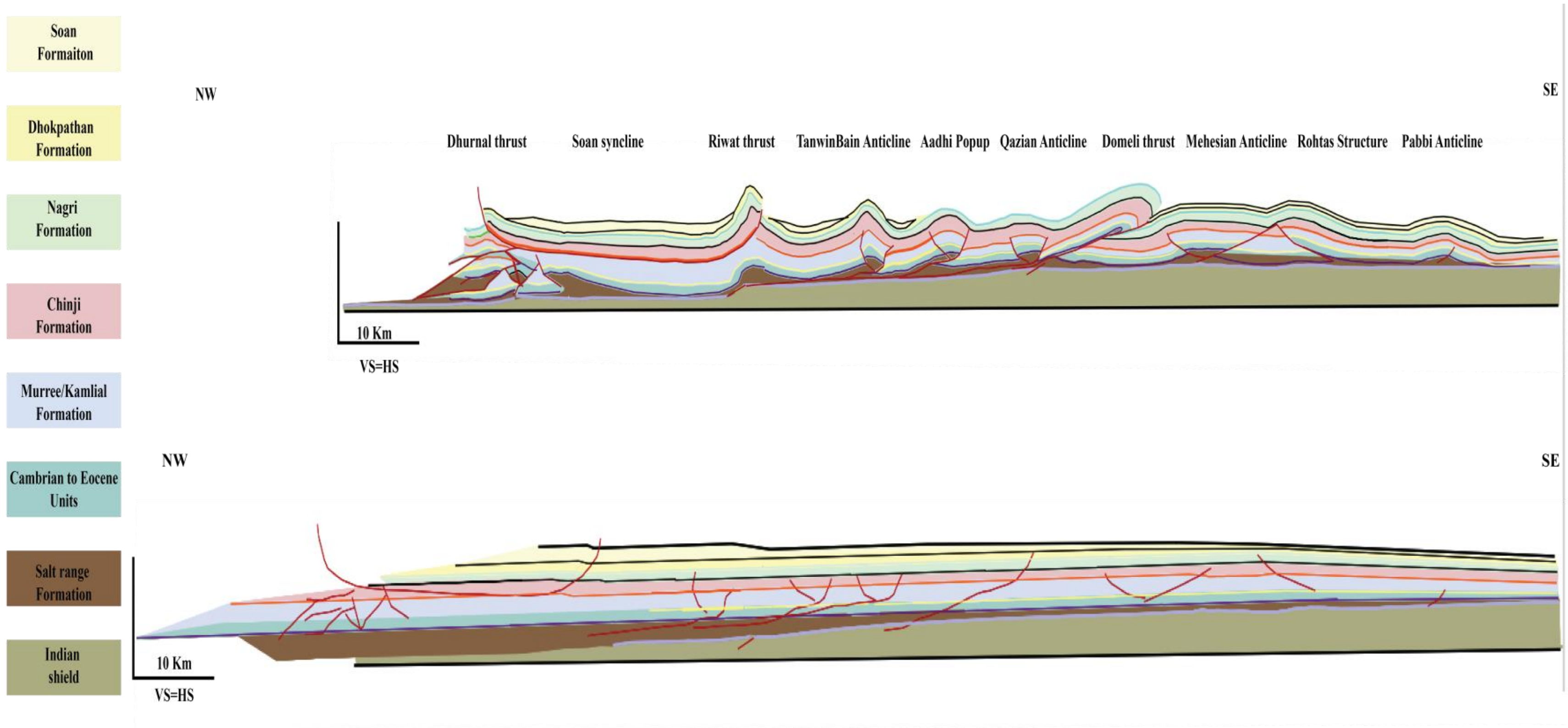

Figure 4.6 Constructed section AA` and its restored section. Section is restored from Top of SRF up to Top of Soan Formation

4.3.6 Western Potwar Plateau & the Saltrange

Two seismic line and one geological cross section are used to develop 118 Km long section BB`. Interpretation of seismic data is done using the comprehensive structural, stratigraphic, filed observations, and characteristics and displacement along the faults in the field.

4.3.7 Seismic Interpretations

Starting from north, seismic line SOX-NP84-44 cover Mianwala Thrust, Kanet Thrust Khapra Thrust and Ratana structures that is expressed in Figure 4.7 (Apendix A2). Basement is marked at 6 km depth on the southern margin of seismic section. Ratana structure is recognized by the thrust faulted salt-cored anticline. The surface expression of Ratana is concealed by the roof thrust called Kanet Thrust.

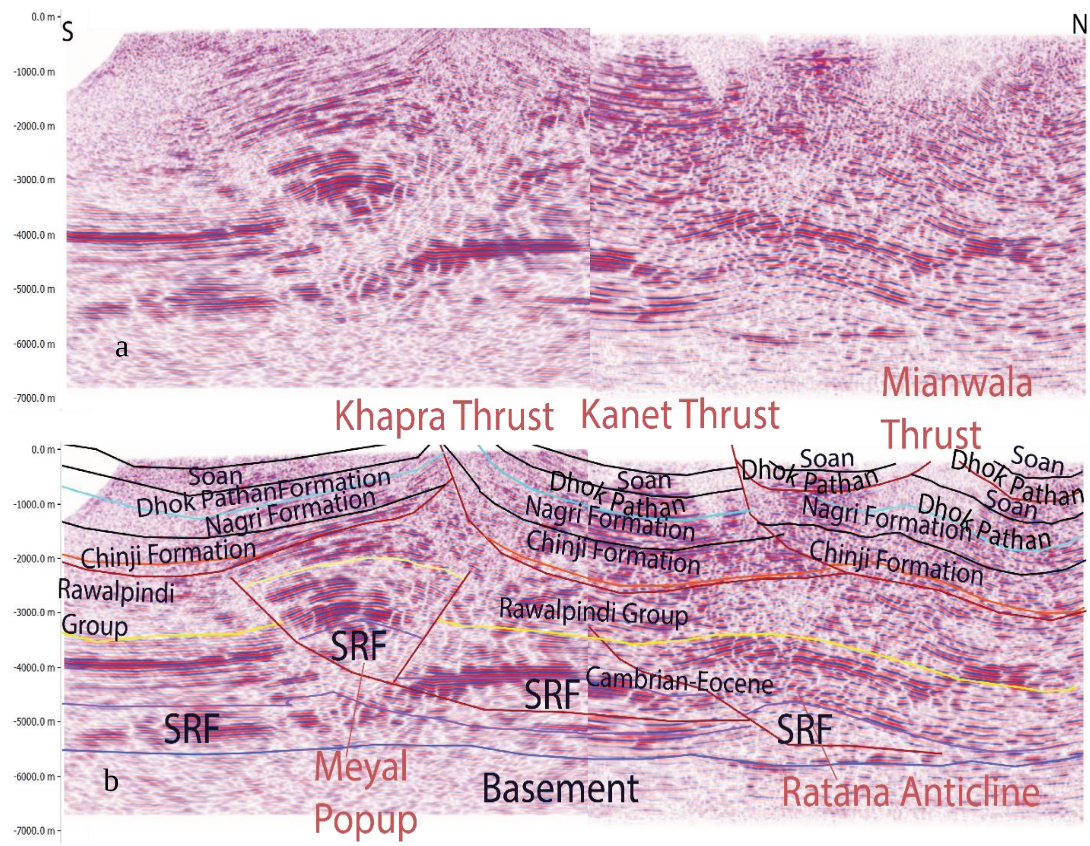

Figure 4.7 a) Un-interpreted and b) Interpreted sections SOX-NP84-44 and S97-MYL-07 (SRF: Saltrange Formation).

To the south, seismic line S97-MYL-07 represents Meyal popup structure concealed by a roof thrust called Kharpa thrust. Basement is identified at 5.5 km depth in this section and translucent inconsistent reflectors are marked as salt in the core of Meyal anticline. Missing section between S97-MYL-07 and G815-KK-28 is constructed using surface data and preexisting maps. Section G 815-KK 28 covers south of the Saltrange where basement is marked at 5 km depth (Figure 4.8). Northern part of the section remains undeformed (Figure 4.8 and Apendix A3). Southern part of the section is joined with the cross section of the Saltrange (Gee, 1989) where the Saltrange developed as Fault bend fold (Figure 4.8 and 4.9)

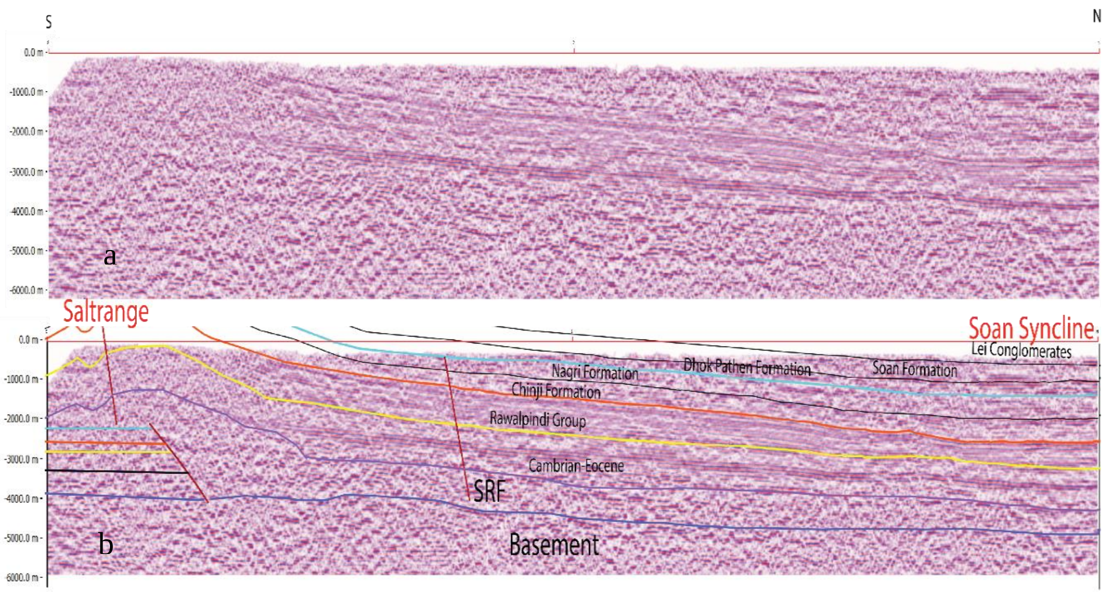

Figure 4.8 a) Un-interpreted and b) interpreted seismic section G 815-KK 28 (SRF: Saltrange Formation).

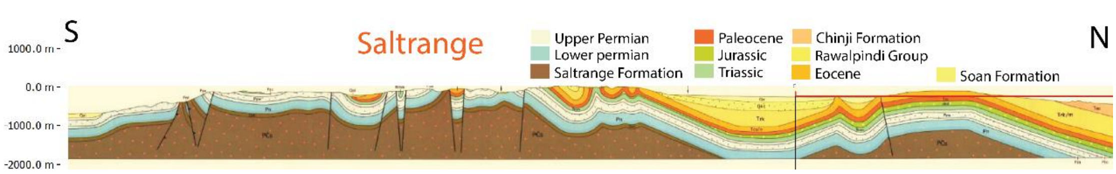

Figure 4.9 Cross section of the western Saltrange adopted from (Gee, 1989).

4.3.8 Balanced Cross Section

Mianwala thrust is developed as roof thrust, which displaced Upper Siwaliks units in the north of section (Figure 4.7). Kanet Thrust also developed in the upper part of Kamlial Formation and displaced Middle Siwaliks and Upper Siwaliks units. Back thrust developed between Mianwala thrust and Kanet thrust is equivalent of Dhurnal Back Thrust (northern margin back thrust of section AA`), Kanet thrust is developed over Ratana faulted salt-cored anticline. Displacement along Ratana structure diminishes in Rawalpindi Group strata (Figure 4.10). To the south, Kharpa thrust developed as roof thrust at the top of Kamlial Formation and displaced younger units above. Underneath the Kharpa thrust, Mial Popup displaced units from SRF to Rawalipindi Group. To the south of Mial structure line of section passes through the Dhullian anticline. Dhullian is an asymmetric salt-cored anticline. Further south until the Saltrange strata have shallow dip towards south. Western Saltrange is develop as fault bend fold over the basement step. Salt is ramped along basement normal step carrying overlaying sediment along (Figure 4.10).

4.3.9 Cross Section Restoration.

From south, the Saltrange translation over the basement ramp accommodated 27 km ~23.2 % of shortening. Siwaliks accommodated 29km ~24.5% of shortening in total. Shortening in above salt to the top of Rawalpindi group is 35.8 km ~ 30.2%. Shortening measured at top SRF is 45.8 km ~38.5%. Amount of internal shortening (total shortening Minus shortening due to the Saltrange ramping) in Siwaliks is 1.4 km ~1.2%. Amount of internal shortening in above SRF units up till Rawalpindi Group is 8237.4 ~7%. Amount of internal shortening in the SRF is 18204.5 km~15.3% (Figure 4.10)

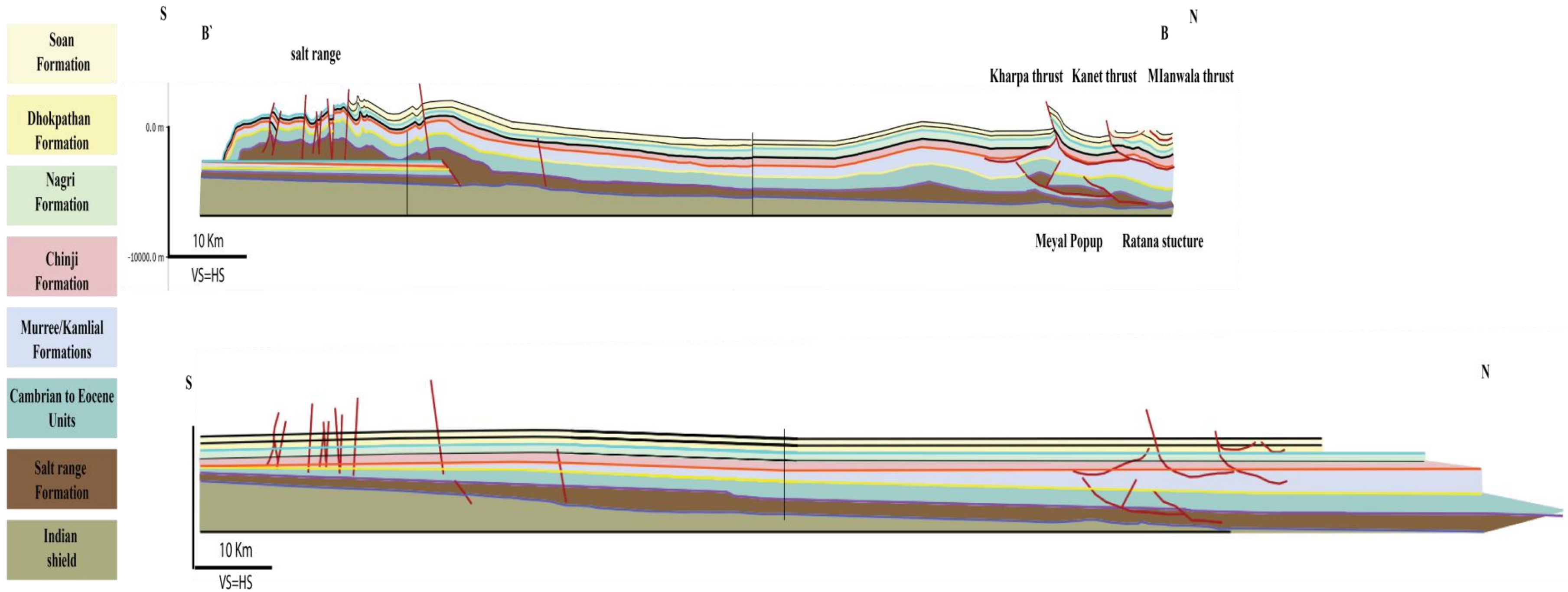

Figure 4.10 Section BB` along with its restored section. Section BB` is restored From SRF up till Soan Formation

Field observations, seismic and structural cross sections are used to develop and balanced cross section AA` and BB` in the Potwar Plateau and the Saltrange. However, Balanced cross-section AA` and BB` are almost 100 km away, so we used smaller seismic profiles to observe the gradual change in structural style from east to west in the Potwar Plateau depending upon the availability of the data.

Section CC` consist of seismic line GO-782-CW-13 is 41 KM long and 58 km east of section BB` and 42 KM west of section AA`. Basement is marked on the northern end of the seismic line at 6 km of depth and towards southern margin of seismic profile basement at 4.2 km of depth Figure 4.11 and 4.12. In the middle of the seismic profile, salt collapse structure is developed bounded by the faults from each side. Salt collapse structures is developed when vertical growth of salt is clogged during the thrusting of the Saltrange and salt migrated from growing dipper to further south. As a result whole structure collapse under the gravity. This typical salt tectonic feature develop where salt is still connect to its autochthonous level (Hudec and Jackson, 2007). Salt collapse structure created a negative shortening at the structure, after restoration and flattening the marker beds, whole section underwent 94 m of shortening (Figure 4.11).

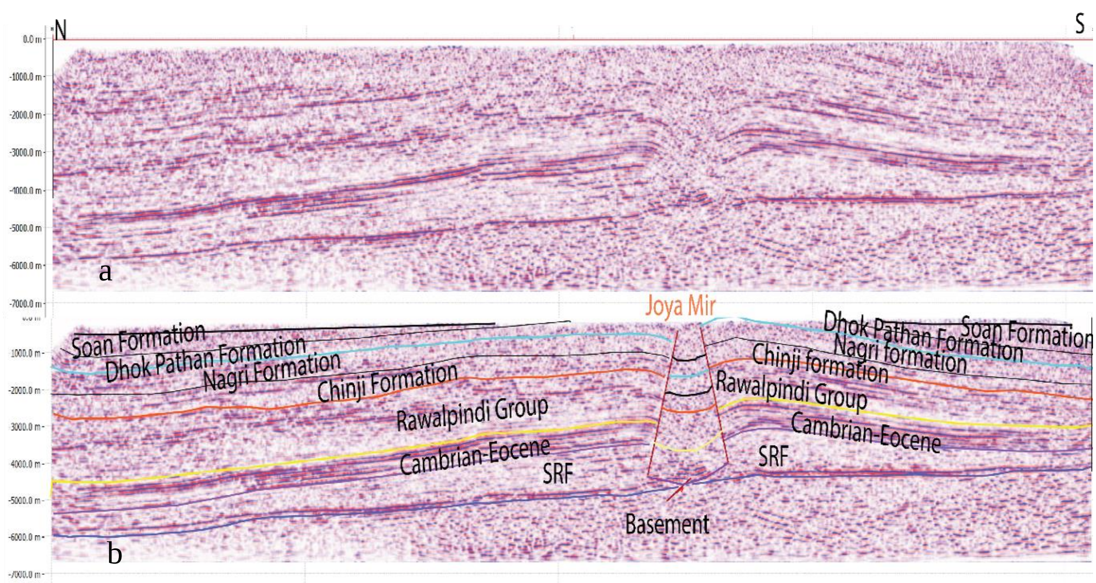

Figure 4.11 a) Un-interpreted and b) interpreted seismic section GO-782-CW-13 (SRF: Saltrange Formation).

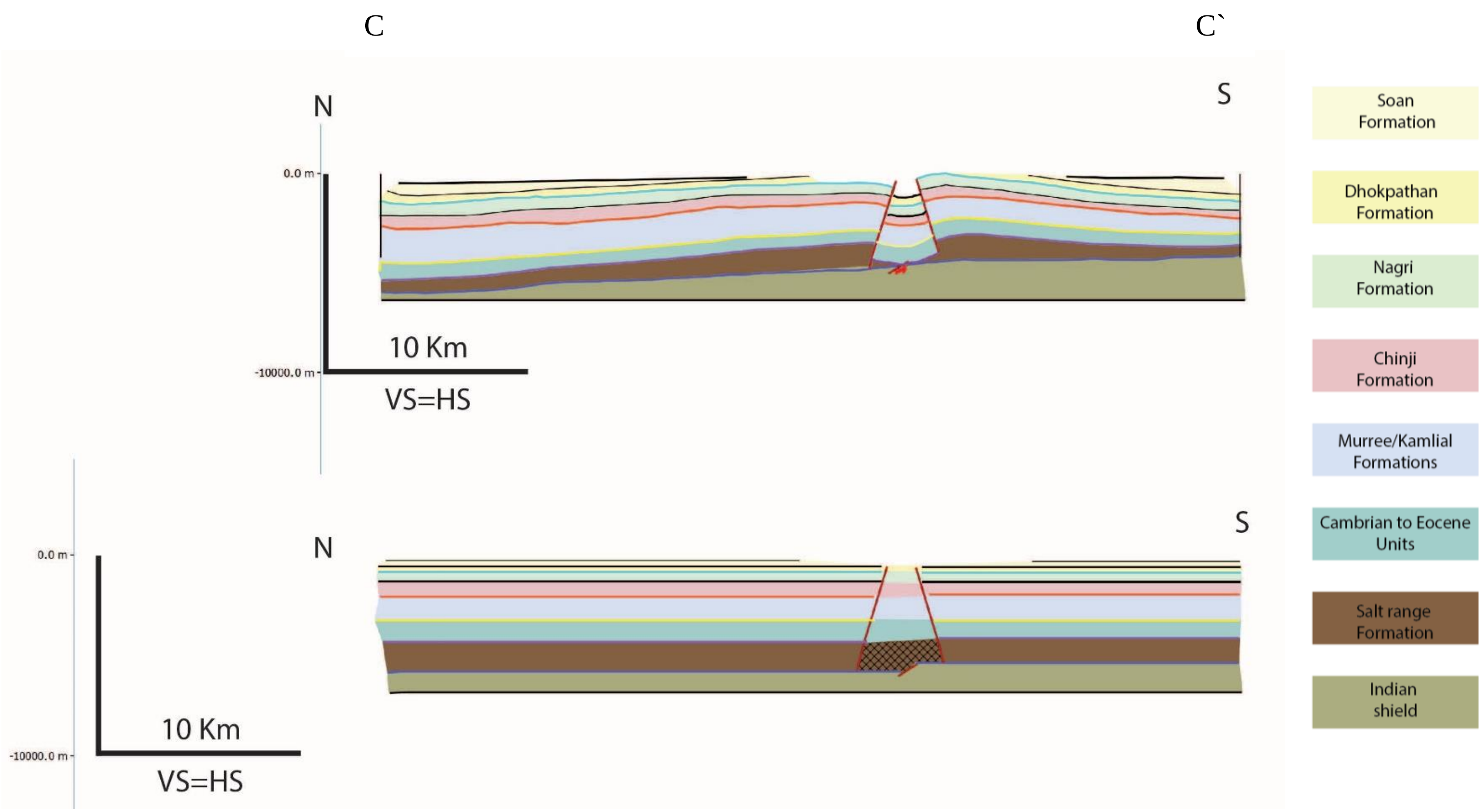

Figure 4.12 Section CC` along with its restored section. Section CC` is restored From SRF up till Soan Formation

Section DD` is 29 km long seismic section GPR-92-20 and located 33 km east of section AA`. Section consist of Riwat Thrust, Tanwin Bain structure, and Aadhi popup structures (Figure 4.13 and 4.14). From the North, Section DD` contains Riwat Thrust developed in two segments, Upper decollement developed in the Rawalpindi Group top. To the south, Tanwin Bain structure is more intensely deformed Anticline. Aadhi popup is faulted salt-cored popup structure however, roof sequence (Siwaliks) is not penetrated by the popup faults (Figure 4.13).

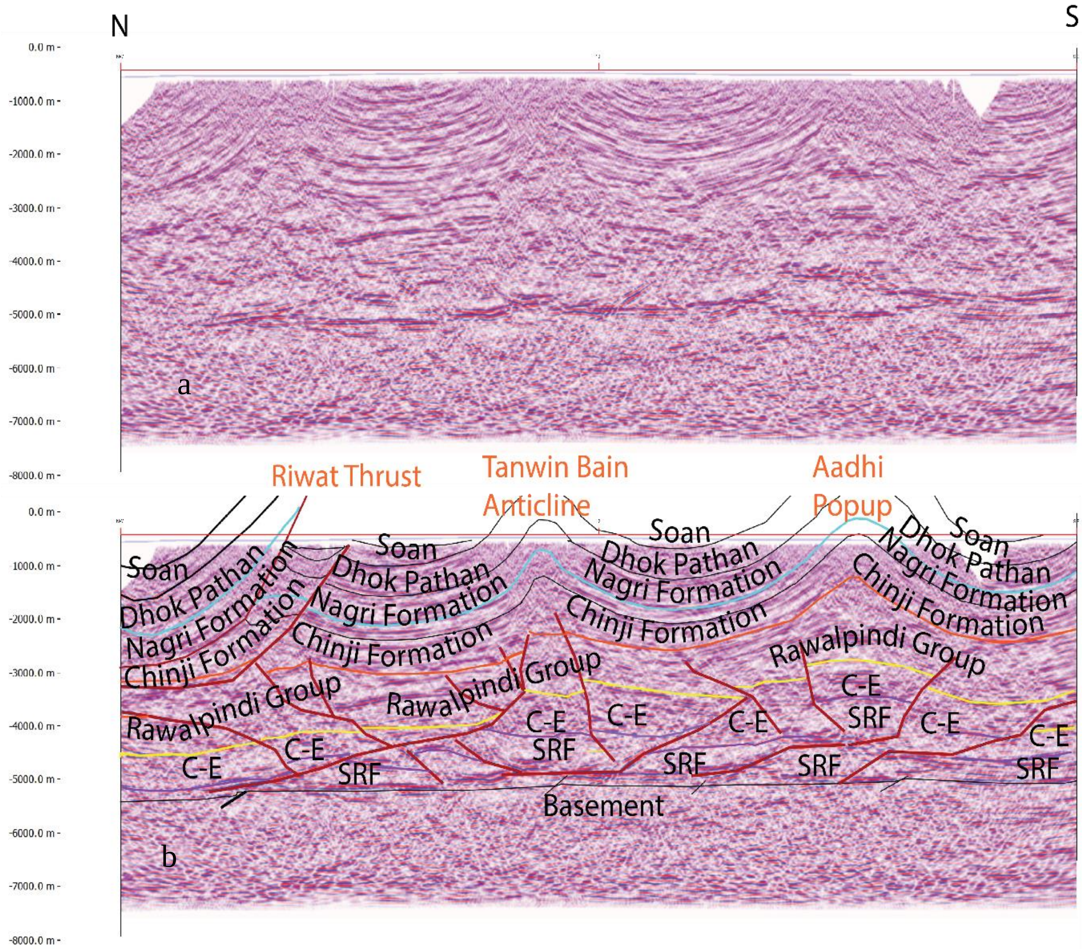

Figure 4.13 a) Un-interpreted and b) interpreted seismic section GPR-92-20(SRF: Saltrange Formation, C-E: Cambrian to Eocene)

In the section DD` Siwaliks accommodated 3.1 km of shortening which is 10.7%. Shortening observed at the top of Murree and Kamlil Formations is 7.3 km, which is 25 %. Shortening observed at the top of SRF is 17.1km, which is 58.3% (Figure 4.13).

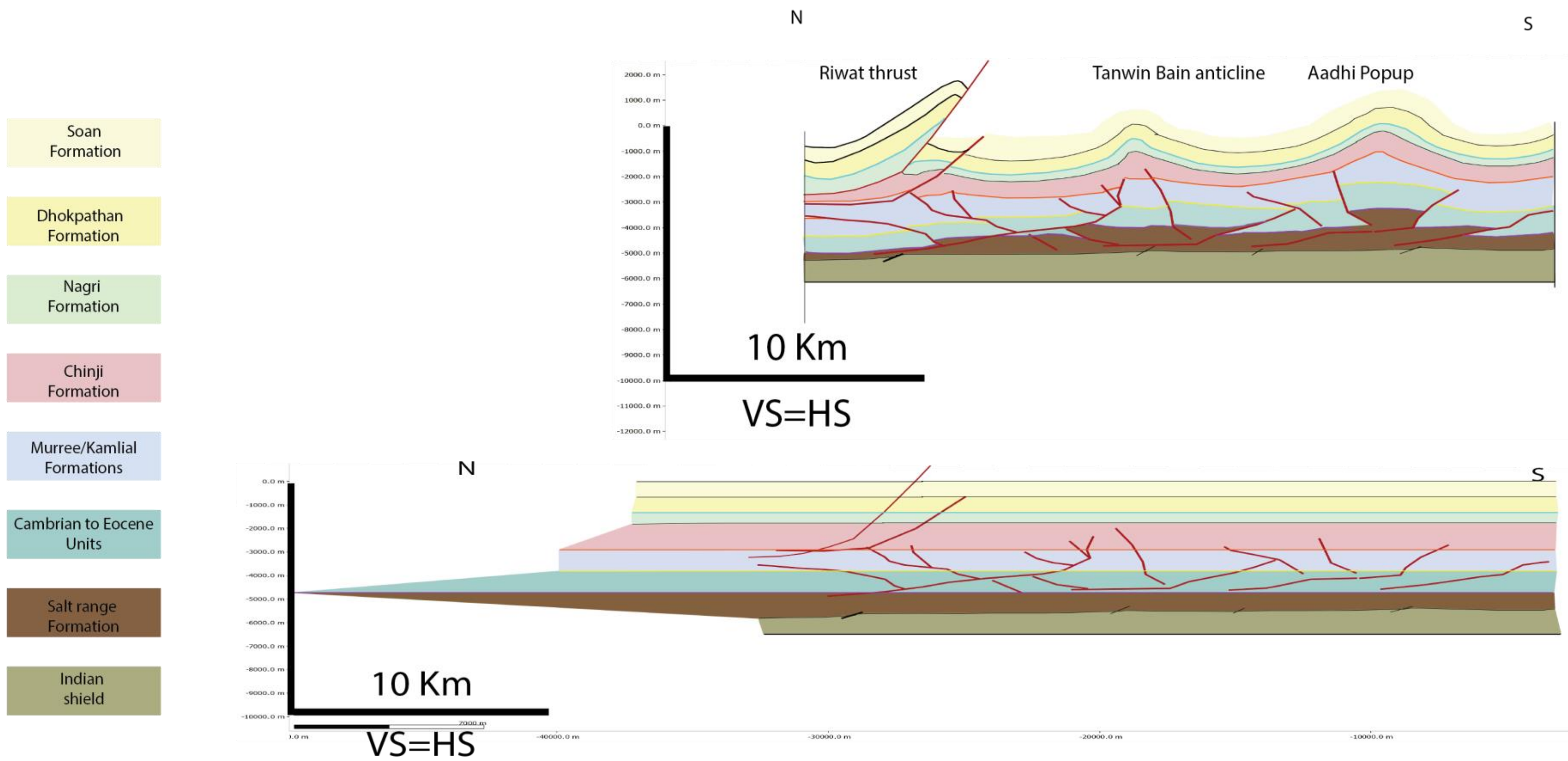

Figure 4.14 Section DD` along with its restored section. Section DD` is restored From SRF up till Soan Formation

4.3.10 Kohat Basin

Structural style of the Potwar Plateau and the Saltrange is compared with the adjacent Kohat basin. Section EE` in 42 Km long section contains the seismic profile of Chanda oil field in Kohat SHD-313 (Figure 4.15 and 4.16). Southern section is drawn based on field observation and previously published data (Abbasi and Mcelroy, 1991; McDougall, J.W, Hussain, A). Northern part of the section EE` developed imbricate stack on the sole thrust and terminates along roof thrust. Imbricate stack developed in the Paleozoic to Mesozoic rocks over the decollement originated at the base of Paleozoic units. Secondary decollement developed in the evaporites of Eocene age in Kohat basin (Bahadar khel salt/Panoba shale) which displaced Rawalpindi Group and Siwaliks. Structural saddle receive syn-tectonic sediments (Kalabagh Conglomerates) that is equivalent of Soan Formation. Secondary decollement terminates along Banda lakhoni thrust. Himalayan frontal thrust is known as Surgher thrust in Kohat basin, which initiated as fault propagation fold.

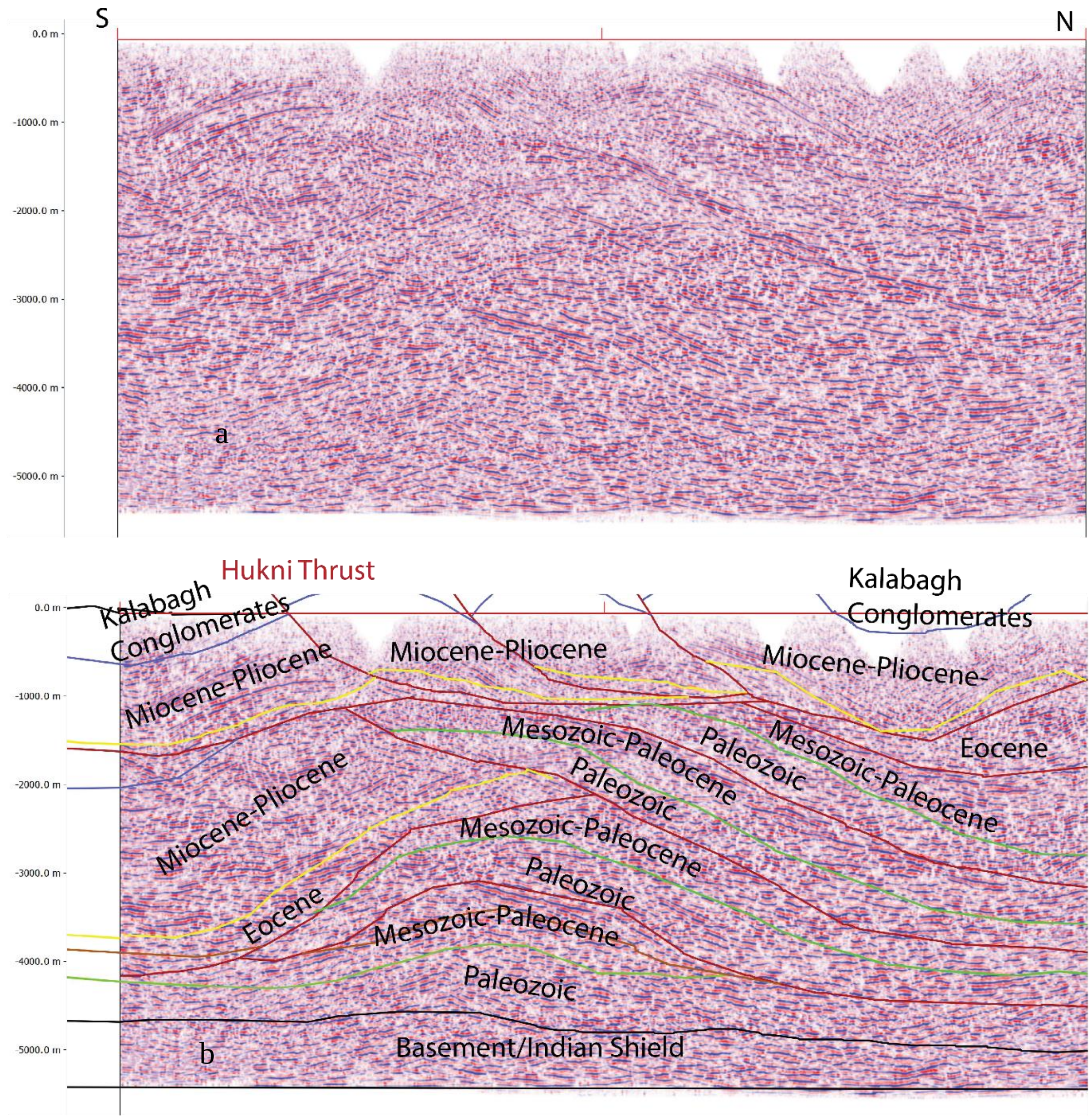

Figure 4.15 a) Un-interpreted and b) interpreted seismic section SHD-313.

4.3.11 Restored section

Total length of the section is 42 Km and shortening calculated above the secondary decollement is 15 Km which is 34%. Shortening calculated in the strata below the secondary decollement is below the and above the sole thrust is 36 Km, which is 85% (Figure 4.15).

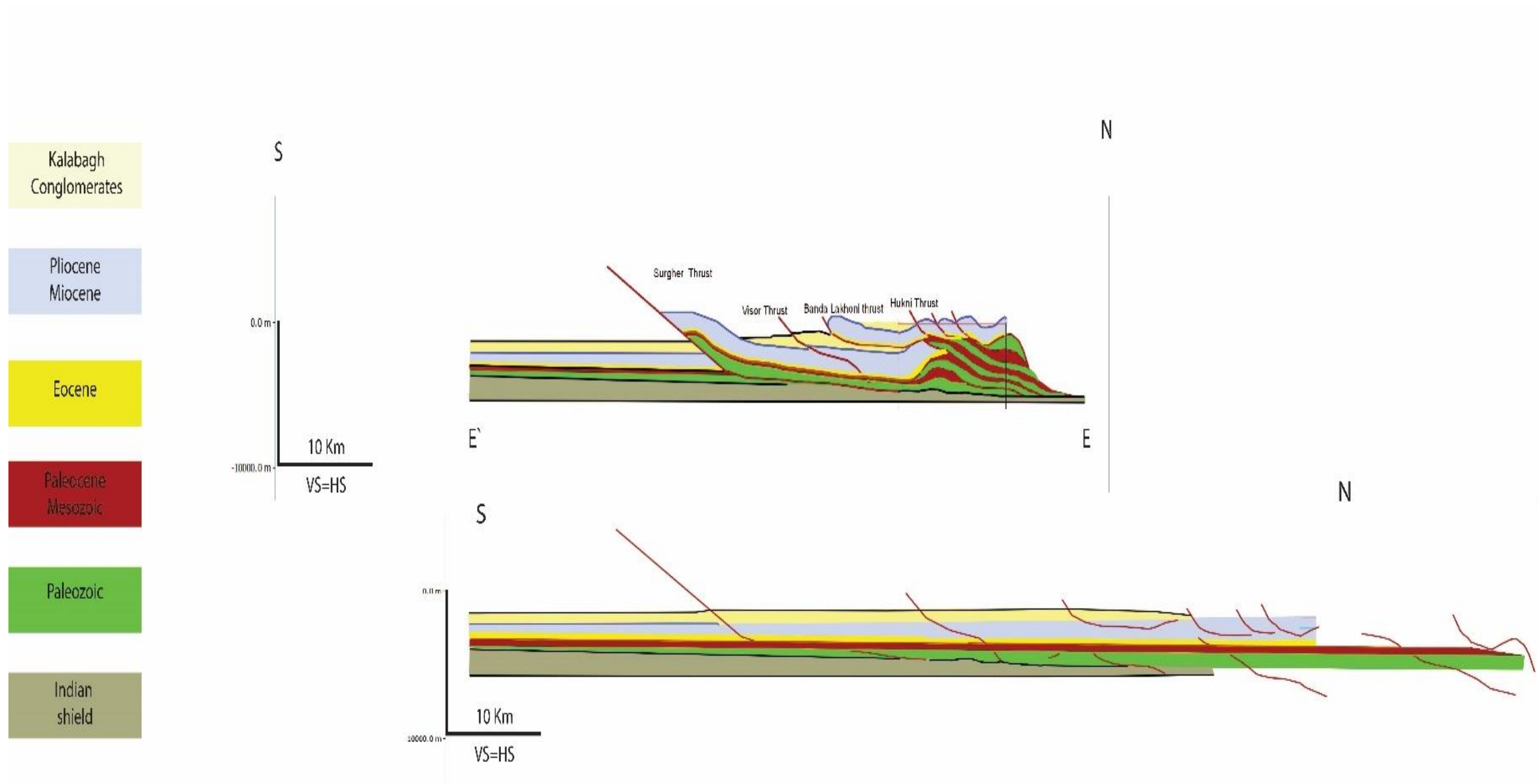

Figure 4.16 Section EE` along with its restored section. Section EE` is restored From SRF up till Soan Formation.

4.4 Discussions

4.4.1 Structural Style

Lateral variation in structural style along the Saltrange and the Potwar Plateau created significant difference in amount of shortening and deformation style. Behavior of decollement layer (SRF) plays an important role in the development of structures. In the Eastern Potwar Plateau and the Saltrange significant thickness of decollement layer is utilized in the development of structures. Tanwin Bain anticline, Aadhi popup, Qazian anticline, Domeli Thrust, Mehesian anticline, Rohtas anticline are salt-cored structures. Utilization of decollement layer in the development of structures decreases the thickness and effectiveness of decollement. In the case of Soan syncline salt is drained towards Riwat Thrust and Dhurnal Back Thrust developing a stratigraphic weld below the Soan syncline (Figure 4.6). Stratigraphic weld disrupts the connectivity of salt at autochthonous level (decollement) as a result salt is squeezed on the either side of Soan syncline in Dhurnal pop-up and towards Riwat basement step. Ramping of salt along the normal step developed salt pillow, which causes the removal of salt below the Soan syncline, which gives its initial geometry of syncline. Similarly, Tanwin Bain structure and Riwat Thrust and associated Chak Beli Khan Anticlines are separated by the syncline, which also developed a stratigraphic weld underneath the syncline axis (Figure 4.6). This causes the further movement of salt towards south so the salt pillow underneath the Riwat fault kept its growth making Riwat Thrust out of sequence. Development of stratigraphic weld increases the basal friction and as a result, a secondary decollement is developed at the top of Rawalpindi Group. Folding style in the eastern Saltrange is represented by fault propagation fold where folding originate at the decollement level and salt migrates in the core of folds. Stratigraphic welds and utilization of salt in the structures significantly decrease the effectiveness of the decollement, which is the reason that eastern Potwar Plateau and the Saltrange developed as fault propagation fold in the eastern Potwar Plateau Section AA` (Figure 4.6).

Compared to the western Potwar Plateau and the Saltrange where fault bend fold over basement normal step allowed the translation of the Saltrange towards south Section BB` (Figure 4.10). In Western Potwar Plateau and the Saltrange primary decollement is developed in the SRF evaporites, unlike eastern Saltrange relatively less thickness of decollement layer is utilized in the internal development of structures. Ratana faulted salt-pillow structure developed at decollement level, which disrupt the continuity of the sole decollement. Similarly, Meyal structure developed as popup structure and salt is drawn in the core of popup. This disruptions in the thickness of primary decollement activated Roof thrust above. Mianwala, Kanet and Kharpa roof thrusts are developed at the top of Rawalpindi Group, however under the Soan syncline and the Saltrange decollement layer remains connected to the autochthonous level that is the reason of very low internal shortening is western Potwar Plateau and the Saltrange as compared to eastern Potwar Plateau. Western Saltrange is developed as fault bend fold where salt is ramped over a basement normal step. Connectivity of autochthonous layer provided low basal friction for the units to glide over and translated to significant distance. Field evidence also suggest same as the SRF remain intact at autochthonous level in western Saltrange and salt is not exhumed to the surface unlike eastern Saltrange. Which exposes Billian wala Salt member and Bhander kas Gypsum members of SRF near Khewra salt mines. Central Saltrange is also similar to the western Saltrange where decollement layer is connected and salt collapsed diaper (Meyal Structure in Figure 4.12) is the evidence that once structure developed as salt anticline and later connected decollement layer at the base of the structure migrated that salt towards south. Section DD` is the eastern most section in the Potwar Plateau suggest the same structures continued which are observed in the section AA` structures in section DD` are more deformed and accommodated more internal shortening in the east.

Structural style in Kohat basin is relatively more brittle as compared to the Saltrange and the Potwar Plateau. Primary decollement developed in SRF northern Kohat developed as imbricate stack over SRF up to the Paleocene rock (Figure 4.16). A secondary decollement is developed at the Eocene Bhaader Khel Salt and Panoba shales. However, Banda Lakhoni thrust is the southern limit of the upper decollement. No significant translation is observed above the Primary decollement (SRF). Multi fold utilization of decollement layer in the imbricate structures developed a relatively ineffective decollement layer at SRF, which developed relatively brittle deformation style as compared to the Potwar Plateau and the Saltrange.

4.4.2 Shortening

Maximum amount of cumulative shortening in the Potwar Plateau and the Saltrange is observed in the Western Potwar Plateau and the Saltrange (section BB`). Siwaliks accommodated 24.5% shortening and Rawalpindi group accommodated 30.2% shortening. Most of the shortening in Section BB` is due to ramping of the Saltrange which is 23.3% as compared to the internal shortening in the Siwaliks is 1.2% and 7% in Rawalpindi group. So most of the shortening in western Potwar Plateau and the Saltrange is accommodated along ramping of the Saltrange. Eastern Potwar Plateau and the Saltrange section AA` accommodated 9% shortening in Siwaliks, 21% shortening in Rawalpindi group. No ramping is observed along the eastern Potwar Plateau and the Saltrange. Further, towards east in section DD` the amount of shortening is increases to 10.7% in Siwaliks and 25% in Rawalpindi group (Table 4.1).

Kohat basin accommodated 59.2% of shortening above the secondary decollement developed in the Eocene rocks. Shortening accommodated above the primary decollement (SRF) is 85%. Which is relatively higher as compared to the Potwar Plateau and the Saltrange (Table 4.1).

Table 4. 1 Comparison of shortening along restored sections

Section / stratigraphy	Cumulative Shortening in AA`	Cumulative Shortening in BB`	Cumulative Shortening in CC`	Cumulative Shortening in DD`	Internal shortening in AA`	Internal shortening in BB`
Siwaliks	9%	24.50%	0.20%	10.7%	9 %	1.20%
From top of SRF to Murree/Kamlial	21%	30.20%	0.20%	25%	21%	7%

Cumulative Shortening in EE` above Eocene	Cumulative Shortening in EE` Above salt & below Eocene
59.20%	85%

4.4.3 Rate of Shortening.

Section AA` provides not only good insight of the subsurface but also good outcrop exposures along the section provided the age constrain of the deformed rock and development of structures. Age of the development of Domeli fault propagation fold is 2.5 M.yr calculated by Raynolds (1980) and our shortening calculation up to Domeli structure form the south is 16 km. Similarly Rohtas deformation was dated previously by Paleomagnetism is 1.4 My (Raynolds and Johnson, 1985). Shortening calculation suggest that the amount of shortening up till Rohtas structure from south is 4.2 km. Riwat Thrust is a reactivated thrust however, truncation of Dhok Pathan Formation along Soan Formation suggested Riwat structure initiated before Soan Formation. We calculated the oldest age of Soan Formation is 3.7 M.yr (Chapter 2) and oldest part of Dhok Pathan Formation is aged 5.5 M.yr (Tauxe and Opdykes, 1982) (Table 4.2).

Table 4. 2 Comparison of shortening of each structure against age of deformation along section AA`

Structure	**Amount of shortening at structure(m)**	**Total amount of shortening(m)**	**Time of deformation initiation(M.yr)**
Dhurnal popup	3882	29471.2	5.5
Dhurnal Back Thrust	918	25589.2	5.3
up to Riwat Thrust	2847	24671.2	5.1
up to Tanwin Bain Anticline	5835.5	21824.2	4
Domeli Anticline	7526.7	15988.7	2.5
Mehesian/Lehri Anticline	4247	8462	2.3
Rohtas Anticline	3935	4215	1.4
Pabbi Anticline	280	280	1.1

Cumulative shortening is plotted against time of initiation of structures. Graph (Figure 4.17) shows two distinct trends of rate of shortening. From 5.5 to 2.5 M.yr calculated rate of shortening is 4.5mm/yr and from 2.5 to 1.1 M.yr is 6.4mm/yr giving an average rate of shortening is 5.4mm/yr in last 5.5 M.yr.

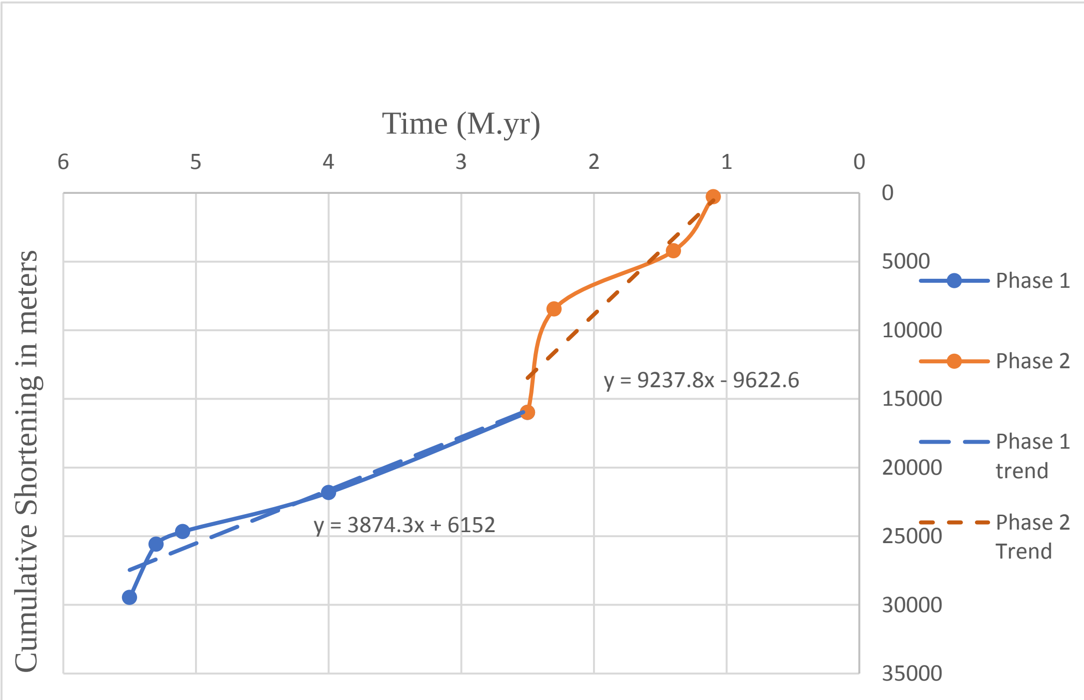

Figure 4.17 Rate of Cumulative shortening indicating two distinct Phases of shortening.

4.5 Conclusions

The Saltrange and the Potwar Plateau are deformed under relatively ductile deformation as compared with Kohat basin where relatively brittle deformation accommodated relatively more shortening. This lateral variation developed a lateral ramp (Kalabagh Fault) on the western margin of the Saltrange and the Potwar Plateau

The Saltrange developed as fault bend fold in the western Saltrange and fault propagation fold in Eastern Saltrange. Lateral structural variation along the Saltrange and the Potwar Plateau developed differential amount of shortening within the Potwar Plateau and the Saltrange.

Cumulative shortenings increase from east towards west in the Potwar Plateau and the Saltrange. However, internal shortening decrease from east towards west in the Potwar Plateau and the Saltrange.

Average Rate of shortening calculated is 5.4 mm/yr in last 5.5 M.yr including two phases of deformation, first phase from 5.5 to 2.5 M.yr with rate of shortening is 4.5mm/yr. During second phase, rate shortening was 6.4 mm/yr in last 2.5 M.yr.

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS

Tectonic loading and development of tectonic wedge squeezed salt from the northern Potwar plateau towards the Saltrange. Removal of salt form subsurface opens of the new accommodation space, which is filled by the syn-tectonic sediments (Soan Formation, Lei conglomerates) below the Soan syncline, near Mujahad village. Salt is exhumed near eastern and central Saltrange represents the possibility of relatively more thickness of autochthonous salt layer, which helped salt to develop as an open toe (Schultz-Ela et al., 1993).

Salt glide along the surface of basement ramp however, change in the attitude of the basement ramp can change the structural style on the surface. Central and western Saltrange appears to be developed over the frontal ramp however, change in the eastern Saltrange structural style might represents the presence of the oblique ramp in the basement. Frontal ramp and oblique ramp inflection points might develop structures such as Jhelum Salient. However sediments above salt is involved in deformation in the eastern Saltrange suggest that significant internal shortening is developed in the eastern Saltrange as compared to the western Saltrange. Relatively younger strata exposed at the propagating fold of Rohtas, Mehesian and Pabbi anticlines suggest relatively younger deformation compare to the western Saltrange. Fault propagation folds are developed in the Jhelum salient where the less thickness of the salt and the region close to the Jhelum Fault and the SR deformation front. The telescoping in the eastern side of the Saltrange and southern Potwar Plateau suggest that relative increase in the basal friction.

To further west of western the Saltrange, Kalabagh Wrench zone is basement-controlled structure where development of lateral ramp in basement restrict the deposition of salt and the Trans Indus ranges were unable to move along with the

Saltrange because of the high friction of decollement making Kalabagh right lateral ramp.

Normal faults present in the Indian shield (in here called Basement step) are developed in Eo-Cambrian age providing the restricted marine environment for the salt deposition. Later after the convergence of India, a flexure developed in the Indian plate developing a new set of normal faults in Early Miocene, which open sedimentation space for the Rawalpindi group and by the time Indian flexure propagated south towards the Potwar Plateau these accommodation space are filled by the Siwalik. These normal faults are reactivated as thrust and provided a ramping surface for the ductile salt. Normal fault with the largest amount of throw, observed below the Riwat Thrust in the Potwar Plateau.

At northern margin of Soan Syncline and NPDZ, preferred horizon for the development of the secondary decollement is at the top of Kamlial Formation due to lithology contrast between top Kamlial Formation and Chinji clays. Top part of Kamlial is the compact sandstone and Chinji Formation is the red clays. It is the major density change observed in the stratigraphic units and all the stratigraphic units younger than Chinji Formation are loose and not well compacted. The secondary decollement is observed in the northern Soan syncline, western NPDZ (Ratana and Meyal) and south Eastern Soan syncline. In effectiveness of the basal decollement triggers a secondary decollement in the northern Potwar Plateau.

Translation is observed where the thickness of the main decollement layer is sufficient to respond to the shortening as the squeezing out towards the south creating the sub horizontal creep in the strata above. Here the structures developed as the salt growth structures like Joya Mir structure were collapsed at the later stage of deformation as salt continued movement to the further south. Western Saltrange developed as fault bend fold as the units above salt are carried to the thrust front. Salt entrapped structures such as the salt-cored anticlines retain the geometry of the original structures however structures that are collapsed as the salt is removed, may invert with the progressive deformation.

5.1 Vertical axis Rotations

Two-stage development of the Potwar Plateau and the Saltrange is established by considering the results of Paleomagnetism, Magnetostratigraphy, Paleostress inversions, structural style and shortening comparison. The Potwar Plateau and the Saltrange underwent net counter-clockwise vertical axis rotation in two episodes. First episode initiated in Early Pliocene and continued until 3.7 M.yr. First episode rotation is characterized by CCW vertical axis rotations present in Siwaliks until Dhok Pathan Formation. Units above Dhok Pathan Formation underwent not significant rotations unless reactivation. Soan Formation, which overlies Dhok Pathan Formation, underwent 0-7° of CCW in the second episode of vertical axis rotation.

Soan sub domain underwent significant rotation, which is observed in Soan Formation are reasoned by the reactivation of the Riwat Thrust and Dhurnal Back Thrust. All the sub domains underwent CCW rotations in the Potwar Plateau and the Saltrange except for the Mial sub domain, which is reasoned as the rotations are accommodated as slip along Pail-Vesnal and Kenhetti faults. Absence of significant amount of rotations in Soan Formation is associated with the post Saltrange development episode characterized by few degrees of CCW rotations. Soan Formation is the chronostratigraphic boundary between first and second episode of rotation. Our magnetostratigraphic results suggests that the oldest part of Soan Formation is 3.7 M.yr old and youngest is 1.95 M.yr old which suggest that Soan Syncline started to develop after deposition of Dhok Pathan Formation which is 5.1 M.yr (Johnson et al., 1985). From 5.1 M.yr to 3.7 M.yr initial thrusting along Riwat Thrust and Dhurnal Back Thrust was initiated. From 3.7 to 1.95 M.yr was the reactivation episode of Dhurnal and Riwat Thrusts. After 2.2 M.yr, Soan Formation underwent 30°of CCW vertical axis rotations which is considered as second phase of Vertical axis rotations which is more pronounced in Soan sub domain but not significant in the Potwar Plateau and the Saltrange.

5.2 Paleostress Inversion and Ams Results

Two different phases of deformation are identified in the Potwar Plateau and the Saltrange. First phase of deformation is characterized by the pre Soan Formaiton structures associated by initiation of thrusting in the Saltrange and early development of structures in the Potwar Plateau. Phase one of deformation initiated around in Early Pliocene and continued until 3.7 M.yr with the σ1 in 12°NE. Post Soan Formation deformation characterizes second phase of deformation started just before the end of deposition of Soan Formation(2.5 M.yr) and continued till present day. σ1 for the phase two (40° NW) of deformation is 52° away from σ1 of first phase (12NE). It is associated with the development of salt growth structures and exhumation of salt along the Saltrange.

Switching of σ1 from NNE to NNW during second phase of deformation is associated with post ramping translation along western the Saltrange (section BB`) ultimately developing Kalabagh Fault. This can also be justified with the presence of net CCW vertical axis rotations in the Potwar Plateau and the Saltrange.

5.3 Structural Style and Deformation

Comparison of shortening suggest that eastern and western part suggests that the Potwar Plateau and the Saltrange underwent differential amount of shortening. As compared with equivalent Kohat basin, shortening in the Potwar Plateau and the Saltrange developed on relatively ductile decollement providing low basal friction. Kohat basin underwent relatively more brittle deformation as the thickness of effective decollement is not sufficient to develop large translation along with western the Potwar Plateau. This sudden change in the basal friction resulted in the differential shortening between the Potwar Plateau and Kohat creating Kalabagh Fault. Eastern termination of the Potwar Plateau and the Saltrange marked by the Jhelum Fault, which is developed due to successive depletion of salt from central saltrange towards eastern margin of Potwar Plateau. Eastren Himalayan frontal fold and thrust is developed a very high critical tapper as compared to low critical tapper in the Potwar Plateau and the Saltrange suggesting deformation occurred on relatively higher basal friction towards eastern Himlayan front.

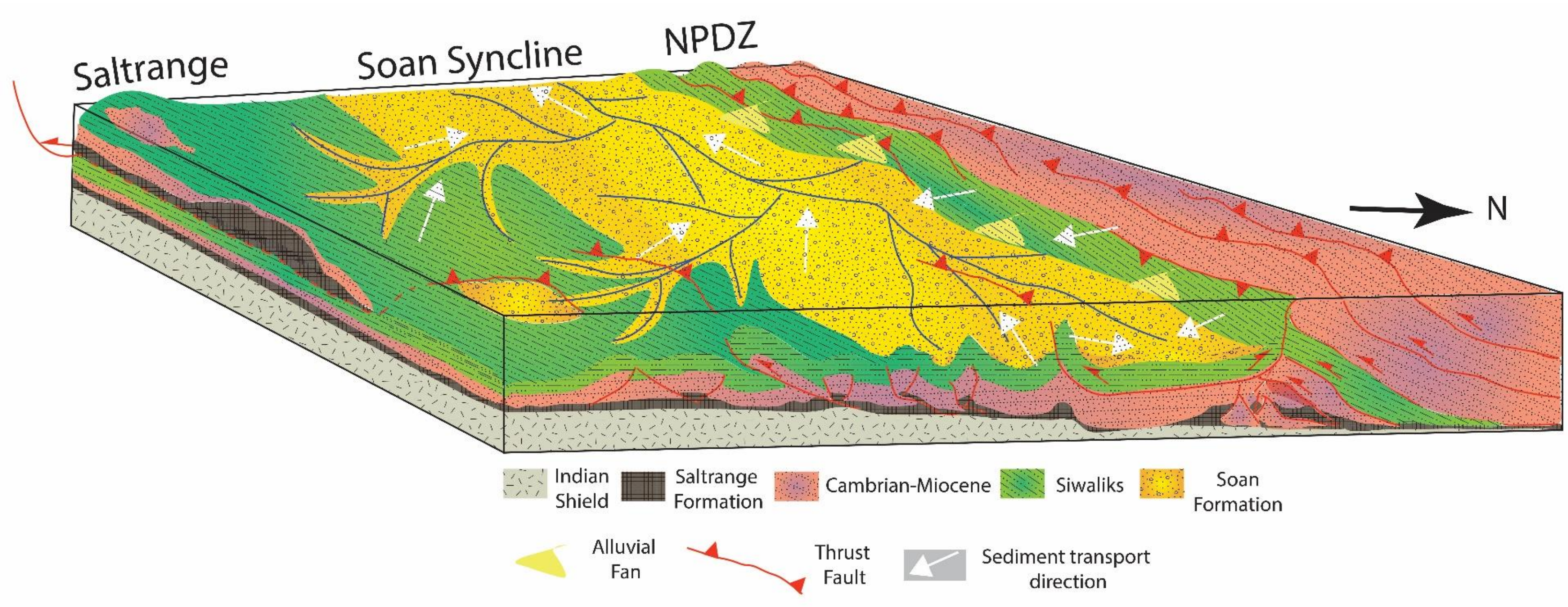

Figure 5. 1 Generalized tectono stratigraphic model of the Potwar and the Saltrange by the end of Pliocene.

Post first stage deformation, sedimentation in the soan syncline developed an angular relationship of Soan Formation with already deformed unit uptill Dhokpathan Formation during first phase of deformation. Continued deformation during the second phase cause the tilting and the development of the faults in Soan Formation (Figure 5.1).

Stratigraphic raltionhips and absence of Soan Formation in NPDZ suggests that NPDZ is developed earlier than the development of the Potwar Plateau and the Saltrange. Countinuation of NPDZ structures across the Kalabagh Fault (Surghar Range) suggest that the NPDZ and the Surgher range is developed diachronous to each other. However, the Surgher range is also frontal thrust and the presence of the younger units like Kalabahg conglomerates in the Kohat basin suggests that Surgher thrust remains active untill recntely whereas in NPDZ deformation is migrated to southern Potwar Plateau and the Saltrange which accommodates most recent shortening.

5.4 Regional Tectonic Implications.

Two-stage deformation of the Potwar Plateau and the Saltrange is consistent with shortening rates calculated by the amount of shortening and the development of structures derived from the eastern Potwar Plateau and the Saltrange. First episode of deformation occurred with a shortening rate of 4.5mm/yr, while second phase experienced shortening at 6.4 mm/yr. Average rate of shortening in eastern Potwar Plateau 5.5 mm/yr. Average shortening rate in western Potwar Plateau is 6.5mm/yr. Which is relatively higher than eastern Potwar Plateau and the Saltrange. Comparing the shortening rate (5.5mm/yr) with the deformation propagation rate

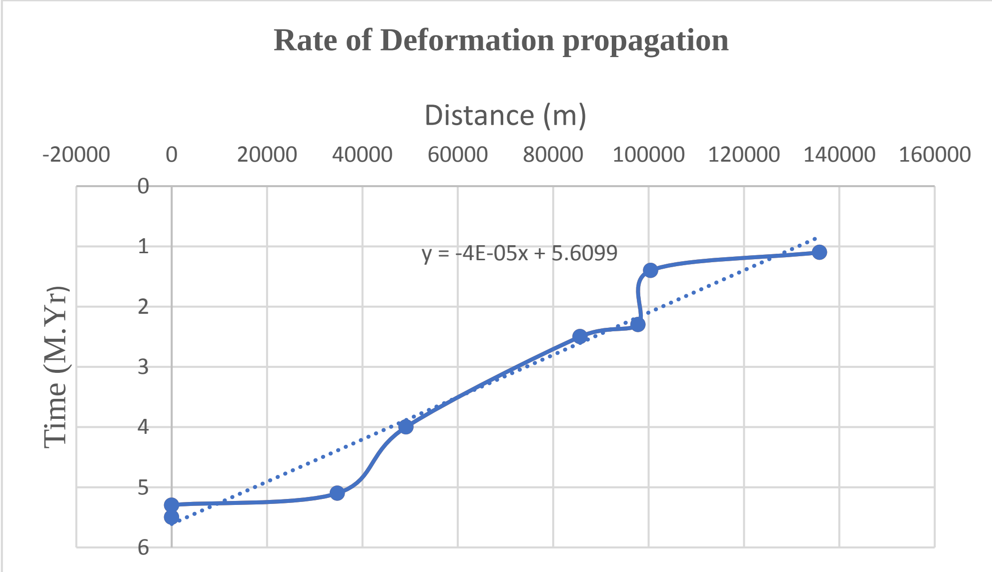

Figure 5. 2. Rate of deformation propagation in the Potwar Plateau and the Saltrange.

Table 5.1 Age of structures and the original distance between structures along Section AA`.

Structure	Origninal distance between s	Age of structure
Dhurnal popup	0	5.5
Dhurnal Back Thrust	0	5.3
Riwat Thrust	34766.1	5.1
Tanvin Bain Anticline	49143.4	4
Domeli Anticline	85654.2	2.5
Mehesian/Lehri Anticline	97817.4	2.3
Rohtas Anticline	100450.1	1.4
Pabbi Anticline	135872.2	1.1

which is 30.8 mm/yr (Figure 5.2) developed using Table 5.1. Deformation propagation rate calculated in the the Potwar Plateau and the Saltrange is fairly close to the convergence rate of India which is 30-35mm/yr (Jouanne, 2014). Only 5.5 mm/yr of 30 mm/yr is accommodated in the N-W Himalayan Front, which is the 18% of the total amount of convergence of Indian/Eurasian plates. Such a small amount of shortening observed in the Potwar Plateau and the Saltrange suggests either there is a significant seismic creep in the Potwar Plateau and the Saltrange or out of sequence displacement along older thrusts are accommodating most of the shortening. Earthquake record from N-W Himalayas suggests that the Potwar Plateau and the

Saltrange has very little earthquake record as compared to earthquakes recorded along the faults present in the north. Proposing that the out of sequence deformation Along Main boundary thrust (MBT) Main Central thrust (MCT) Main Karakorum thrust (MKT) and along HKS (Hazara Kashmir syntaxis). 18 % of the shortening which is accommodated in the Potwar Plateau and the Saltrange should be reflected in the earthquake records. However, active decollement in SRF suggest that rest 88% shortening is not accommodated along older thrusts but there must a significant creep in the Potwar Plateau and the Saltrange to accommodate such large amount of convergence, which is developed due to Indian/Eurasian collusion but not reflected as shortening along NW Himalayan front.

5.5 Conclusions

The Saltrange and the Potwar Plateau were deformed in two stages. First stage comprises of rapid vertical axis rotations along with relatively slow shortening rate. Second stage comprises of relatively slow rotations along with relatively fast shortening rate (Translation).

Soan Formation is the post-date first episode of deformation in the Potwar and the Saltrange, wihich is dated 3.7 Ma from oldest part by the magnetostratigraphic method.

Post-first deformation phase vertical axis rotations causes switching of $\sigma1$ from 12° NE to 40° NW, it is developed due to the significant translation along western Saltrange and development of Kalabagh Fault.

18 % of shortening of total amount of Indian/Eurasian convergence rate is accommodated in the Potwar Plateau and the Saltrange, rest of the shortening is accommodated as A-seismic creep within the Potwar Plateau and the Saltrange and by the out of sequence deformation in the north of NW Himalayan front.

Translation in the western Saltrange bounded by a lateral ramp and relatively ductile deformation along eastern Saltrange bounded by a left lateral strike slip fault suggests the Potwar Plateau and the Saltrange are developed in distinct deformation style as compared to Kohat basin in the west and eastern Himalayan front in the east.

The Kalabagh Fault and the Jhelum Fault developed as the relatively ductile basal friction changes to brittle basal friction. Sudden change in the case of Kalabagh and regressive change toward the east developed the Hazara Kashmir Syntaxis and the Jhelum Fault.

Brittle to relatively ductile transition within the Potwar Plateau developed a left lateral shear between Jhelum Fault and Kalabagh Fault, which is reflected as 1: Significant counter clockwise vertical axis rotations within Potwar and the Saltrange. 2: Switching of $\sigma1$ from NNE to NW 3: Lateral variation within the Potwar Plateau and saltrange causing differential amount of shortening.

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APPENDICES

Table A. Paleomagnetic results of sites included in each sub domains

Block name	sample/Formation name	N	Ns	Cutoff	S	mDec	mInc	R	k	α95	K	A95	A95min	A95max	ΔDx	ΔIx	λ
Nammal	CJ 07	13	13	45	11.2	326.9	35.8	12.8	54.7	5.7	52.6	5.8	4.3	16.3	6.1	8.6	19.9
	Daud Khel	4	4	45	7.8	348.2	39.7	4	108.4	8.9	108	8.9	6.9	34.2	9.6	12.3	22.5
	DP 25	12	12	45	7.3	347.4	39.2	11.8	70.1	5.2	125.2	3.9	4.4	17.1	4.2	5.5	22.2
	Block Mean	29	29	45	13.4	338.1	38.2	28.3	39.8	4.3	36.9	4.5	3.1	9.8	4.8	6.4	21.5
	Dhok pathan Fmn	12	12	45	7.3	347.4	39.2	11.8	70.1	5.2	125.2	3.9	4.4	17.1	4.2	5.5	22.2
	Kamlial fmn	13	13	45	11.2	326.9	35.8	12.8	54.7	5.7	52.6	5.8	4.3	16.3	6.1	8.6	19.9
Injira	DP 03	3	3	45	12.3	360	46.7	3	69.6	14.9	43.7	18.9	7.7	41	21.5	22.8	27.9
	DP 04	6	6	45	7.1	352.4	48.7	6	181.1	5	130.8	5.9	5.9	26.5	6.8	6.8	29.6
	DP 05	5	5	45	7.9	355.4	61.9	5	207.4	5.3	105.3	7.5	6.3	29.7	10.3	6.2	43.1
	DP 21	11	11	45	9.4	357.7	24	10.8	41.8	7.1	75.4	5.3	4.6	18.1	5.4	9.3	12.5
	DP 22	4	4	45	4.3	359	27.6	4	350.8	4.9	363.6	4.8	6.9	34.2	5	8.1	14.6
	Block Mean	29	29	45	14.2	356.9	38.5	27.7	21.7	5.9	32.8	4.7	3.1	9.8	5.1	6.7	21.7
	Dho kpathan fmn	29	29	45	14.2	356.9	38.5	27.7	21.7	5.9	32.8	4.7	3.1	9.8	5.1	6.7	21.7
Dhullian	Malawala kas	31	35	45	21	352.1	24.9	28.1	10.4	8.4	15.3	6.8	3	9.4	7	11.8	13.1
	Bora kas	48	49	45	21.7	343.3	33.5	44.2	12.4	6.1	14.2	5.7	2.6	7.2	6	8.7	18.3
	Dp 01	4	4	45	11.9	309	63.7	4	114	8.6	46.5	13.6	6.9	34.2	19.5	10.8	45.3
	Block Mean	80	88	45	21.7	345.9	31.2	72.9	11.1	5	14.2	4.3	2.1	5.2	4.5	6.9	16.9
	Chinji fmn	48	49	45	21.7	343.3	33.5	44.2	12.4	6.1	14.2	5.7	2.6	7.2	6	8.7	18.3
	Dhokpathan fmn	33	39	45	22.4	351.1	27.4	29.6	9.5	8.6	13.4	7.1	3	9.1	7.3	11.9	14.5
Mial	CJ 04	10	10	45	14.8	9.4	21.2	9.6	21.3	10.7	30.5	8.9	4.8	19.2	9.1	16	11
	DP 10	7	7	45	15.3	357.6	5.7	6.8	25.3	12.2	28.3	11.5	5.5	24.1	11.6	22.9	2.8
	DP 11	12	12	45	14.5	5.5	46.1	11.7	40.2	6.9	31.5	7.8	4.4	17.1	8.9	9.6	27.4
	DP 13	11	11	45	14.6	6.6	51.7	10.8	46.7	6.8	30.9	8.3	4.6	18.1	9.9	9	32.4
	DP 16	12	12	45	6	21.5	4.2	11.9	142.1	3.7	184.5	3.2	4.4	17.1	3.2	6.4	2.1
	Block Mean	52	52	45	19.7	9.7	27.6	47.3	10.9	6.3	17.3	4.9	2.5	6.8	5.1	8.2	14.7
	Chinji	10	10	45	14.8	9.4	21.2	9.6	21.3	10.7	30.5	8.9	4.8	19.2	9.1	16	11
	Dhok pathan fmn	42	42	45	20.6	9.8	29.2	37.8	9.8	7.4	15.8	5.7	2.7	7.8	6	9.4	15.6
Talagang	PS 06	15	15	45	9.8	350.1	32.9	14.8	67	4.7	69.8	4.6	4.1	14.9	4.8	7.2	17.9
	CJ 05	13	13	45	10.6	345.4	43.3	12.8	52.3	5.8	58.8	5.5	4.3	16.3	6	7.1	25.2
	Nagri	25	26	45	18.4	355.4	36.7	23.6	17.5	7.1	19.6	6.7	3.3	10.8	7.2	9.8	20.4
	Ng 03	11	11	45	7.5	353.1	30.9	10.9	71.9	5.4	117	4.2	4.6	18.1	4.4	6.8	16.7
	Ng 02	9	9	45	11.2	341.1	34.6	8.8	39.2	8.3	52.8	7.1	5	20.5	7.6	10.8	19
	NG 01	10	10	45	9.8	338.9	31.2	9.8	44.7	7.3	69.3	5.8	4.8	19.2	6.1	9.3	16.8
	DP 06	11	11	45	12	347.8	42.6	10.8	41.7	7.2	45.8	6.8	4.6	18.1	7.5	9	24.7
	DP 07	5	5	45	18.8	332	59.4	4.9	36.3	12.9	19	18	6.3	29.7	23.9	16	40.3
	DP 08	11	11	45	13.6	356.2	38.8	10.7	37.5	7.5	35.7	7.7	4.6	18.1	8.4	10.9	21.9
	DP 14	13	13	45	13.2	330.6	49.4	12.8	59.4	5.4	38.1	6.8	4.3	16.3	7.9	7.7	30.3
	DP 20	16	16	45	7.9	345.5	41	15.9	109.8	3.5	104.8	3.6	4	14.3	3.9	4.9	23.5
	Block Mean	139	140	45	15.2	347.2	39.3	134	27.9	2.3	28.9	2.3	1.7	3.7	2.4	3.2	22.3
	Soan_Fmn	11	11	45	12	347.8	42.6	10.8	41.7	7.2	45.8	6.8	4.6	18.1	7.5	9	24.7
	DhokPathan fmn	75	75	45	14.8	343	41.8	72.6	31.5	3	30.6	3	2.1	5.4	3.3	4	24.1
	Nagri Fmn	24	24	45	10.8	349.3	37.7	23.5	42.7	4.6	57	4	3.4	11.1	4.2	5.7	21.1
Chakwal	PS 03	6	6	45	11.5	347.5	26.5	5.9	52	9.4	49.7	9.6	5.9	26.5	9.9	16.3	14
	PS 04	12	12	45	9.5	349.7	36.8	11.8	52	6.1	72.5	5.1	4.4	17.1	5.5	7.5	20.5
	Ng 09	5	5	45	14.9	345.9	15.9	4.7	15.9	19.8	29.7	14.3	6.3	29.7	14.4	26.9	8.1
	DP 18	12	12	45	8.5	343.2	53	11.9	119.9	4	91.2	4.6	4.4	17.1	5.5	4.8	33.6
	Chakwal Baun	25	25	45	19.8	332.3	34	23.5	15.8	7.5	17.2	7.2	3.3	10.8	7.6	11	18.6
	Block Mean	60	60	45	17.8	340.7	36.4	56.6	17.4	4.5	21.1	4.1	2.3	6.2	4.4	6	20.3
	Dhokpathan Fmn	12	12	45	8.5	343.2	53	11.9	119.9	4	91.2	4.6	4.4	17.1	5.5	4.8	33.6
	Nagri Fmn	5	5	45	14.9	345.9	15.9	4.7	15.9	19.8	29.7	14.3	6.3	29.7	14.4	26.9	8.1
	kamlial Fmn	18	18	45	10.5	348.9	33.4	17.6	45.6	5.2	59.9	4.5	3.8	13.3	4.7	7	18.2

Soan	Rhata kas	36	39	45	23.6	330.6	36.8	33	11.8	7.3	12.1	7.2	2.9	8.6	7.7	10.5	20.5
	kulial kas	45	45	45	20.3	349.3	39.9	42.4	17.1	5.3	16.3	5.4	2.6	7.5	5.9	7.5	22.7
	Soan	40	42	45	22.5	338.3	37	36	9.9	7.6	13.2	6.5	2.7	8	6.9	9.4	20.6
	Soan 29	7	7	45	8.7	339.7	43.8	6.9	105	5.9	86.4	6.5	5.5	24.1	7.2	8.4	25.6
	Block Mean	127	133	45	22	340.8	38	117	12.5	3.7	13.9	3.5	1.7	3.9	3.7	5	21.4
	Soan Fmn	47	49	45	21	338.5	38.1	42.9	11.3	6.5	15.2	5.5	2.6	7.3	5.9	7.9	21.4
	Nagri Fmn	80	84	45	22.6	342.2	38	74.1	13.3	4.5	13.1	4.5	2.1	5.2	4.9	6.5	21.3
Gujar k	PS 01 CH	8	8	45	17.3	316.1	34.2	7.7	20.7	12.5	22.4	12	5.2	22.1	12.7	18.3	18.7
	DP 23	5	5	45	14.4	4.8	55.9	4.9	38.5	12.5	31.9	13.8	6.3	29.7	17.2	13.4	36.5
	Block Mean	13	13	45	27.8	330.3	44.8	11.9	10.5	13.4	8.7	14.9	4.3	16.3	16.7	18.7	26.4
	Dhokpathan Fmn	5	5	45	14.4	4.8	55.9	4.9	38.5	12.5	31.9	13.8	6.3	29.7	17.2	13.4	36.5
	Chinji fmn	8	8	45	17.3	316.1	34.2	7.7	20.7	12.5	22.4	12	5.2	22.1	12.7	18.3	18.7
Jehlum	Tatrot	45	45	45	15.5	331.6	33.4	43.3	25.4	4.3	27.8	4.1	2.6	7.5	4.3	6.4	18.2
	Kotal kund	66	66	45	17.5	322.6	34.7	62.7	19.8	4	21.7	3.8	2.2	5.9	4.1	5.8	19.1
	Dhala Nala	37	37	45	19.9	322.2	32.6	34.7	15.4	6.2	16.9	5.9	2.8	8.4	6.2	9.2	17.7
	Pabbi Hills	86	89	45	14.4	354.5	41.5	82.5	24.3	3.2	32	2.7	2	5	3	3.7	23.9
	ESN 07	15	15	45	16.9	349.9	23.4	13.5	9.1	13.4	23.2	8.1	4.1	14.9	8.3	14.3	12.2
	Rohtas	38	42	45	21.8	349.7	35.1	35	12.4	6.9	14.2	6.4	2.8	8.3	6.8	9.6	19.4
	Block Mean	281	294	45	20.9	338.5	36.1	260.8	13.8	2.3	15.3	2.2	1.3	2.4	2.4	3.3	20.1
	Soan Fmn	124	131	45	17.1	353	39.6	117.3	18.4	3	22.9	2.7	1.7	3.9	2.9	3.8	22.5
	Dhokpathan Fmn	60	60	45	17.8	336.2	31.3	56.2	15.4	4.8	21.1	4.1	2.3	6.2	4.3	6.5	16.9
Surgher	Mn 01	5	5	45	10.7	347.6	22.5	4.9	47	11.3	57.3	10.2	6.3	29.7	10.4	18.1	11.7
	Mn 02	9	9	45	7.7	322.1	24.6	8.9	94.8	5.3	110.6	4.9	5	20.5	5	8.6	12.9
	MN 03	11	11	45	20.8	312.1	49.2	10.6	23	9.7	15.5	12	4.6	18.1	13.9	13.6	30.1
	Block Mean	24	25	45	19.4	325.8	34.3	22.7	17.1	7.4	17.8	7.2	3.4	11.1	7.6	11	18.8
shmir	KSH 02	18	18	45	8.8	83.6	32.3	17.7	67.3	4.2	84.9	3.8	3.8	13.3	4	5.9	17.5
	KSH 01	6	6	45	11.8	67.5	59.4	5.9	92.4	7	47.4	9.8	5.9	26.5	12.9	8.7	40.3
	Block Mean	24	24	45	15	80.9	39.2	23.1	26.2	5.9	29.3	5.6	3.4	11.1	6	7.8	22.2
	MBT 01	14	14	45	13.6	339.7	29.7	13.4	21.9	8.7	35.8	6.7	4.2	15.6	7	11	15.9
	Block Mean	14	14	45	13.6	339.7	29.7	13.4	21.9	8.7	35.8	6.7	4.2	15.6	7	11	15.9
Margala																	
Jehlum	Tatrot	45	45	45	15.5	331.6	33.4	43.3	25.4	4.3	27.8	4.1	2.6	7.5	4.3	6.4	18.2
	Kotal kund	66	66	45	17.5	322.6	34.7	62.7	19.8	4	21.7	3.8	2.2	5.9	4.1	5.8	19.1
	Dhala Nala	37	37	45	19.9	322.2	32.6	34.7	15.4	6.2	16.9	5.9	2.8	8.4	6.2	9.2	17.7
	Pabbi Hills	86	89	45	14.4	354.5	41.5	82.5	24.3	3.2	32	2.7	2	5	3	3.7	23.9
	ESN 07	15	15	45	16.9	349.9	23.4	13.5	9.1	13.4	23.2	8.1	4.1	14.9	8.3	14.3	12.2
	Rohtas	38	42	45	21.8	349.7	35.1	35	12.4	6.9	14.2	6.4	2.8	8.3	6.8	9.6	19.4
	Block Mean	281	294	45	20.9	338.5	36.1	260.8	13.8	2.3	15.3	2.2	1.3	2.4	2.4	3.3	20.1
	roatation uptill DP	339	346	45	19.3	338.7	37.3	319.3	17.1	1.9	18	1.8	1.2	2.1	2	2.7	20.9
	Rotaiton in Soan	135	142	45	16.8	352.6	39.9	128	19.2	2.8	23.7	2.5	1.7	3.7	2.8	3.5	22.7

Table B. Paleostress inversion solutions for each site.

Site	Age	n/nt	σ1	σ2	σ3	R	DS
Tatral fault	Early Pliocene	72/72	007/55	267/34	172/34	0.42	Extensional
KMT1	Early Pliocene	26/26	333/09	241/74	097/74	0.67	Contractional
Dhurnal thrust	Early Pliocene-Recent	13/13	355/15	086/75	181/75	0.69	Contractional
MBT2	Early Miocene	8/8	042/02	311/59	135/59	0.5	Contractional
Dhak pass	pleistocene-Recent	66/66	046/06	145/34	311/34	0.61	Transcurrent
kb4	Late Pliocene-Recent	29/29	030/12	269/19	124/19	0.44	Transcurrent
kb3	Late Pliocene-Recent	22/22	058/04	252/01	149/01	0.48	Transcurrent
DT	Late Pliocene	26/27	151/17	244/71	004/71	0.75	Contractional
DT2	Late Pliocene	24/30	123/04	032/77	228/77	0.56	Contractional
DT 1.31	Late Pliocene	8/8	124/16	216/72	332/72	0.44	Contractional
JE1	Early Pliocene- Recent	55/56	099/00	189/32	009/32	0.26	Transcurrent
JFE2	Early Pliocene- Recent	154/153	285/12	180/37	024/37	0.28	Transcurrent
JFW	Early Pliocene- Recent	173/179	132/06	032/31	225/31	0.53	Transcurrent
Khud Thrust 1	Late Pliocene	78/78	100/24	010/66	279/66	0.65	Contractional
KHud 2	Late Pliocene	23/23	312/06	046/49	215/49	0.54	Contractional
KHud 3	Late Pliocene	39/39	156/01	065/59	247/59	0.71	Contractional
Khud 4.4	Late Pliocene	39/39	319/11	229/79	127/79	0.68	Contractional
Khud 4.52	Late Pliocene	18/19	355/16	095/54	241/54	0.53	Contractional
KK_KDJ	Early Pliocene	309/309	353/00	263/56	084/56	0.18	Contractional
KDJ1.1	Early Pliocene	40/73	156/08	257/35	061/35	0.54	Transcurrent
KDJ 1.2	Early Pliocene	20/20	002/14	230/15	096/15	0.57	Transcurrent
KD1.3	Early Pliocene	25/25	323/05	219/20	054/20	0.66	Transcurrent
KDJ 1.44	Early Pliocene- Recent	19/19	180/07	281/31	086/31	0.29	Transcurrent
DJ 1.45	Late Pliocene	14/14	153/04	061/60	249/60	0.71	Contractional
KDJ 1.46	Early Pleistocene	24/24	157/11	257/44	056/44	0.29	Contractional
KK 1.2F	Early Pliocene	6/7	328/06	200/08	059/08	0.5	Transcurrent
KK 1.16	Early Pliocene	20/20	182/01	277/17	092/17	0.47	Transcurrent
kk1.180	Early Pliocene	6/6	322/06	163/02	052/02	0.67	Transcurrent
kk 1.190	Early Pliocene	43415	016/01	283/13	106/13	0.44	Transcurrent
KK2.20	Early Pliocene	29/29	135/05	239/20	043/20	0.47	Transcurrent
KK2.21	Early Pliocene	14/26	009/06	248/10	100/10	0.5	Transcurrent
KK 2.24	Early Pliocene	46/52	038/04	146/12	308/12	0.32	Transcurrent
Riwat S	Early Pliocene-Recent	10/10	346/13	236/31	084/31	0.4	Transcurrent
Riwat1T	Early Pliocene-Recent	5/6	206/30	305/55	061/55	0.5	Contractional
Ponch f	Early Pliocene	46/46	168/05	258/83	027/83	0.83	Contractional
PV 1.3F	Early Pliocene	11/16	040/12	219/00	310/00	0.5	Transcurrent
PV 1.2	Early Pliocene	33/33	177/08	278/33	082/33	0.55	Transcurrent
PV 1.4	Early Pliocene	11/11	197/01	291/20	106/20	0.5	Transcurrent
PV1.11	Early Pliocene	5/5	317/08	203/17	050/17	0.5	Transcurrent
Kenhetti 1.1	Early Pliocene	51/51	002/01	254/03	092/03	0.31	Transcurrent
Kenhetti fault 1.2	Early Pliocene	52/52	005/12	218/08	097/08	0.34	Transcurrent
K_PV	Early Pliocene	158/158	354/10	256/48	095/48	0.28	Contractional
Phase1	Early Pliocene	455/455	192/12	289/56	084/56	0.35	Contractional
Phase 2	Late Pliocene- Recent	824/824	140/00	230/85	045/85	0.25	Contractional

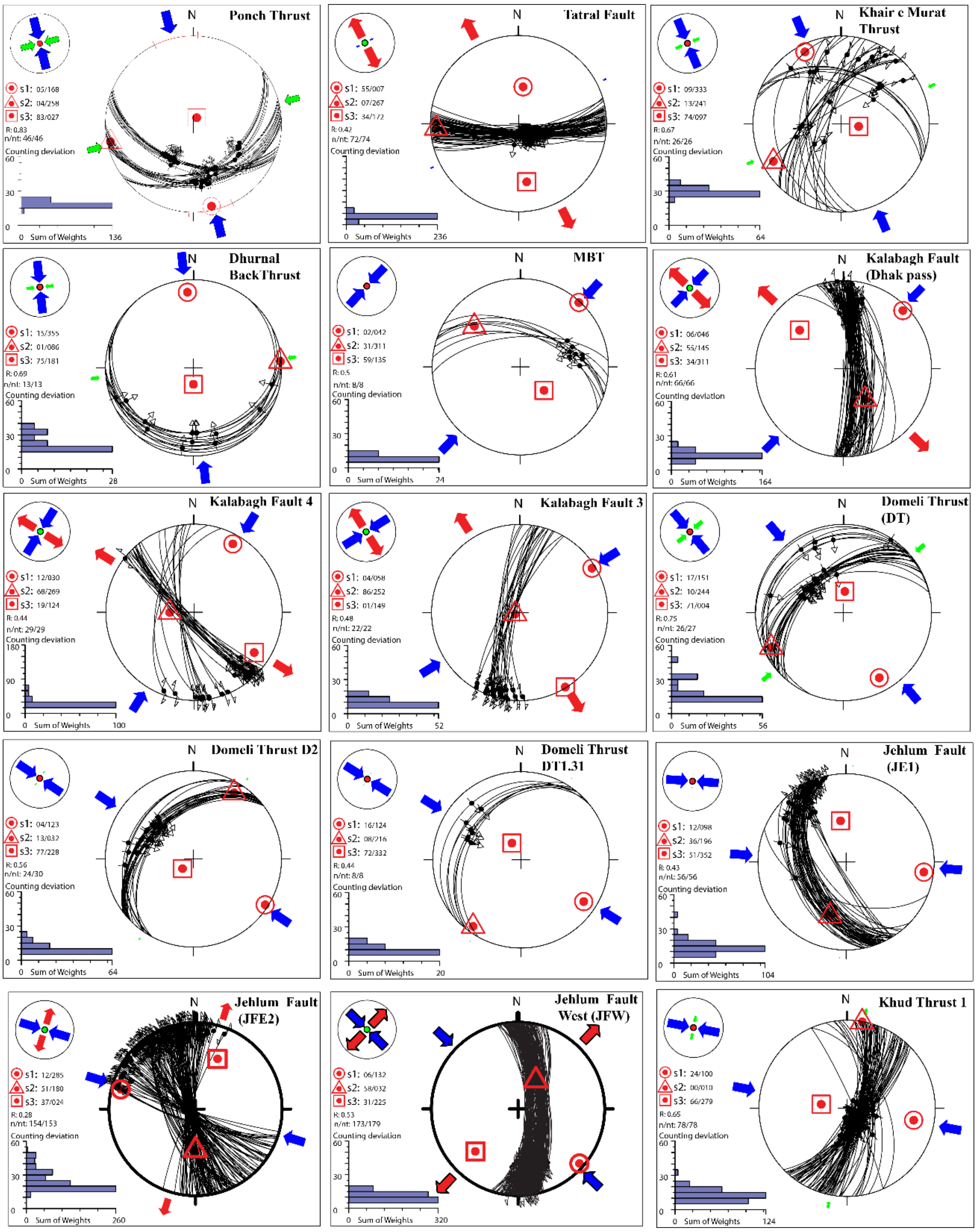

Figure A1. Stereographic projections of constructed paleostress configurations for each site and Mean solution. (Equal area, lower hemisphere projection) (See Fig 3.1 for the locations of sampling sites).

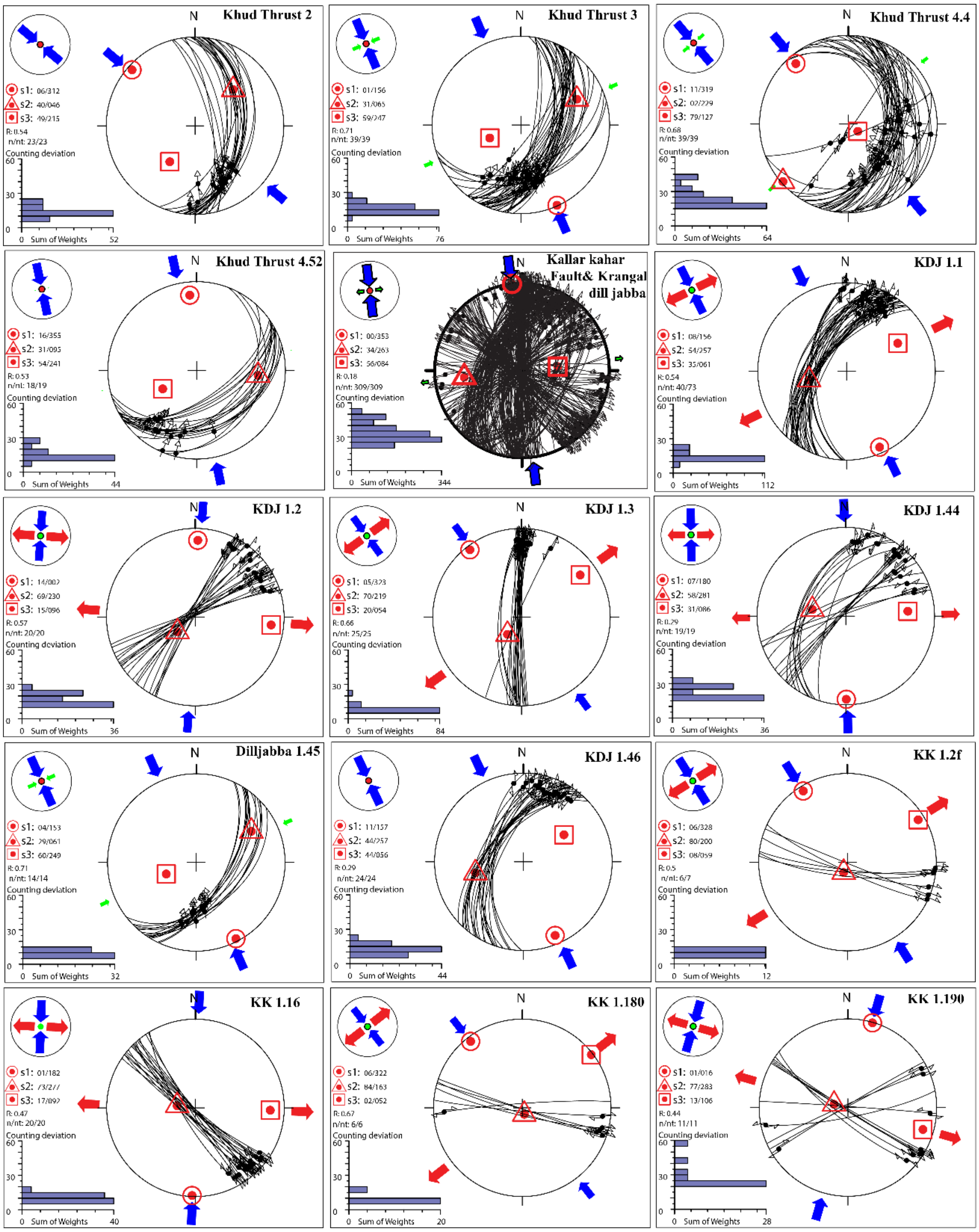

Figure A1 (Continued)

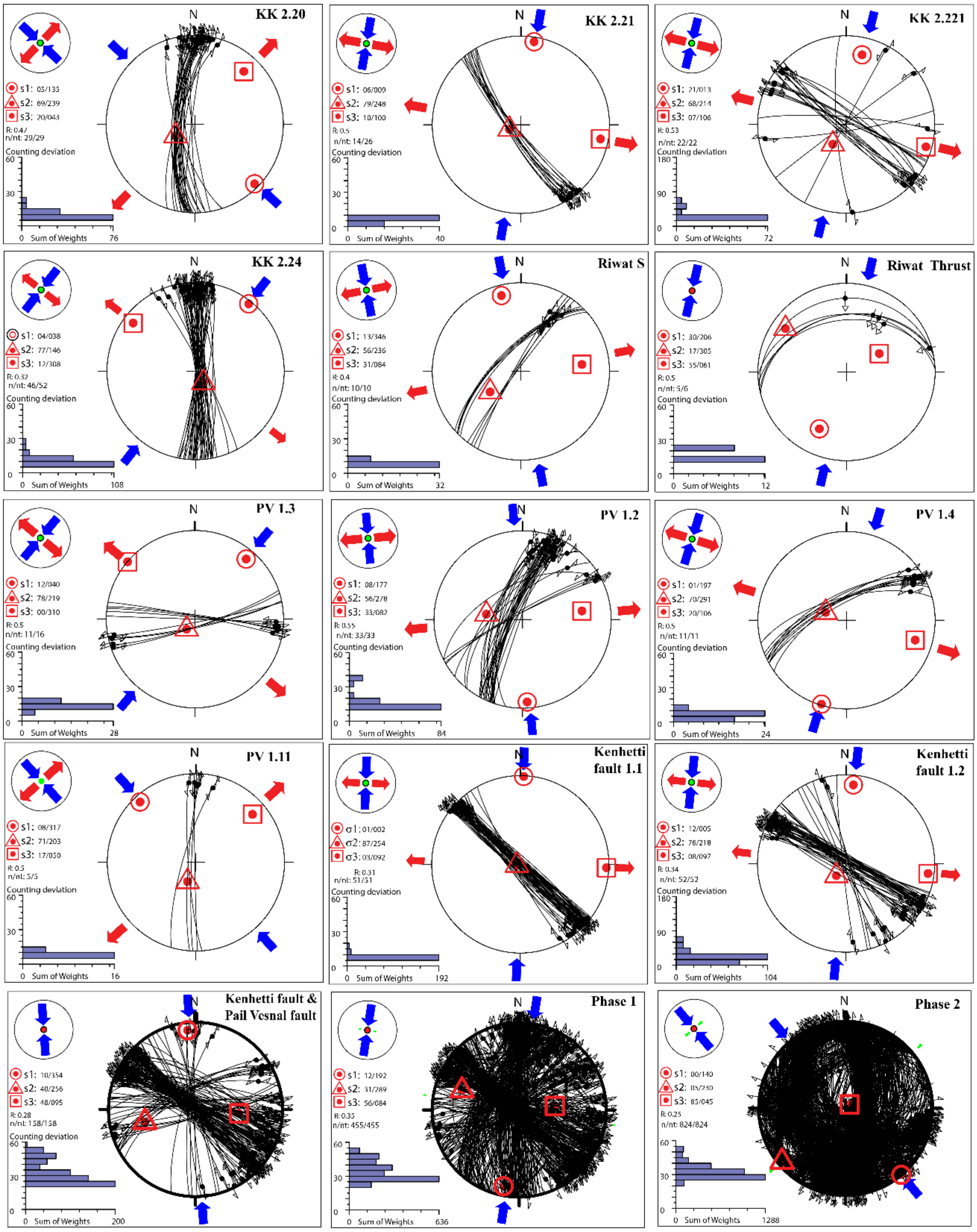

Figure A1 (Countinued)

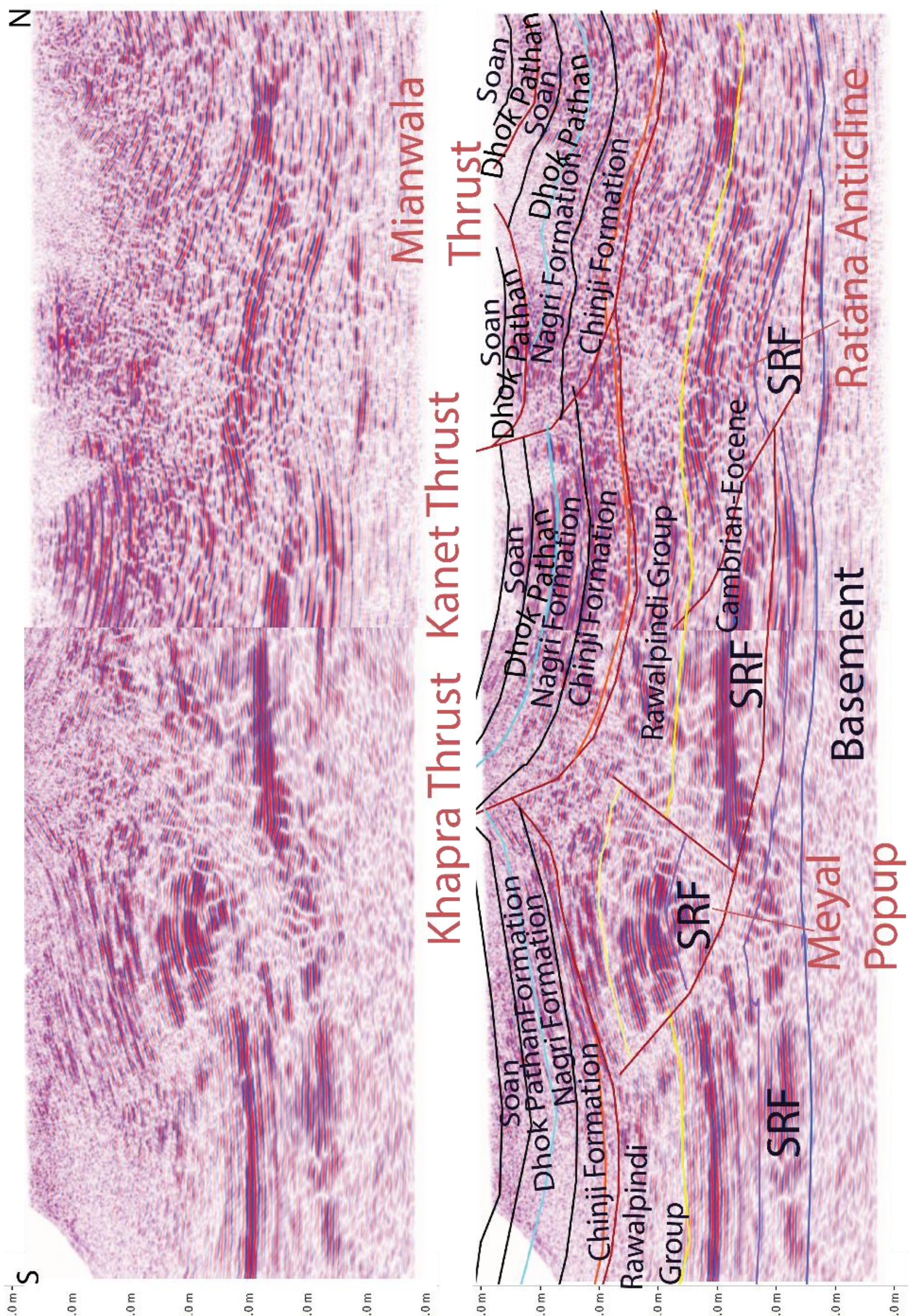

Figure A2 (Figure 4.7)

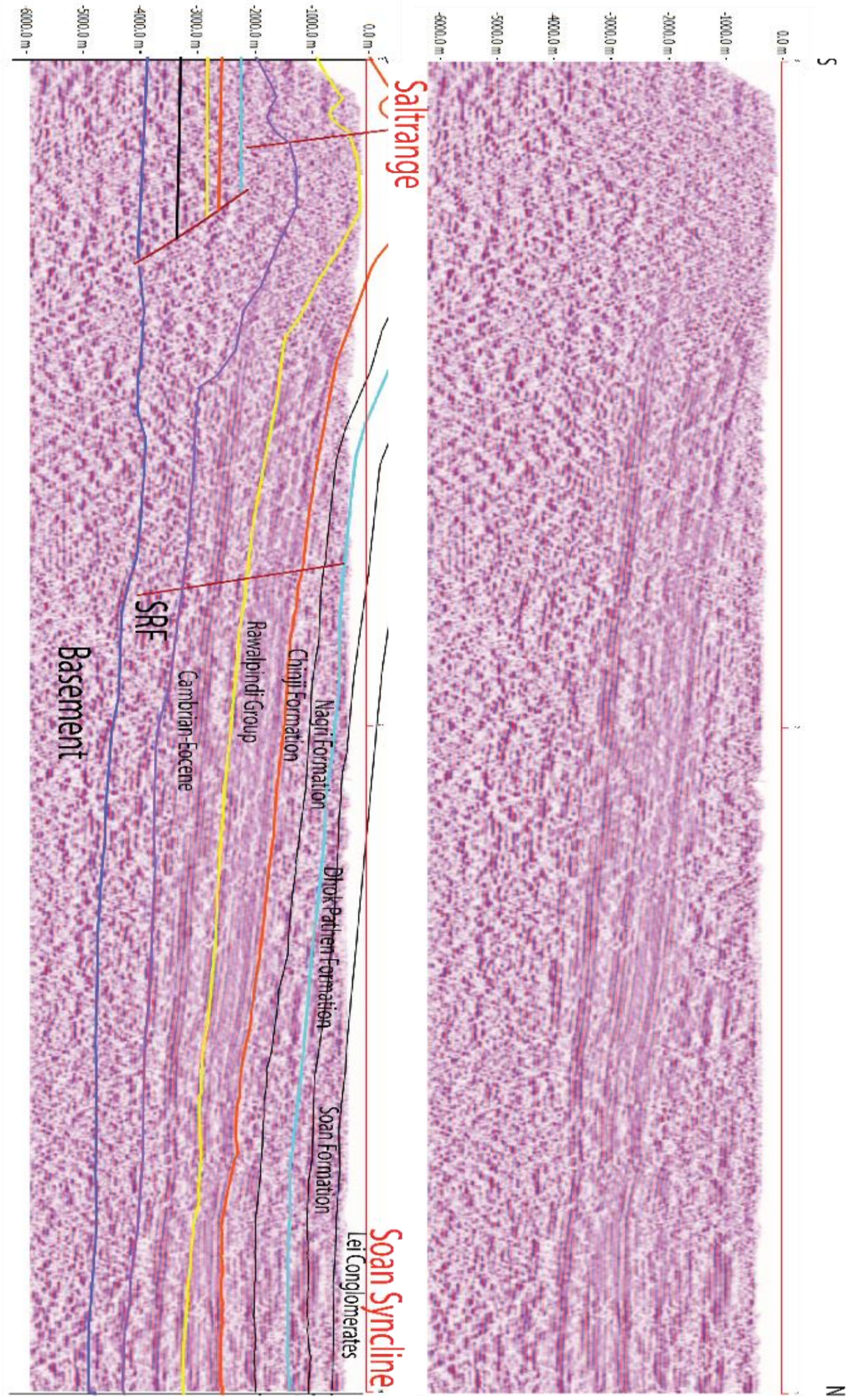

Figure A3 (Figure 4.8)

CURRICULUM VITAE

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High School	Elite scienc sollege Sargodha	2005
School	Dar-e-Arqam School Sargodha	2003

FOREIGN LANGUAGES

English, Turkish