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Himalayan-Induced Deformation and Kinematics of the Arcuate Nature of The Trans Indus Salt Range, North Pakistan

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ABSTRACT

The structural elements of the NW Himalayan Pakistan include a chain of arcuate orogenic belts known previously as arcs, oroclines, syntaxis, and re-entrants. One of such belts is the Trans Indus Salt Range which is the focus of this study. The Himalaya-induced deformation that has affected the Trans Indus Salt Range is distinguished into three distinct episodes including a) pre-molasse, b) syn-molasse and c) post-molasse deformation. The pre-molasse episode of deformation is correlative with the Oligocene unconformity during which the region was eroded down to the level of Eocene in the eastern, up to Triassic in the central and Paleocene in the western Trans-Indus Salt Range. The syn-molasse deformational episode is interpreted by the gradual south-younging deposition of molasse sediments in the Kohat Basin. The post-molasse deformational episode started in the region at the time when the regional basal detachment underneath the Kohat Basin ramped at the site of Trans Indus Salt Range producing the present day frontal ranges. Based on the early paleomagnetic studies conducted in the Surghar Range, it is believed that the arcuate nature of the Trans Indus Salt Range is in-situ without any significant rotation. The arcuate geometry of the Trans Indus Salt Range is probably controlled by pre-existing basement irregularities, down to the north basement normal faults and possible strain partitioning. The strain-partitioning may also be caused by synchronous multi directional stresses produced by the oblique subduction of the northwestern indenter of the Indian Plate.

INTRODUCTION

The Trans Indus Salt Range of Northwestern Himalayas defines a sinuous fold-and-thrust belt (Figure 1). The Kalabagh Hills, the Surghar-Shinghar Ranges, the Marwat-Khisor Ranges, Sheikh Budin Hills and the Manzai Range are collectively known as the Trans-Indus Salt range. The Precambrian to Cenozoic platform and Pliocene-Pleistocene fluvial strata outcrop along the Trans Indus Salt Range and is characterized by the present day ongoing deformation at the mountain front (Khan et al., 1988, Blisniuk, 1996 and Alam et al., 2005). The Kalabagh Hills occupy the eastern part of the Trans Indus Salt Range and are the Trans-Indus equivalent of the Western Salt Range, located north of Kalabagh City in Mianwali District. These hills occupy the important structural transect between the Western Salt Range and the Surghar Range, and can serve to establish the structural relationship between these two important tectonic regimes of Pakistan. The Surghar Range follows an east-west structural trend along the southern margin of the Kohat Basin and changes to a north-south trend along its eastern flank. Along the Surghar Range, Paleozoic-Eocene platform rocks are exposed at surface. The Marwat-Khisor Ranges border the Bannu Basin towards south, stretching from Paniala in the west up to Dara Tang in the east (Figure1). The Marwat Range is an anticlinal feature with surface exposure of Siwalik Group rocks. The Khisor Range that lies south of the Marwat Range exposes Cambrian to Triassic rocks. The Marwat-Khisor ranges are characterized by east-west to east-northeast structural trends. The structural style of the range includes parallel to en-echelon fold trends detached at the base of Jhelum Group rocks of Cambrian age (Alam et al., 2005). The Cambrian to Pliocene-Pleistocene rocks of the Khisor Range are thrust southwards over the Punjab plain along the Khisor Thrust that is probably the western equivalent of the Salt Range Thrust (Gee, 1980). Cambrian to Triassic age shallow marine lithologies predominantly underlies the Khisor Range that is unconformably overlain by the Pliocene-Pleistocene Siwalik Group rocks. The exposed stratigraphic sequence of the Khisor Range is broadly correlative with that of the Western Salt Range with the exception that the Rawalpindi Group rocks (Miocene) are missing in the Khisor Range (Alam et al., 2005).The Manzai Range is the western most surface expression of the Trans-Indus Salt Ranges. At surface no rocks older than Siwalik Group outcrops along the Manzai Range and its structure is characterized by a broad anticlinal feature with associated east-verging thrust fault.

This paper is aimed to address the deformational scheme and the arcuate nature of the Trans Indus Salt Range which is an important part of the foreland fold-thrust belt of North Pakistan.

SEDIMENTATION AND DEFORMATION OF THE TRANS-INDUS SALT RANGE

The sedimentary rock assemblages outcropping along the Trans Indus Salt Range indicate a fairly quiet period of continuous sedimentation in a shallow sea with the down-sagging of the Kohat-Potwar Basin, occasionally interrupted by localized block uplifts, resulting in disconformities (Figure 2) at the close of the Mesozoic Era, there was a widespread uplift, with a rise during Cretaceous times when terrestrial conditions prevailed in parts of the area of sedimentation. The block uplift led to the denudation of the newly emerged areas. Marine conditions again prevailed during early Tertiary times, but soon after the deposition of the Middle Eocene the initial phase of Himalayan up-lift set in and the sea receded from the Kohat-Potwar Basin leaving a fluviatilelacustrine environment

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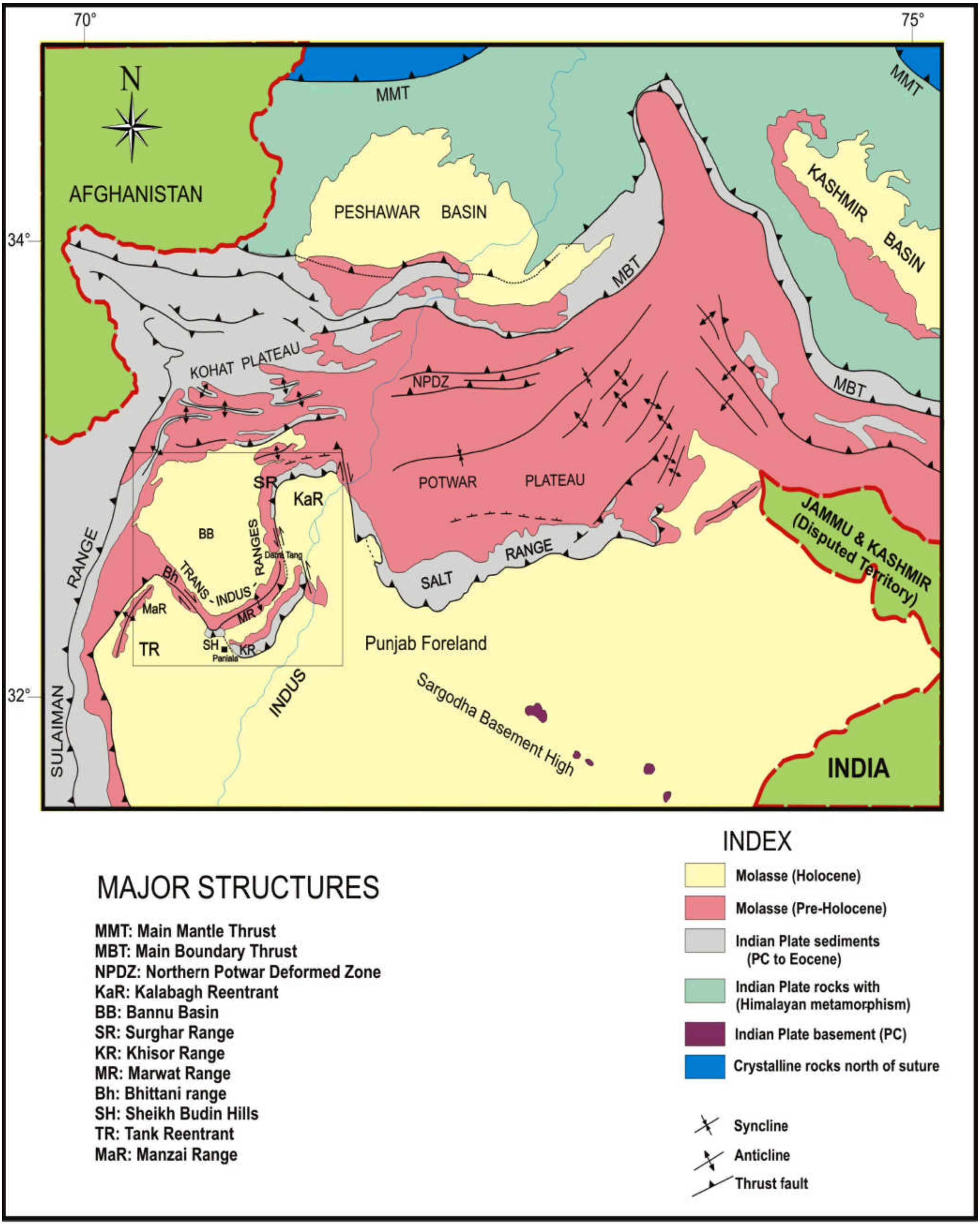

Figure 1- Generalized geological map of the NW Himalayan foreland fold and thrust belt. Inset shows location of the Trans-Indus Salt Range

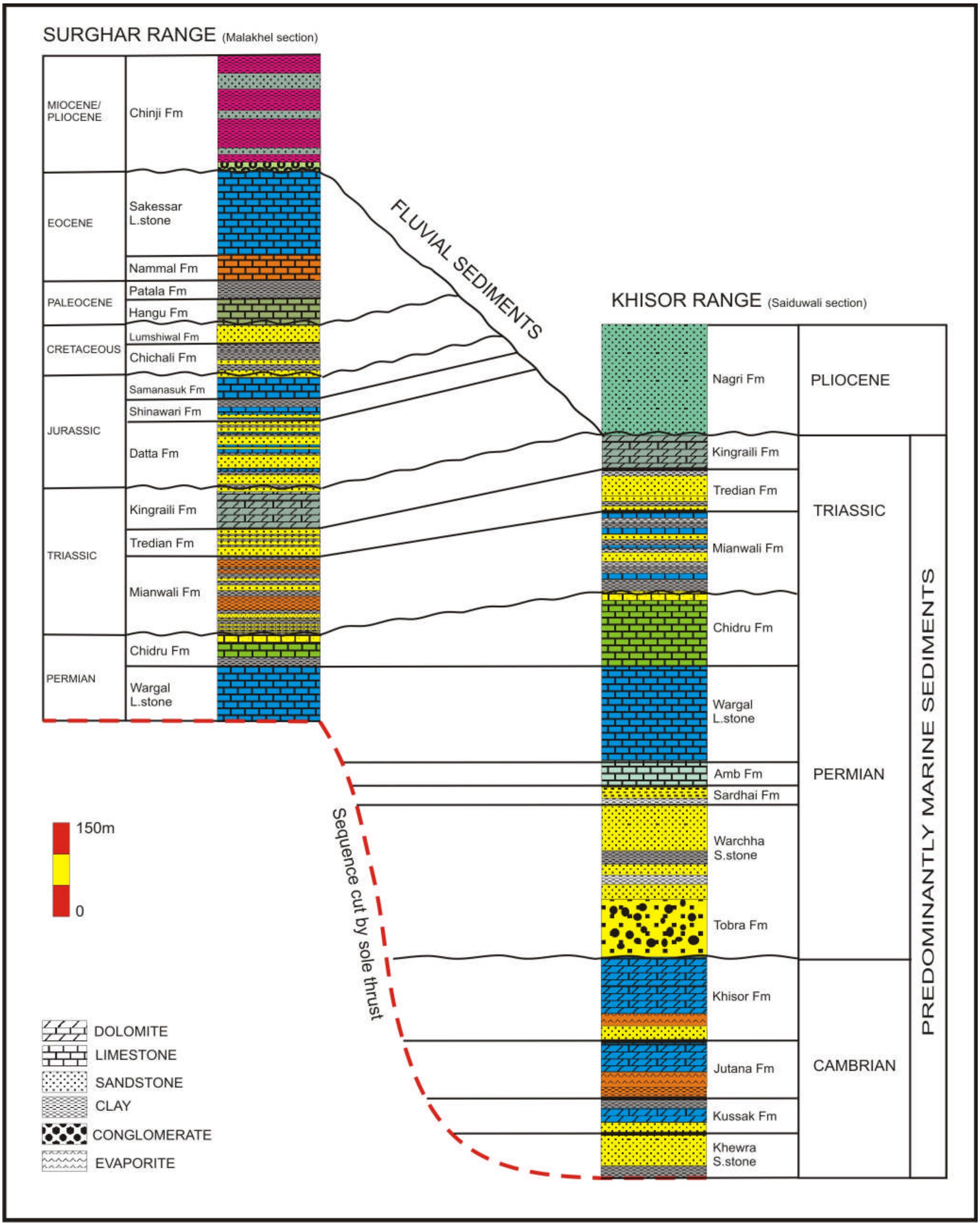

Figure 2- Stratigraphic column of the Surghar and Khisor ranges.

in the region. This event is marked by the widespread Oligocene unconformity in the region which has been responsible for a considerable denudation and erosion of the Eocene rocks in the area, pebbles and rolled fragments of Eocene limestone, therefore, form a widespread and prominent constituent of the conglomerates marking the Oligocene unconformity (Khan et al.,1988, Blisniuk, 1996 and Alam et al., 2005). In Mio-Pliocene and Pleistocene times the area received an enormous thickness of detrital material in a fluviatile and lacustrine environment of sedimentation and the rivers flowing down the rising Himalaya to the north poured their detrital matter into the molasse trough of the Kohat-Potwar Basin. In late Pliocene times the effect of Himalyan orogeny propagated southwards with the development of the Salt Range and its Trans Indus extension. Erosion down to the level of Eocene limestone contributed to the detrital pebbles and boulders occurring in the conglomerate lenses of the Dhok Pathan and Nagri formations (Blisniuk, 1996 and Alam et al., 2005). At the close of the Tertiary Era earth movement of considerable magnitude, defining the final phase of the Himalayan orogeny, affected the entire area and led to the development of the numerous folds and faults of the area.

The Himalaya-related deformation that has affected the Trans Indus Salt Range can be distinguished into three discrete episodes including pre-molasse, syn-molasse and post-molasse deformation. The three major episodes collectively represent the affects of Himalayan collision. The pre-molasse episode of deformation in the region is correlatable with the Oligocene unconformity during which the region was uplifted and was eroded down to the level of Eocene in the eastern, up to Triassic level in the central and Paleocene level in the western Trans Indus Salt Range (Figure 2). The pre-molasse deformation represents the activity caused by the lithospheric bending of the Indo-Pakistani Plate. This initial extensional tectonic activity resulted in the development of the normal basement faults with down thrown side to the north documented in the Salt and possibly in the Trans Indus Salt Range (Lillie et al., 1986 and 1987, Leather, M., 1987, Baker et al., 1988, Pennock et al., 1989 and Blisniuk et al., 1998).This normal faulting of the basement tilted the Pre-Miocene sequence and accommodated syn-tectonic deposition of thick pile of molasse sediments. According to Blisniuk et al., 1998 the timing of basement normal faults is ~6-5 Ma in the Salt Range and > 3.5 Ma in the Khisor Range and the Sheikh Budin Hills.

The syn-molasse deformational episode is demonstrated by the distribution of molasse deposits in the Kohat Basin. In the northern Kohat Basin older molasse including Murree and Kamlial formations are well developed at the Oligocene unconformity and are involved in faulting along the Main Boundary Thrust front (Figure 4). This older molasse sequence is traceable in the south up to the Basia KhelSurdag-Karak fault system and does not extend further southwards (Ahmad et al., 2003). Along the Surghar Range the Oligocene unconformity is marked by Eocene and younger molasse sequence that changes to Triassic and younger molasse along the Khisor Range (Figure 2). This gradual younging of molasse sequence from north to south clearly demonstrates the occurrence of a syn-molasse deformational episode which prevailed in the region.

The post-molasse deformational episode started in the region at the time when the macroscopic thrust slab underneath the Kohat-Potwar Basin ramped up section at the site of Salt Range and Trans Indus Salt Range. This ramping led to the internal deformation of the thrust slab and created the present day frontal ranges. According to previous workers, thrusting started at ~2 Ma in the central Salt Range (Frost, 1979, Johnson et al., 1985 and 1986 and Burbank et al., 1989a). Whereas along the Surghar Range the onset of thrusting is reported to be ~1 Ma (Khan et al., 1988, Blisniuk et al.,1996 and Pivnik and Khan, 1996). The post-molasse deformational episode is reported to be still continuing as reported by (Frost, 1979 and Yeats et al., 1984).

ARCUATE NATURE OF THE TRANS INDUS RANGES

The Trans Indus Salt Range consists of a couple of re-entrants including the Kalabagh Re-entrant in the east and Tank Re-entrant in the west. The origin of these re-entrants is debatable (Sarwar and De Jong, 1979). One hypothesis for the origin of Kalabagh and Tank Re-entrant could be wrapping of folds in ductile manner along a pre-existing buried buttress of the basement, such as the main Sargodha ridge. A buried buttress of basement rocks in the area close to the Kalabagh may have offered a strong resistance to the compressional forces of the Himalayan orogeny directed from the northerly direction. This eventually may have led to the development of the arcuate outline of the folds in the regions closer to it, but in the distant areas, the influence of this basement wedge gradually diminished (Klootwijk et al., 1986). Paleomagnetic rotation vectors (rotation relative to the Indo Pakistani shield) follow the observed rotations of the main structural trend (Figure 4). Another hypothesis regarding the arcuate nature of the Trans Indus Salt Range is that the Kalabagh Re-entrant has formed as a result of deep basement strike slip faults (Johnson et al., 1979 and Kazmi, 1979a).

Other possibilities about the curvature in an orogenic system include flexing of an initially linear mountain belt and an original curvature caused by the irregularities in the basement as well as strain partitioning. Paleomagnetism can be used as an effective tool for explaining the arcuate nature of an orogenic belt (Eldredge et al., 1985 and Vander et al., 1980). Two possible magnetic signatures can be expected in the analysis of arcuate mountain chain; a) magnetic declinations in case of original curvature should not correlate with a change in the fold axis trend, but remain parallel and b) change in magnetic declinations should mimic the change in the fold axis trend on a one to one basis if the belt had an initially linear configuration.

Unfortunately, little paleomagnetic studies have been conducted in the Trans Indus Salt range. However, some significant paleomagnetic work in the molasse sediments has been done in the eastern-most part of the Trans Indus Salt Range (northern Surghar Range) that provide useful information in defining the arcuate nature of this part of the Trans Indus Salt Range (Khan et al., 1985). According to these paleomagnetic studies the magnetic declinations does not correspond with the change in the fold axis trend but remain parallel suggesting the in-situ nature of the curvature in the Surghar Range.

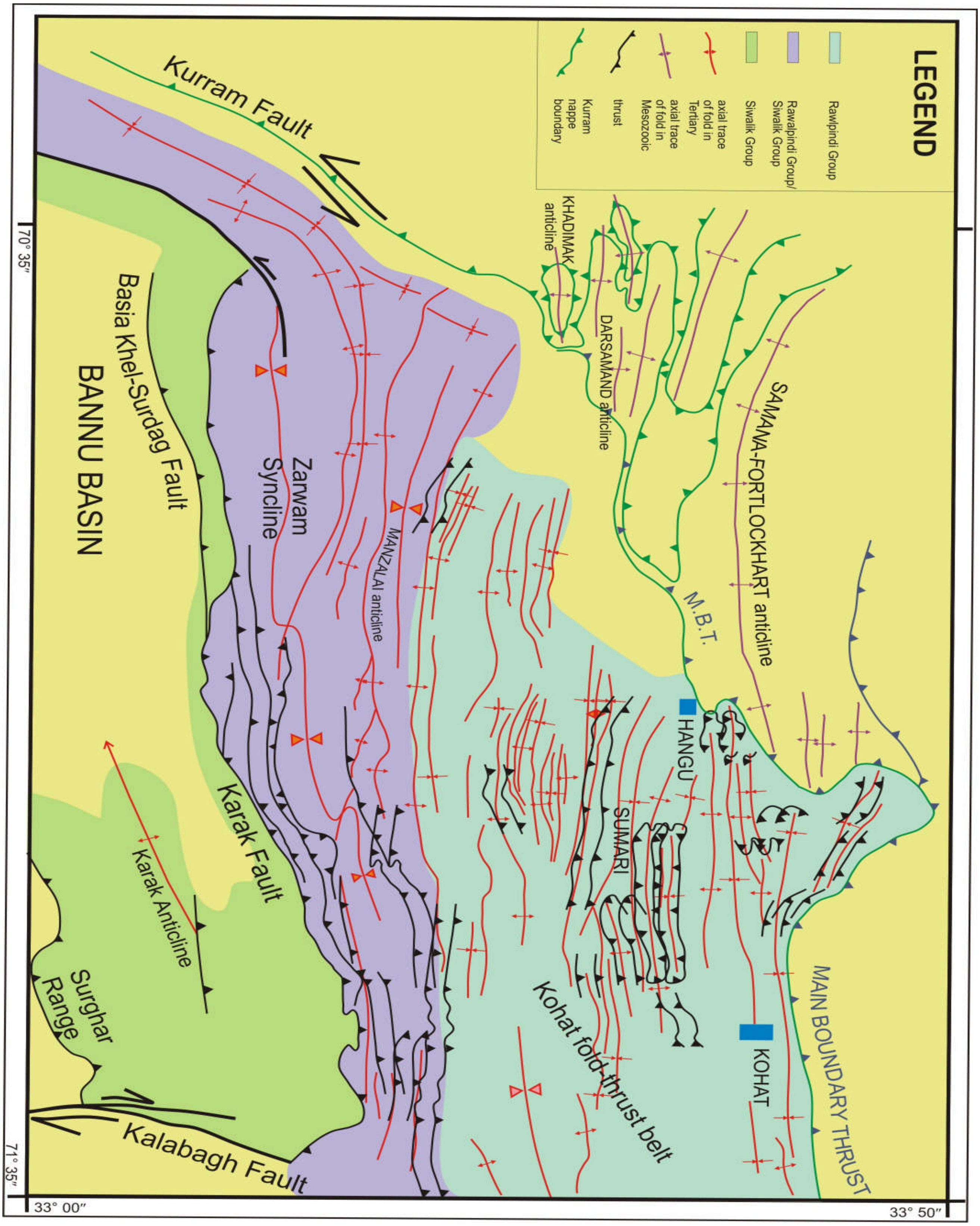

Figure 3 - Tectonic framework and areal extent of the molasse sediments of the Kohat fold-thrust belt

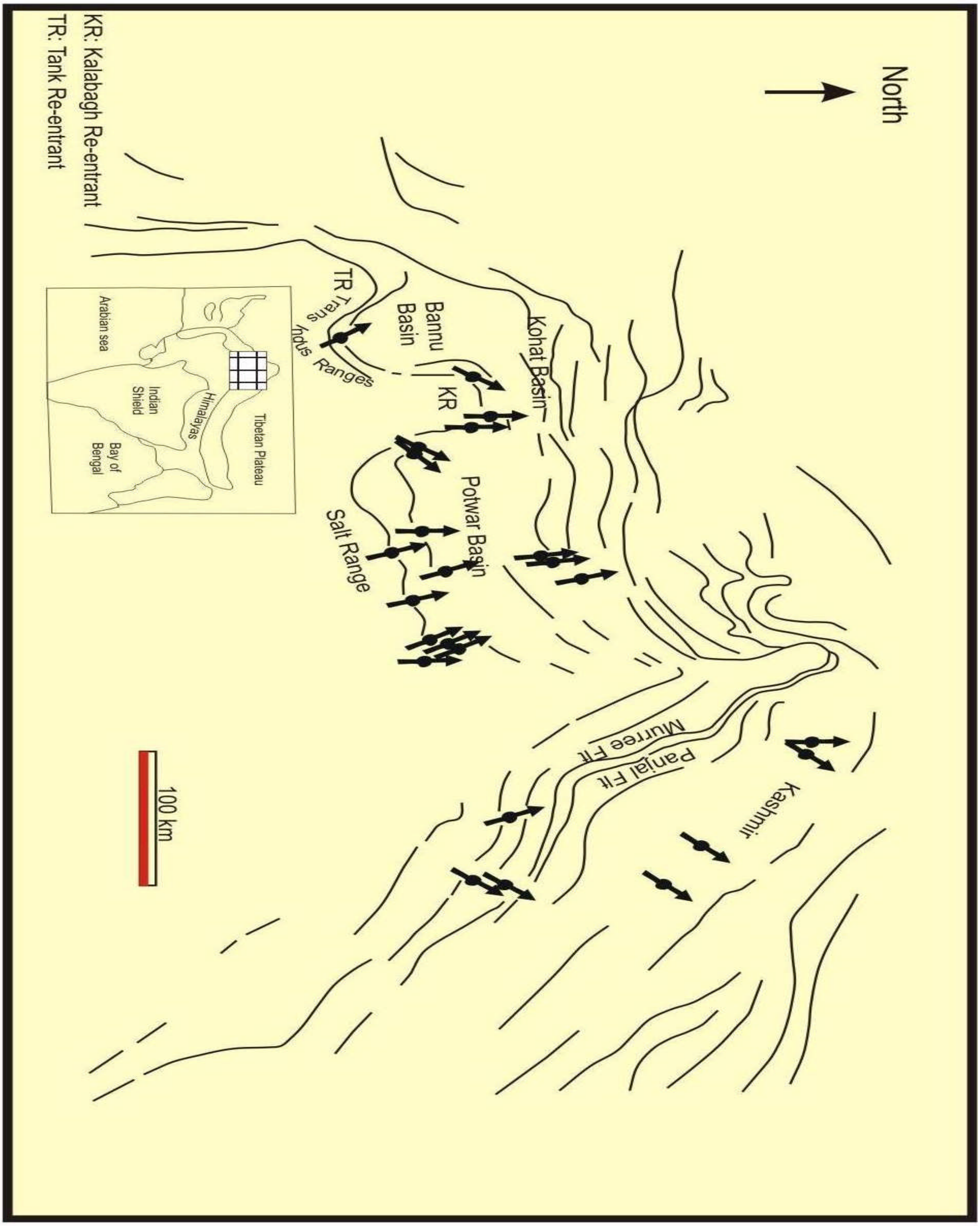

Figure 4 - Paleomagnetic rotation vectors of early Tertiary and older formations after Klootwijk et al.,1986. (The azimuths of rotation vectors indicate the magnitude of rotation with respect to the Indian Shield).

Based on the above-mentioned observation, it is believed that the arcuate front of the Trans Indus Salt Range does not record any rotation and is controlled by pre-existing basement irregularities, likely down-to-the-north basement related normal faults (Figure 5 A-F), and possible strain partitioning caused by synchronous multi directional stresses produced by the oblique subduction of the northwestern indenter of the Indian Plate (Figure 6). It is interpreted that the onset of compression at the northern and southern Surghar Range and Manzai Range was synchronous caused by north-south and east-west compression induced by proto Main Boundary Thrust in the north and Kurram Fault in the west respectively. At the time when Proto MBT was transmitting south directed stresses at the site of the northern Surghar Range, left lateral wrenching along the Proto Kurram Zone was transmitting east directed compressive stresses resulting in the north-south oriented folds in the Manzai Range and southern Surghar Range. The stress variation is believed to be responsible for the arcuate structural trends present at the northwestern corner of the Bannu Basin where the north-south trending rocks of the Sulaiman Range merge with the east-west trending rocks of the Kohat Basin. These variations have caused a northwest oriented lineament separating the two stress regimes in the Trans Indus Salt Range (Figure 6).

SEQUENTIAL EVOLUTION OF THE TRANS INDUS SALT RANGE

The Eocene collision of Indo-Pakistani Plate with Eurasia gave rise to the convergent tectonics in the proto Himalayan Zone. Stacking of thrust in the proto Kurram and Main Boundary thrust zones, and to the west and north of it created gravity potential in response to which the thrust sheet underneath Kohat-Potwar Basin moved to the south and southeast with the development of the Northern Potwar Deformed Zone (NPDZ) (Figure 1) and the Kohat fold thrust belt (Figure 4). The coherent thrust slab beneath the Kohat Basin and NPDZ was severely sliced with a lot of internal deformation probably due to the lack of Salt Range Formation that could have served as an easy glide horizon for the southward migration of the thrust sheet underneath the Kohat Basin and southern Potwar Basin (Ahmad et al., 2003). The structural analogy between the Kohat Basin and NPDZ is also documented by Izzat (1993). The thrust sheet encountered an easy glide horizon that is Salt Range Formation south of NPDZ underneath the Potwar Basin and moved rapidly south-eastwards as compared to its western analog that is the Kohat Basin where no salt exist at basal decollement (Ahmad et al., 2003). The no salt situation underneath the Kohat Basin led to the development of an internally more deformed fold-thrust belt. It is believed that due to the lithological variations at the basal decollement underneath the Kohat and Potwar basins caused the faster rate of thrust propagation underneath the Potwar Basin resulting in the onset of wrenching along a pre-existing basement-involved normal fault (Figure 5a and b) that is at present recognized as Kalabagh Fault (Figure 4). The commencement of ramping at the Salt Range front post date the wrenching along the Kalabagh Fault supported by the chronostratigraphy of molasse rocks developed in Potwar and southern Kohat Basin. Along the Salt Range front, thrusting began at ~2 Ma in the central Salt Range (Frost, 1979, Johnson et al., 1985 and 1986 and Burbank et al., 1989a.) whereas at the site of Surghar Range front the onset of thrusting is reported to be ~1 Ma (Blisniuk, 1996, Pivnik et al., 1996 and Yeats et al., 1984). About a 1Ma jump in timing of ramping across the Indus River suggests early wrenching along Kalabagh Fault. The early wrenching along Kalabagh Fault possibly helped the progression of Potwar thrust slab quite rapidly towards south. Whereas beneath the Kohat thrust slab the basal decollement was offered more resistance due to the lack of salt that consequently created more internal deformation in less aerial width within the Kohat Basin as compared to the Potwar Basin. Furthermore, the northern Surghar Range front lies in close proximity to the MBT in the north as compared to the Salt Range front. The north Surghar Range front may have received the impact of stresses earlier than the Salt Range front which is not the case.

The ramping at the site of northern Surghar Range with minor sinistral wrenching along the pre-existing Makarwal ramp in the southern Surghar Range started at about ~1 Ma (Khan et al., 1988). This southward thrusting event was immediately followed by an east directed compressional deformation presumably caused by the Kurram Fault in the west resulted in the onset of east directed ramping along the Makarwal wrench zone giving rise to Makarwal anticlinal ridge with east-verging thrust fault (Figure 6). Based on these observations, it is interpreted that during this event there was regional scale strain partitioning axis, oriented in northwest direction, extending from Malla Khel area in the Surghar Range towards the northwestern apex of the Bannu Basin in the northwest (Figure 6). Synchronized with this event, south-east directed thrust related folding was also on-going at the site of the Manzai Range. This event was followed by a general south-eastward translation of the thrust sheet underneath Bannu Basin causing the onset of wrenching at Kundal, Makarwal and Pezu faults, with synchronous thrusting at the Khisor range front. These strike slip faults are believed to have facilitated the south-eastward movement of the coherent thrust sheet underneath Kohat and Bannu Basint by providing steep lateral ramps parallel to the thrust direction.

In the final stage, south-westward thrusting along Pezu Fault with synchronous thrusting along Marwat Fault in the subcrop initiated. The basement ramp underneath the Marwat blind thrust started to develop probably simultaneously with the development of the blind Marwat Thrust. As such it appears that the Khisor Thrust is older than the Marwat Thrust disturbing the south younging sequence of faulting in the region. The Marwat Range being the latest tectonic event is supported by the fact that it is un-affected by the Kundal Fault whereas the Khisor Range has been substantially offset by the Kundal Fault.

CONCLUSIONS

The Himalayan deformation in the Kohat foreland basin and associated Trans Indus Salt Range is interpreted to be represented by an early phase of pre-molasse deformations followed by syn-molasse and post-molasse deformation that

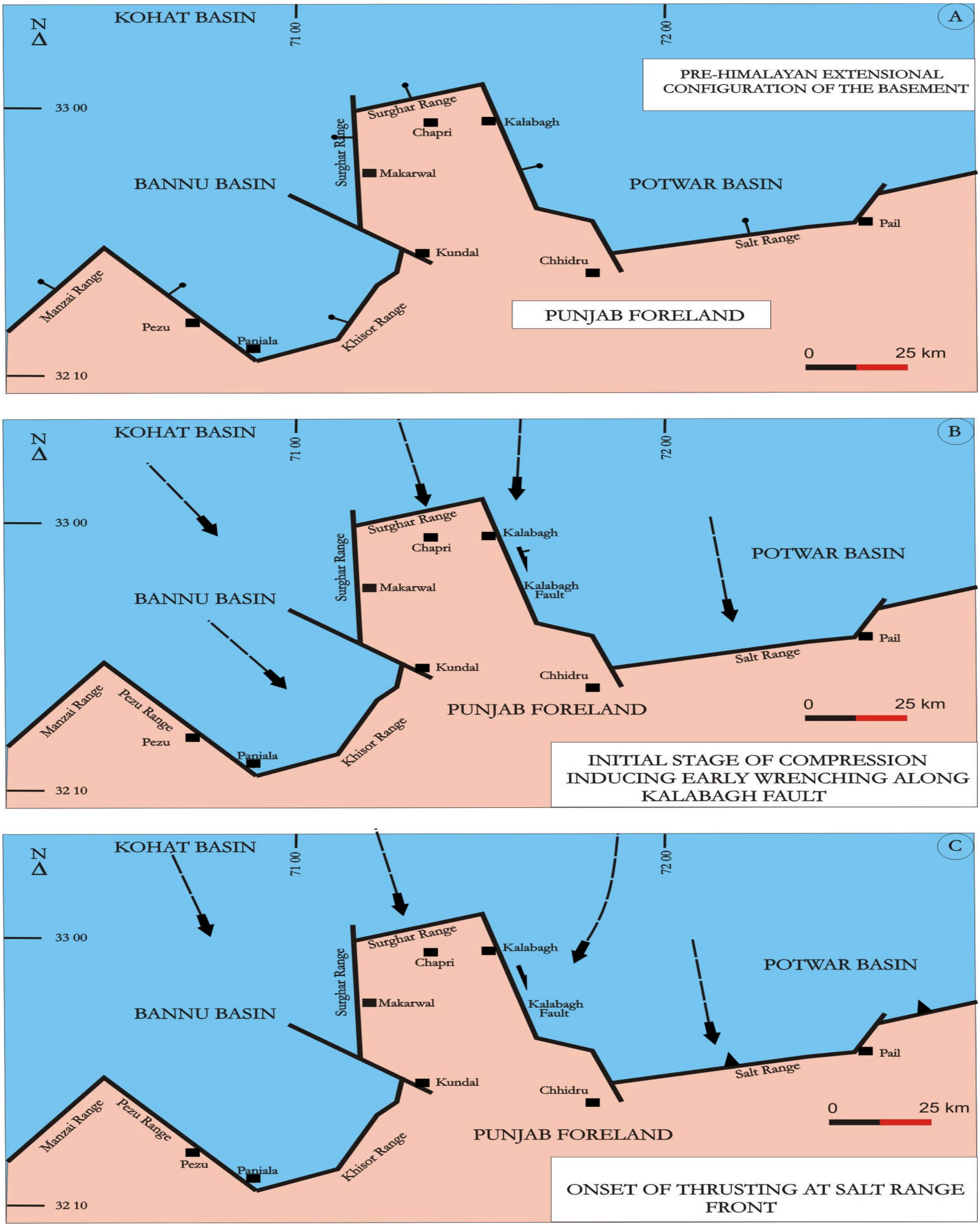

Figure 5 A-C - Proposed model showing pre-existing basement irregularities and the sequential evolution of the Trans Indus Salt Range

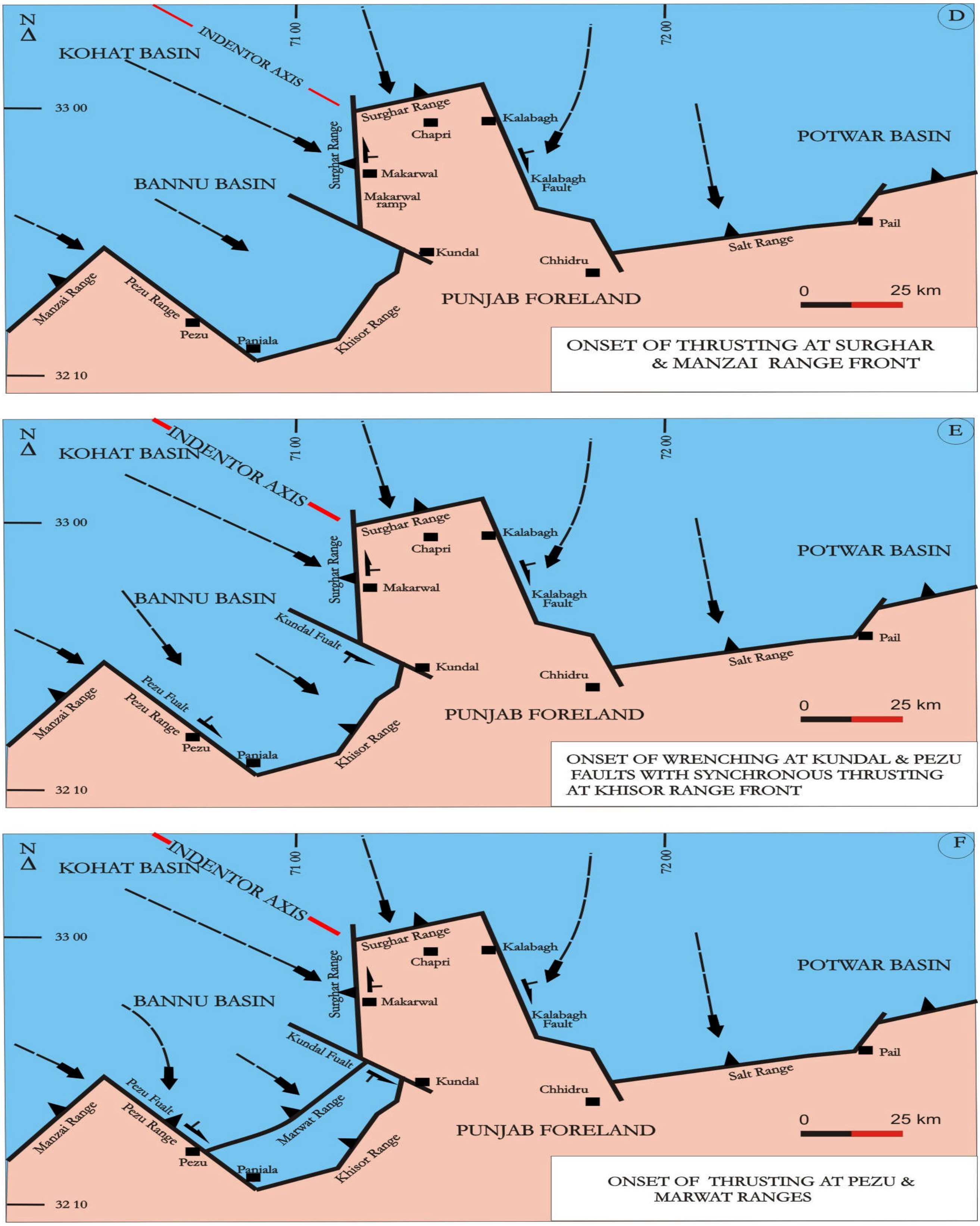

Figure 5 D-F - Proposed model showing pre-existing basement irregularities and the sequential evolution of the Trans Indus salt Range.

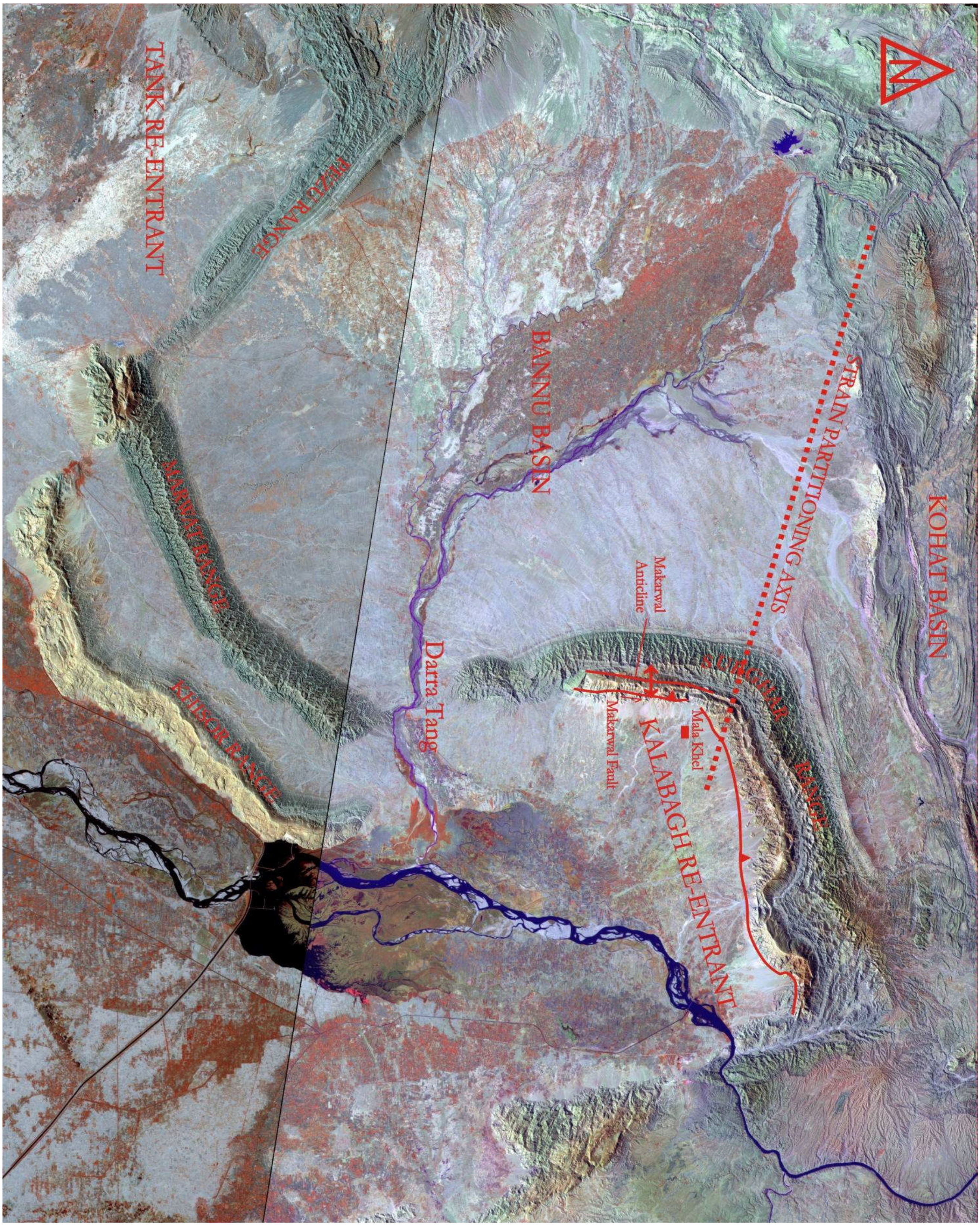

Figure 6 - Satellite image of the southern Kohat-Bannu Basin and Trans Indus Salt Range showing location of the strain partitioning axis oriented in the north-west direction.

are still active. The Trans Indus Salt Range may have evolved as an in-situ arcuate orogenic belt controlled by the geometry of pre existing basement irregularities.

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