NEOTECTONICS AND SEISMIC HAZARDS ASSESSMENT OF RAIKOT SASSI FAULT ZONE, NANGA PARBAT SYNTAXIS, NORTH PAKISTAN

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IN THE NAME OF ALLAH
THE MOST BENEFICIAL, THE MOST
MERCIFUL

DEDICATED TO MY BELOVED PARENTS
AND HONOURABLE PROFESSORS
<table>
<thead>
<tr>
<th>S.No</th>
<th>Title</th>
<th>Page No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acknowledgement</td>
<td>1-2</td>
</tr>
<tr>
<td></td>
<td>ABSTRACT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHAPTER 1</td>
<td>3-6</td>
</tr>
<tr>
<td></td>
<td>INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>1.1.</td>
<td>Objectives</td>
<td>4</td>
</tr>
<tr>
<td>1.2.</td>
<td>Methodology</td>
<td>4</td>
</tr>
<tr>
<td>1.2.1.</td>
<td>Digitisation</td>
<td>4</td>
</tr>
<tr>
<td>1.2.2.</td>
<td>Image Analysis</td>
<td>5</td>
</tr>
<tr>
<td>1.2.3.</td>
<td>Field and Structural Data Collection</td>
<td>5</td>
</tr>
<tr>
<td>1.2.4.</td>
<td>Geological Maps, Sketches, Illustrations</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>CHAPTER 2</td>
<td>7-31</td>
</tr>
<tr>
<td></td>
<td>REGIONAL TECTONICS</td>
<td></td>
</tr>
<tr>
<td>2.1.</td>
<td>Introduction</td>
<td>7</td>
</tr>
<tr>
<td>2.2.</td>
<td>The Karakoram Terrane</td>
<td>10</td>
</tr>
<tr>
<td>2.2.1.</td>
<td>Tectonic Subdivision</td>
<td>11</td>
</tr>
<tr>
<td>2.2.2.</td>
<td>Principal Fault Structures</td>
<td>12</td>
</tr>
<tr>
<td>2.2.2.1.</td>
<td>Shyok Suture/Main Mantle Thrust</td>
<td>12</td>
</tr>
<tr>
<td>2.2.2.2.</td>
<td>Thrust Faults in the Karakoram Metamorphic Belt</td>
<td>12</td>
</tr>
<tr>
<td>2.2.2.3.</td>
<td>Rehun Fault</td>
<td>16</td>
</tr>
<tr>
<td>2.2.2.4.</td>
<td>Tirich Mir-Kikl Boundary Fault</td>
<td>16</td>
</tr>
<tr>
<td>2.2.2.5.</td>
<td>Karakoram Strike-Slip Fault</td>
<td>16</td>
</tr>
<tr>
<td>2.3.</td>
<td>The Kohistan Terrane</td>
<td>17</td>
</tr>
<tr>
<td>2.3.1.</td>
<td>Tectonic Subdivision</td>
<td>19</td>
</tr>
<tr>
<td>2.3.2.</td>
<td>Major Fault Structure</td>
<td>19</td>
</tr>
<tr>
<td>2.3.2.1.</td>
<td>Main Mantle Thrust/(MMT)</td>
<td>20</td>
</tr>
<tr>
<td>2.3.2.2.</td>
<td>Kamilla-Jal Shear Zone</td>
<td>21</td>
</tr>
</tbody>
</table>
2.3.2.3 Jaglot Syncline and associated Thrust Faults 22
2.4 Indian Plate 24
2.4.1 Tectonic Subdivision 25
2.4.2 Major Structures 26
2.5 Synthesis of Regional tectonic evolution 29

CHAPTER 3
THE NANGA PARBAT SYNTAXIS 32 – 53

3.1 Introduction 32
3.2 Lithologies 32
3.2.1 Iskere-Mushkin-Rupal Gneisses 33
3.2.2 Shengus-Harchu Gneiss 33
3.2.3 Haramosh-Tarshing Schists 35
3.2.4 Intrusive rocks 35
3.3 Structure in Nanga Parbat Syntaxis 36
3.3.1 Folds 36
3.3.2 Faults 39
3.3.2.1 Main Mantle Thrust 40
3.4 Tectonic Evolution of the Nanga Parbat Syntaxis 50

CHAPTER 4
NEOTECTONICS 54 – 96

4.1 Introduction 54
4.2 Neotectonics appraisal of the Nanga Parbat Syntaxis 55
4.3 Eastern margin of the Nanga Parbat Syntaxis 59
4.4 Western margin of the Nanga Parbat Syntaxis 59
4.4.1 Rakhot Sassi fault Zone (RSFZ) 59a
4.4.1.1 Segmentation 60
4.4.1.2 Accessibility
4.4.1.3 Terminations
4.4.1.4 Field Description, Kinematics and Evidence for
   Neotectonic activity
   4.4.1.4.1 Darshan-Khaltoro-Shahbatot Segment
   4.4.1.4.2 Shahbatot River Bend
   -Buchi-Unjal Nala Segment
   4.4.1.4.3 Bunji-Ramghat-Astor Segment
   4.4.1.4.4 Lachhar-Raihet Segment
   4.4.1.4.5 Jallipur-Bunar Gah Segment

CHAPTER 5
SYNTHESIS AND DISCUSSIONS 97 – 110

5.1 Rupturing 97
5.2 Segmentation 98
5.3 Splaying 98
5.4 Subsurface geometries 99
5.5 Evidence for Neotectonic Activity 102
   5.5.1 Drainage Pattern Displacement 104
   5.5.2 Fault Scars 106
   5.5.3 Deformation in Quaternary Sediments 106
   5.5.4 Seismicity 107
5.6 Neotectonic activity and seismic hazards for the
   Proposed Dam site area 109

CONCLUSION & RECOMMENDATIONS 111 – 112

REFERENCES 113 – 123
<table>
<thead>
<tr>
<th>S.No</th>
<th>Title</th>
<th>Page No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 2.1</td>
<td>A sketch map of the South Central Asia showing principal tectonic blocks/ microplates with respect to Nanga Parbat Syntaxis</td>
<td>9</td>
</tr>
<tr>
<td>Fig. 2.2</td>
<td>Palaeogeographic setting of the South-Central Asia in Late Triassic-Early Jurassic, showing closure of the Palaeotethys between Asia and Lahasa-Karakoram-Afghan blocks.</td>
<td>9</td>
</tr>
<tr>
<td>Fig. 2.3</td>
<td>Middle Cretaceous Palaeogeographic setting, showing separation of the Indian Plate from Gondwana and its drifting towards north and development of the Kohistan Island Arc in Neo Tethys as a product of intra-oceanic subduction.</td>
<td>10</td>
</tr>
<tr>
<td>Fig. 2.4</td>
<td>Mid Cretaceous palaeogeographic setting of the Kohistan Terrane with respect to Karakoram and Indian plates.</td>
<td>11</td>
</tr>
<tr>
<td>Fig. 2.5</td>
<td>Regional geological map of the Karakoram Plate.</td>
<td>14</td>
</tr>
<tr>
<td>Fig. 2.6</td>
<td>A: Geological map of Hunza Karakoram showing Shyok Suture Zone between Kohistan and Karakoram blocks and tectonometamorphic subdivision of the Karakoram block. B: Simplified cross section illustrating the structural relations between the principal units.</td>
<td>15</td>
</tr>
<tr>
<td>Fig. 2.7</td>
<td>Geological map of the Kohistan Terrane, N. Pakistan.</td>
<td>18</td>
</tr>
<tr>
<td>Table 2.1</td>
<td>A detailed review of the MMT showing the tectonic history into following stages.</td>
<td>20</td>
</tr>
<tr>
<td>Fig. 2.8</td>
<td>Schematic east-west cross section along the strike of the Main Mantle Thrust.</td>
<td>21</td>
</tr>
<tr>
<td>Fig. 2.9</td>
<td>Geological map of eastern Kohistan and Himalayas to the east of Besham.</td>
<td>22</td>
</tr>
<tr>
<td>Fig. 2.10</td>
<td>Geological cross section across the Kohistan island arc terrane, and the southern part of the Karakoram block exposed in the Hunza valley.</td>
<td>23</td>
</tr>
<tr>
<td>Fig. 2.11</td>
<td>Regional geological map of the NW Himalaya, N. Pakistan, showing positions of the internal (metamorphic) and external (non-metamorphic) zones</td>
<td>25</td>
</tr>
</tbody>
</table>
Table 2.2  Showing major structural events in the Himalayas, N. Pakistan.  

Fig. 2.12  Geological map of NW Himalayas of N. Pakistan showing positions of the major faults.  

Table 2.3  Showing major structures and deformation phases in the Himalaya-Kohistan-Karakoram blocks N. Pakistan.  

Fig. 3.1  Regional geological map of the Himalayas.  

Fig. 3.2  3-D representation of the fold and fault structures in the Nanga Parbat Syntaxis and adjacent Kohistan Arc terrain.  

Fig. 3.3  Geological section of the Astor valley, Nanga Parbat Syntaxis, showing principal lithological units and structures.  

Fig. 3.4  Simplified cross section (downplunge projection) of the syntaxial structure derived from structural data collected along the Indus gorge section. The inset shows a diagrammatic representation of the basement-cover imbrication that preceded the fold structures in the Nanga Parbat Syntaxis.  

Fig. 3.5  Section across the Raikot-Sassi Shear Zone at Liacher showing NW verging nature of the thrust with Indian Plate gouges in its hanging wall and the vertical Kohistan sequence in the foot wall unconformably overlain by recent Indus Valley alluvium.  

Fig.3.6a.  Geological map of the SW margin of Nanga Parbat Syntaxis as exposed in the Bunar Gah area, east of Chilas.  

Fig. 3.6b  Cross-sections across the Diamir Shear Zone, Bunar Gah, showing folding of MMF by the west trending Diamir Shear Zone.  

Fig.3.7  Geological map of the eastern margin of Nanga Parbat Syntaxis as exposed at Stak in the Indus Valley.  

Fig. 3.8  Geological map of the Nanga Parbat Syntaxis showing location of the Subsar thrust.  

Fig. 3.9  A geological sketch map of the Churut Fault near the eastern margin of Nanga Parbat Syntaxis between Raka and Rupal valleys.
Fig. 3.10 Geological map of Nanga Parbat Syntaxis showing major fault structures

Fig. 3.11 Lateral termination of the Main Himalayan Thrusts at a pinning point showing displacement direction of movement.

Fig. 3.12 A schematic NW-SE cross-section across the Nanga Parbat Syntaxis. The Aril Gali Shear Zone is an active structure producing mechanism for Quaternary uplift and exhumation of the Nanga Parbat Syntaxis.

Fig. 4.1 Regional tectonic sketch map of north Pakistan, showing major tectonic zones and fault lineaments.

Plate 4.1 Photomicrograph showing a view of the Indus valley from Shabbatot towards Sassi, two brittle faults mylonites.

Plate 4.2 Photomicrograph showing mylonites with strong stretching lineation: 335°/48°NW.

Plate 4.3 Photomicrograph showing a crush zone marked by brittle faults with gouges, Khaltoro.

Plate 4.4 Photomicrograph showing a view of the Khaltoro Fault.

Plate 4.5 Photomicrograph showing slipped valley face, at Khaltoro.

Plate 4.6 Photomicrograph showing major strand, Khaltoro Fault and associated gouge zone.

Plate 4.7 Microphotograph showing the western face of the Khaltoro gorge comprising mylonites is cut across by a steeply east-dipping brittle fault.

Plate 4.8 Photomicrograph showing close-up of the brittle fault shown in Plate 4.7.

Plate 4.9 Photomicrograph of a E-W oriented ridge at the Shabbatot river bend as viewed from north.

Plate 4.10 Microphotograph of a fault gouge zone at the Shabbatot River Bend (view from south).

Plate 4.11 Microphotograph of a knife-edge sharp brittle fault cross cutting the dipping Afghan Amphibolites and marbles.

Plate 4.12 Photomicrograph showing the aerial view of the Indus valley from Khaltoro valley towards south.
Plate 4.13 A) Photomicrograph of Hapchal village near the top of the Sarkund Ridge, north of Bunji.
B) Mylonite outcrops above the Hapchal village
C) Feldspar porphyroclasts in mylonites showing dextral sense of displacement in mylonites.

Plate 4.14 Photomicrograph of the eastern slopes of the Sarkund ridge, showing transition from undeformed Kamila Amphibolite to sheared rocks related with the Raikot-Sassi Fault Zone.

Plate 4.15 Microphotograph showing the close up of the marked area in Fig.4.17.

Plate 4.16 Microphotograph of a brittle fault zone above the the Burchi village.

Plate 4.17 Microphotograph showing close view of gouge zone above the Burchi village separated by intact bedrock.

Plate 4.18 Photomicrograph of the gouge zone associated with the Raikot-Sassi Fault Zone exposed on the eastern slope of the Sarkund ridge, above the Burchi village.

Plate 4.19 Photomicrograph showing close view of mylonite zone immediately east of the Unjhi-Bunji intersection, upper Bunji Gorge.

Plate 4.20 Microphotograph of northern face of the Bunji Gorge, showing two.

Plate 4.21 Photomicrograph of the downstream view of the northern face of the Ramghat Gorge.

Plate 4.22 Microphotograph of the two brittle fractures on the northern face of the Ramghat gorge.

Plate 4.23 Microphotograph of the the eastern Indus valley and its eastern face at Astors confluence showing location of MMT and trace of the Raikot Thrust.

Plate 4.24 Microphotograph of the northern face of the Astor Valley, comprising of Nanga Parbat metasediments, Kamila Amphibolite and Kohistan Diorite.

Fig. 4.2 Geological cross section of the Astor (north) Ridge showing relationship between Main Mamlie Thrust and the Liacher Thrust.

Plate 4.25 Photomicrograph of a large fault gouge zone exposed on the eastern face of the Indus valley near the Astor-Indus confluence.
B) Geological sketch of fault gouge zone shown in Plate 4.25.
Fig. 4.3 Sketch map of shear zone shown in Plate 4.23.

Plate 4.26 A) Microphotograph of an active thrust fault at Liacher.  
B) Close up of Liacher Thrust.

Fig. 4.4 Sketch map of slope failure-mass movement in the Indus Valley in the area between the Raikot Bridge and Bunji.

Plate 4.27 Microphotographs showing features indirectly related with the Raikot-Liacher Thrust.  
A) Hattu Pir landslide 1841, eastern face of the Indus valley that the landslide blocked the river.  
B) Major landslide zone on the eastern face of the Indus Valley between Liacher and Raikot where the Nanga Parbat gneisses thrust onto alluvium.  
C) Linear array of hot springs Tatta Pani along the active fault, and on the left bank of the Indus River.

Fig. 4.5 Geological map of the NW margin of Nanga Parbat Synaxis.

Fig. 4.6 Geological cross section across the Diamir Shear Zone at Banar Gah.

Plate 4.28 Photomicrograph of the Gushat fold structure exposed at the western margin of Nanga Parbat Synaxis at the eastern flank of Banar Gah.

Plate 4.29 Photomicrograph of steep east dipping brittle faults exposed on the northern face of the Diamir gorge.

Plate 4.30 Photomicrograph of the Jaipur tilites deformed into a tight syncline on the right of the Indus River, near Ke Ghar.

Plate 4.31 Photomicrograph of Dalipur tilites with steep dips towards south

Plate 4.32 Photomicrograph showing close up of Plate 4.31.

Fig. 5.1 A) Broadband and short-period array (triangles), regional and local events from four month recoring window.  
B) Detail of Nanga Parbat short period array and  
C) The base of seismicity forms a prominent antiformal shape beneath the massif.

Plate 5.1 Photomicrograph showing relationship between 34-15 Ma old pegmatite dykes and deformation associated with the Raikot-Sassi Fault Zone.  
A) Kohistan diorites cut across by an irregular network of acidic dykes. The host rock as well as the dykes show no signs of deformation;
B) Kamila Amphibolites exposed at Nanuchal village showing strong vertical foliation cross cut by pegmatite dykes, and
C) Sassi mylonites. The 34-15 Ma year old pegmatite are deformed and sheared.

Fig. 5.2. Two possible scenarios for the Indus River drainage displacement in response to tectonics of the Nanga Parbat Syntax.
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ABSTRACT

This study is on the geological and neotectonic appraisal of Nanga Parbat region in N. Pakistan. The area encompassing various elements has a geological setting defined by two tectonic blocks namely Kohistan Island arc terrane and Indian plate, which are sutured by a regional fault termed the Main Mantle Thrust. The rocks east of the Main Mantle Thrust are included in the Nanga Parbat Syntaxis and those to the west are part of the Cretaceous Kohistan terrane. Tectonic activity responsible for the formation of the Nanga Parbat Syntaxis, a N-S oriented crustal-scale fold, structure re-oriented the Main Mantle Thrust to a NS orientation, superimposed by a new fault zone called Raikot-Sassi Fault Zone.

Different types of Potential hazards are noticed directly or indirectly associated with neotectonics of the region. Geotechnical properties of the constituent rocks are not a subject of this study. General observations during the course of this study suggest that except for the ~700 m wide gouge/shear zone, all other lithologies (Nanga Parbat Gneisses, Kamsila Amphibolite and Kohistan Batholith) are highly competent and most suitable for the study engineering structures. However, overall strength of the gouge/crush zone, firstly because of derivation from competent igneous/metamorphic lithologies and secondly, because of partial re-cementation by hydrothermal solutions is better than many rock types. Presence of an active fault zone, in the study area is already documented in literature. This work conducted a detailed study of the Raikot-Sassi Fault Zone. The Raikot-Sassi Fault Zone is apparently divisible in two segments one between Bunji and Darchan in the north and the other between Ramghat and Bonar in the south.

Both the fault segments cut across Quaternary glacial till and alluvial deposits of 20-30 thousands years in age, with possibility of even deforming alluvial fans as young as 3 thousands in age. Presence of active fault scarps, displacement of drainage patterns (including the formation of the Indus loop around the Saralrud ridge) and presence of a linear array of hot springs from Sassi in the north to Tatta Pani in the south coinciding with the fault trace, further substantiate the active nature of the fault zone. The two principal differences noted between the northern and the southern fault segments include kinematics and seismicity record. A WNW vergent thrust zone predominantly characterizes the southern segment, although the footwall shows evidence of both E/SE vergent minor thrusts and vertical faults with dextral strike-slip movement. Further, this segment is demonstratably associated with seismic events in last 160 years.
geological and historical record shows that Licher area was epicentre of a major
earthquake (7.8 M) in 1841 that triggered at least four large landslides in the area
between Banji and Tatte Pani. The other seismic event was on November 20, 2002. With
a magnitude of 6.7, the event was epicentred near Doian (Astor Valley). Both these
events were associated with the active western margin of the Nanga Parbat Synaxis that
is manifested in the Raikot-Sassi Fault Zone. In comparison, the northern segment has a
dominant component of dextral strike-slip movement. Further, no historical or
instrumental record of recent seismic activity associated with this fault segment is known
to the authors. Whereas it may imply that the northern segment of the Raikot- Sassi Fault
Zone is dormant for last about 3000 years, there is an alternative possibility that the
northern segment is accumulating elastic strain all this time and thus has a higher
potential of a major earthquake and associated rupturing and ground failure anytime in
future. As noted above, potential for a local earthquake sourced at Raikot-Sassi Fault
Zone or other major faults within the Nanga Parbat Synaxis e.g., the Churit Fault and
Rupal-Chhichi-Shengus Shear zone, is high. A careful seismic hazard analysis based on
parameters derived from the Raikot-Sassi Fault Zone, Rupal-Chhichi-Shengus fault, and
Churit Fault at local level, and Kohistan Seismic Zone, Main Karakoram Thrust and
Karakoram Strike-Slip Fault at regional level, needs to be carried out for determination of
peak ground acceleration as well as design spectra. This present study is focussed on
neotectonics and related aspects. Therefore there is a detailed account of active faults and
associated rocks.
CHAPTER 1
CHAPTER 1

INTRODUCTION

Earthquakes are the consequences of the breaking and shifting of rocks beneath Earth’s surface. Most of them take place along faults or breaks in the Earth’s crust. Methodologies used for assessing the seismic potential of a region are therefore highly dependent upon geophysical and geological studies. Record of seismic data yields useful clues about the degree of vulnerability of a region regarding the earthquake hazards. In most parts of the world, seismicity is regularly and systematically recorded using seismographs and ground shaking expressed as ground acceleration (g) is recorded by accelerometers. This type of quantitative data is however, available for the last few tens of decades. John Milne invented first seismograph in 1880 and in the beginning of the 20th century an accurate recording of earthquakes was possible. Seismologists are able to present a complete list of the major earthquakes that have occurred on earth from 1953 onward. But not until the end of the 1950’s did this observation network reach a global scale. Since then it has been possible to record and measure earthquakes, both on small and major scale, all over the world. Reliability of seismicity data for regions like N. Pakistan, where no local seismic network is available has remained doubtful. Jackson (1980), while analysing the Dar, Harwar and Pattan earthquakes in Kohistan, found that some attributes of these earthquakes, especially their depth of focus was highly incorrect as recorded by seismic stations located outside this region.

Lack of reliable instrumental record and an inadequate historical account of past earthquakes in region like N. Pakistan, assessment of seismic hazard potential of such region depends on geological investigations. Grove Karl Gilbert(1972) for the first time documented the relationship between earthquakes and geology i.e structures, when he after studying the fault scarp from the 1872 Owens Valley, California earthquake, concluded that the faults were a primary feature of earthquakes. Faults are therefore considered to represent a valuable source of information about the seismic potential of a region and there is a clear relationship between the fault ruptures and magnitude of earthquakes.

This study was conducted to formulate a reappraisal of the geology of Nanga Parbat Synclines and its adjacent Kohistan terrane, with emphasis on structures that depict nectectonic activity.
1.1 OBJECTIVES

The main objectives of this study are:

- Evaluation of the regional geotectonic setting of the area and recognition of fault structures, which may be a seismic source.
- Detailed geological study of the area to delineate faults, shear zones, folds and other structural defects.
- Recognition of active fault zones and their distinction from older, dormant fault zones.
- Determining relationship between tectonics and seismicity.
- Recommendations for seismic hazard analyses.

1.2 METHODOLOGY

Geological investigations are primarily based on fieldwork and accurate mapping. However, with the advent of new techniques in image analyses and remote-sensing and geological mapping is greatly assisted by analytical studies of satellite images prior to conducting the fieldwork. This study therefore included an elaborate programme of digitization and image analyses complementing the necessary fieldwork.

1.2.1. Digitization

A set of thirteen topographic sheets prepared by Survey of Pakistan and supplied by WAPDA was scanned and digitized using on-screen digitizing method. The digitization was conducted using ILWIS 3.1 Geographic Information System (GIS) Software. The digitized objects included, drainage, locations, and contours. The contour interval used for digitization was 2000 m. Additionally, a degree sheet I/43 on a scale of 1: 250,000 were digitized for drainage and locations.
1.2.2. Image Analyses

A variety of satellite imagery provided by the SUPARCO, Islamabad, was used during the present studies. This include:

- SPOT 2, Panchromatic, 10 m resolution
- SPOT 2, XS Multispectral, 20 m resolution, 3 bands
- SPOT 5, Panchromatic, 5 m resolution.

Additionally, two datasets were used for this study.

- TM, Multispectral 7 bands, 30 meter Resolution
- ETM+, Multispectral 9 band, 36 m resolution.

These satellite imagery data were processed using ER Mapper 6.2 software. The techniques included band combinations, spectral ratios, principal component analyses, and decorrelation stretch analyses. Additionally techniques like Georeferencing and Geocoding, defined as the “act of assigning locations to things within the geographic frame of reference” (Goodchild, 2001) were applied to the above mentioned satellite images.

The image analyses of the satellite data by using the ER Mapper software enabled to:

1) Preparation of images, which directly matched the digitised topographic maps and thus were ready for their use as base maps for geological mapping.

2) Recognition of geological entities such as lithologies, contacts and fault/fault zones to various extents. For instance, the use of TM/ETM data with RGB (742 bands) enabled to distinguish between lithologies of the Kohistan arc sequence from those of Nanga Parbat sequence. Likewise, the scarp related with the Raikot fault became highly visible when seen on integrated SPOT and TM/ETM images.

1.2.3 Fieldwork and Structural Data Collection

Since the inception of the project in middle July 2003, three visits were made to the project area.

July 21-27, 2003. This field visit was used to outline the most critical areas for detailed investigations.

September 22-October 7, 2003. The principal objective of this field visit was to take a traverse from Buni village, across the 14,000 high Sarkund ridge occupying the medial axis of the Indus River loop, to the village Burshi. This traverse greatly helped in assessing the geological and engineering properties of the rocks. This traverse also
resulted in identifying a ~ 700 meter wide shear zone on the eastern face of the Indus valley, associated with the southern extension of the Raitot-Sassi Fault Zone (RSFZ). Besides this hiking traverse, a week was spent on roadside outcrops for mapping and observing features related with the RSFZ fault.

A separate phase of this fieldwork involved visits to other tectonic elements in the Kohistan Nanga Parbat region covering Indus Valley, Ghizar Valley and Hunza valley. December 5-22, 2003. This fieldwork was focused at studying the neotectonic features a wide region from north of Sassi all the way to the Bumar Gah (46 km upstream from Chilas).

1.2.4 Geological maps, sketches, illustration

Efforts have been made using conventional geological techniques, the state-of-the art computer aided image analysers and cartographic techniques to integrate field mapping and satellite images for the development of geological maps, field sketches and illustrations.
CHAPTER 2.
REGIONAL TECTONICS

2.1. INTRODUCTION

The Bunji-Shongsa area is located at the western margin of the Nanga Parbat Syntaxis: a broad, crustal-scale antiformal structure in northern Pakistan. This region is significant for its geographical position at the junction of world’s three major mountain ranges including the Hindukush, the Karakoram and the Himalayas (Fig. 2.1). These mountains owe their origin to plate tectonics. Several evidences based on diverse geological studies including lithological and structural mapping, fossil findings, radiometric date determinations have suggested that N. Pakistan is comprised of three, previously discrete and distant apart, plates named Karakoram, Kohistan and Indian. These plates collided with each other during Cretaceous-Early Tertiary to form the present-day landmass of south central Asia. This era of collision tectonics and mountain-building activity is termed as the Himalayan orogeny.

The Nanga Parbat Syntaxis is comprised of rocks belonging to the Indian Plate, once a part of a mega-continent called Gondwana, located at the southern pole of the Earth. Of the other two plates in N. Pakistan, the Karakoram plate was also once a part of Gondwana. The Gondwana passed through several episodes of division through rifting and drifting of its dislodged blocks/plates resulting in collision with the southern margin of Asian plate as well as with Kohistan island arc, the major present-day continents including Africa, S. America, Australia and Antarctica. Several of the continental pieces at the northern extremity of Gondwana separated from it during the Permian and drifted towards the north to collide at the southern edge of another large continent called Eurasia, located in the northern hemisphere. These pieces included Lhasa (Tibet), Karakoram, Afghan and Iran microplates and Indian plate. The ocean that originally intervened between the Eurasia and Gondwana, (termed Palaeo-Tethys) was squeezed between the northward drifting Lhasa-Karakoram-Afghan-Iran continental blocks and was obliterated when these pieces collided with Eurasia. To their south, however, they opened up another ocean termed Neo-Tethys that separated them from the remaining parts of the Gondwana (Fig. 2.2). During the Early Cretaceous (~130 Ma ago), India became dislodged from the Gondwana and started drifting towards north as a result the Neo-Tethys started shrinking.
in response to its subduction at the southern margin of the Karakoram as well as at a site within the interior of the ocean (Fig. 2.3). This latter intraoceanic subduction resulted in the development of Kohistan island arc at the equatorial (Tahirkheili et al., 1979). The subduction zone at the southern margin of the Karakoram Plate consumed the part of the Neo-Tethys north of Kohistan that resulted in the collision of the Kohistan arc with the Karakoram plate at its southern margin at around 90 Ma (Tahirkheili et al., 1979; Petterson and Windley, 1995). The site where the Kohistan-Karakoram collision took place is called the Shyok suture (Searle and Khan, 1996). At the time of collision between the Kohistan and the Karakoram, India was still located south of equator and a major part of the Neo-Tethys separated India from Kohistan (Fig. 2.4). The continued subduction at the southern margin of Kohistan took another about 32-35 my to completely consume the Neo-Tethys that resulted in collision of the Indian plate with Kohistan at the southern margin of the Eurasia. The site of obliteration of the Neo-Tethys and India-Kohistan collision is termed the Indus Suture (Gansser, 1964) which, in Pakistan, is termed the Main Mantle Thrust (MMT) as it involves rocks as deep as mantle (Tahirkheili et al., 1979).

Since the western margin of the Nanga Parbat Synaxis is located in close proximity of the collisional boundaries between the Karakoram, Kohistan and Indian plates, it is pertinent to review tectonics of all these three plates to assess their possible contributions as sources of seismicity and driving mechanisms for tectonic activity in the area (Fig. 2.5).
Fig. 2.1. A sketch map of the South Central Asia showing major tectonic blocks/ microplates with respect to Nanga Parbat Syntaxis (after Gaetani and Leven, 1997).

Late Triassic-Early Jurassic

ASIAN COMPOSITE PLATE
Subduction of the Paleoethys

Early Jurassic rotation

CENTRAL

EASTERN

TRIASSIC-AJYURINSKY

CENTRAL
SOUTH FAMIR
GEOSYNCLINE

KARAKORAM

DOMAR

LHASA

MEGA

LHASA

NEOTETHYS

INDIAN PLATE

Fig. 2.2. Palaeogeographic setting of the South-Central Asia in Late Triassic-Early Jurassic, showing closure of the Paleoethys between Asia and Lhasa-Karakoram-Afghan blocks. The Neotethys closed in Eocene (~55 Ma), (after Gaetani and Leven, 1997).
2.2. THE KARAKORAM TERRANE

The remnants of the Karakoram plate occur in the northern most parts of Pakistan, in an east-west trending belt roughly coinciding with the extent of combined Hindukush and Karakoram (Fig. 2.1, to 2.5). Northern Baltistan (including K2), Upper Hunza, Ishkuman, Yasin, Yarkhan and Chitral are parts of northern Pakistan, which occur in the Karakoram plate. The Karakoram plate is a lateral equivalent of the Lhasa block in the east, and Afghanistan and Iran microcontinents in the west. All these microplates are Gondwanic in their faunal affinity and are considered to have been separated from the Gondwana sometime in Permian. The southern contact of the Karakoram plate is with the Kohistan island arc terrane at the site of the Shyok-Chalt suture. To the north, the Karakoram terrane is in contact with the southern Pamir terrane along the Tirich Mir-Kilik suture zone (Gastani and Leven, 1997).

![Map of the Middle Cretaceous Palaeogeographic setting](image)

**Fig. 2.2**. Middle Cretaceous Palaeogeographic setting, showing separation of the Indian Plate from Gondwana and drifting to north. Note development of the Kohistan Island Arc in Neo-Tethys as a product of intraoceanic subduction. (after Khan et al., 1997)
Fig. 2.4. Mid Cretaceous palaeogeographic setting of the Kohistan Terrane with respect to Karakoram and Indian plates (after Khan et al., 1997)

2.2.1. Tectonic Subdivision

The Karakoram terrane in N. Pakistan was assigned a status of a microplate or a terrane by Windley (1985) as it is bounded by regional fault structures (suture zones) on all its sides. Recently, Gaetani and Leven (1993) and Zanchi et al. (2000) recognized Tirich Mir Fault in upper Chitral and assigned it a status of a suture zone on the basis of occurrences of peridotites, gabbros, metavolcanics and gneisses associated with it. These authors propose a two-fold division of the Karakoram-Hindukush terrane into the Karakoram block to the south and Eastern Hindukush block in the north.

The Karakoram block is bounded by the Shyok suture or the Main Karakoram Thrust in the south, Tirich Mir-Kulik Boundary Zone in the north, the Karakoram strike slip fault in the east. It is geologically divisible into three tectonic units (Zanchi et al., 2000), which from south to north...
include: 1) The Karakoram Metamorphic Belt, 2) Tibe Axial Batholith, and 3) Barphil-Chauparson Sedimentary Belt (Scarl, 1991).

2.2.2. Principal Fault Structures

The Karakoram-Hindukush is amongst the southerly tectonic elements of Pamir knot, which is popularly interpreted to represent the apex of the tectonic activity related with indentation of relatively stronger crust of India northward into relatively softer crust at the southern margin of Eurasia. As expected from the Tapponier model, the faults in the Karakoram-Hindukush terrane are thrust/reverse in their sense of displacement and strike-slip at the eastern and western margins. The following major faults are recognized in the Karakoram-Hindukush terrane.

2.2.2.1. Shyok Suture/Main Karakoram Thrust.

This fault separates the Cretaceous Kohistan sequence in the south from the Karakoram Metamorphic belt in the north and carries a status of suture zone as it marks closure of an ocean (termed Shyok Ocean by Khan et al., 1997). The fault follows the Shyok river in eastern Pakistan-Ladakh region, passes north of Nanga Parbat Synaxis along the Chang Pughma glacier and is well exposed in the Hunza valley at the Chalt village. Further westwards it passes through Chatorkhas village (Ishkuman valley) and Yain. In Chitrail it follows the Shis valley and northern slopes of the Chitrail River and runs into Afghanistan north of the Rondu village. Stretching in north suggest the fault is a thrust fault in the region north of Gilgit but changes into a strike-slip fault to the west in the Chitrail area (Coward et al., 1986; Pudsey et al., 1985). There is no direct reporting of reactivation of the Shyok suture zone, but recent radiometric dating in the Hunza and eastern Karakoram Metamorphic Belt suggest that other faults in this zone might be as young as post 5 Ma. (Fraser et al. 2001)

2.2.2.2. Thrust Faults in the Karakoram Metamorphic Belt

Mapping in Hunza valley has revealed a 20-25 km thick succession of metamorphosed sedimentary rocks mainly pelitic slates, schists and gneisses with subordinate marbles. These metasedimentary rocks are divisible into five zones based on grade of metamorphism that starting from low-grade chloritoid slates near the Shyok suture extends to highest-grade gneisses of sillimanite grade in the vicinity of the Axial
Karakoram Batholith. Each of the five metamorphic zones i.e., biotite, chloritoid-garnet, staurolite, staurolite-kyanite, and sillimanite is in tectonic contact with each other characterized by thrust faults (Fig. 2.6). Including the Shyok zone, a series of six major thrusts are therefore recognized in the Hunza area of the Karakoram metamorphic belt. Considering the original age of suturing at the Shyok suture to be around 90 Ma, these thrusts could have been assigned a similar or older age (Khan et al, 1997). However, work by Searle (1997) had already recognized that metamorphism peaked in Karakoram between 50-35 Ma and hence the thrusts may be younger than that. Recent radiometric dating has discovered that whereas some of these thrusts especially the one separating the Karakoram Axial batholith from the Karakoram Metamorphic Complex could be as old as Eocene, others formed after the staurolite-grade metamorphism that peaked at 16±1 and prior to the intrusion of the 9±0.1 Sumayar (Nagar) pluton(Fraser et al. 2001). The youngest metamorphism recognized in the Kanskoram metamorphic Complex is from the Dasu Gneiss (northern Shigar valley) dated at 5 Ma which could be associated with a deformation phase, which is yet to be confirmed (Fraser et al., 2001)
Fig. 2.5. Regional geological map of the Karakoram Plate. Note that Karakoram Strike Slip Fault bounds the plate in its east and Shyok Suture Zone (Main Karakoram Thrust) in the south. The Tirich Mir Fault (TMF) separates the Karakoram Block in the south from Eastern Hindukush Block in the north (after Fraser et al., 2001; Gaetani and leven, 1997; Searle and Khan, 1996).
Fig. 2.8.
A) Geological map of the Hunzaz area showing position of Shyok Suure Zone between Kohistan and Karakoram blocks and tectonic subdivision of the Karakoram block characterized by different zones separated from each other by discrete thrust faults. (Fraser et al. 2001).

B) Simplified cross section through the hunza Karakoram illustrating the structural relations between the principal units. (Fraser et al. 2001).
2.2.3. Resun Fault

The Karakoram block in the western portion in Chitral is divided into two parts by a regional fault termed the Resun Fault (Fig. 2.5) (Cakins et al., 1981; Pudsey et al., 1985). This is a SE verging thrust that stacks Paleozoic rocks in the north thrust over the Paleozoic-Mesozoic succession in the south. The fault involves the Cretaceous Resun Formation comprising felsicite red conglomerates, sandstone, siltstone and shale. The Resun Fault is characterized by brecciation and stickends. The Resun fault is assigned a Cretaceous probably synchronous with the Shyok Suture. According to Hildebrand et al. (2000), the part of the Karakoram block in the Chital region suffered a phase of transpressional deformation dominated by left-lateral strike-slip faulting after 24 Ma that reactivated both the Resun Fault as well as Shyok suture.

2.2.4. Tirich Mir-Kılık Boundary Fault

This fault has recently been identified as a secure zone that separates the Karakoram block in the south from the E-Hindukush-Wakhan block in the north (Fig. 2.5). The fault is well exposed in the upper Chitral between Shah Jilali Pass in the east to Garam Clashma area, where it is associated with a suite of mafic peridotites, gabbros and metavolcanics. The fault is traceable all along the western flanks of the Yarkhun River all the way to Baroghil. Further eastward, the fault is tentatively linked with the Kılık fault that separates the Misgar slates, north of Sost (upper Hunza valley) from the Sost sedimentary belt.

2.2.5. Karakoram Strike-Slip Fault

To the East of the Karakoram terrane, the Karakoram Fault separates the Karakoram-Ladakh-Indian accreted blocks from the Lhasa-Qingang blocks (Fig. 2.1, 2.5). The Karakoram Fault is a dextral shear zone. It reactivates former sutures between the tectonic blocks, branching in the NW into Pamir thrusts and strike-slip faults and to the SE into the Shyok and Indus-Tsango sutures (e.g., Armijo et al., 1989; Matte et al., 1996). The magnitudes of right lateral offset and slip rate and the duration of slip of the Karakoram strike-slip fault are debated. Peltozer and Tappoalni (1988) have estimated a large offset (1000 km), based on correlation of the Ladhakh and Gangdese batholiths, and this has led
to an estimate of elevated slip rates of 32 mm yr⁻¹, also suggested by the offset of topographical features (Liu et al., 1992; Liu, 1993). In contrast, Searle (1996) and Searle et al. (1999) have proposed a smaller offset estimate (120 km), from the correlation of the Baltoro and Tangtse granites and Shyok and Baogong Sutures in the central part of the fault.

2.3. THE KOHISTAN TERRANE

The Kohistan terrane in North Pakistan is a fossil island arc of Middle Cretaceous-Early Tertiary age. This is an east-west trending belt covering an area of ~ 25000 km², encompassing the Kohistan region of North Pakistan i.e., Indus, Swat and Dir valleys. The Baltistan region in the east is included in the Ladakh terrane, which is considered to be a continuation of the Kohistan terrane now separated from it by the later Nanga Parbat Syntaxis structure. The Kohistan terrane originated as an intraoceanic island arc (similar to the present day Mariana Island arc in Pacific ocean) in middle Cretaceous (~130 Ma ago) (Fig. 2.3, 2.4). It suffered two collisions: firstly it collided with the southern margin of previously accreted Karakoram-Eurasia at about 90-80 Ma along the Chalt-Shyok suture), when it became an Andean-type continental margin. Finally the terrane was sandwiched when the Indian plate collided at its southern margin during Early Tertiary (55-58 Ma ago) at the site of the Main Mantle Thrust (MMT) or Indus Suture (Khan et al. 1997).
Fig. 2.7. Geological map of the Kohistan terrane, N. Pakistan, showing position of the Main Karakoram Thrust and Main Mantle Thrust (after Khan et al 1987).
2.3.1. Tectonic Subdivision

Unlike the Karakoram terrane, the Kohistan terrane is mostly coherent i.e., it lacks major faults, which can be used to divide it into separate tectonic blocks (Fig. 2.7). In general, the southern parts of the Kohistan terrane contain ultramafic-mafic plutonic complexes (Jijal Complex, Sapat Complex Kanjila Ambelite Belt and Chilas Complex), while the northern part comprises basic volcanic rocks and sediments, most of them metamorphosed (Jaglot Group, Chalt Group). These mainly middle Cretaceous lithologies constituted the crust of the Kohistan island arc in its intra-oceanic setting. At ~90 Ma the Kohistan island arc was accreted to the Karakoram Plate along the Shyok Suture (also called the Main Karakoram Thrust). This transformed the tectonic setting into an Andean-type continental margin, whereby part of the Neotethys between the Kohistan’s southern margin and the Indian plate started subducting northward beneath the Kohistan-Karakoram plate. This gave rise to an extensive Andean-type batholith of granitic composition that extensively intruded the Kohistan terrane during the Late Cretaceous and Early Tertiary. A set of fore-arc and back-arc basins developed in this Andean-type continental margin phase, now preserved as Palaeocene-Eocene volcanic rocks (e.g., Uttar Volcanic Formation; Sullivan et al., 1993 in Upper Dr-Swat area and Teni-Sharan volcanic Formation in the Shandur Pass area (Sullivan et al., 1993; Daninbhar et al., 2001). A sequence of marine sediments (turbidites) termed the Barauli Bandha Slate Formation was deposited in the Dr-Kalam fore-arc basin during the Earliest Palaeocene (Sullivan et al., 1993). Marine sedimentation ceased at the time of collision of the Indian plate with the southern margin of the Kohistan-Karakoram continental margin at about 55 Ma at the site of the Indus Suture or the Main Mantle Thrust. Granitic magmatism sporadically continued until 34 Ma (Indus Confluence and Parri granitic sheets/ dykes).

2.3.2. Major Fault Structures

As mentioned earlier, the Kohistan terrane is bounded by two suture zones, Main Karakoram Thrust or the Shyok Suture in the north and the Mais Mantle Thrust/Indus Suture Zone in the south. In the interior of the Kohistan terrane, Tvedhaar et al. (1990) documented a 28 km wide shear zone from Indus Valley south of Kafir, while Asis Khan and Coward (1990) described a shear zone at the southern contact of the Chilas Complex in valleys to the south of Chilas (Busar Gag, Tah Gah, Thor Gah). Further
northward, Khan and Searle (1996) reported an array of divergent thrusts associated with the Jafot Syncline and Gilgit anticline structures.

2.3.2.1. Main Mantle Thrust (MMT)

The Main Mantle Thrust/Indus suture defines the tectonic boundary between the Kohistan terrane and the Indian Plate (Tahirkheli et al., 1979). It extends eastward from Afghanistan, through Dir, Swat, Upper Hazara, Upper Kaghan, Babusar and then northward around the Nanga Parbat Synaxis into Ladakh. The type locality of the MMT is considered to be at Jijal, north of Besham (Karakoram Highway). Here the fault is a sharp, planar contact with mylonitic and brittle fabrics, juxtaposing quartzo-feldspathic gneisses of the Precambrian Besham Group in the footwall and the Cretaceous Jijal ultramafic Complex in the hangingwall. Elsewhere, the MMT is represented by a series of faults with different ages and tectonic history. In some areas along the MMT, a thick imbricated mélangé zone of greenschist, blueschist, espenite and ultramafic rocks represents the MMT (e.g., Mingora, Shangla).

<table>
<thead>
<tr>
<th><strong>Late Cretaceous</strong></th>
<th>SW directed thrusting and mélangé emplacement along the Batal, Banna, Shergarh, Khisor and Dargai faults</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Early Eocene</strong></td>
<td>Synmetamorphic SSE directed thrust emplacement of Malakand and Dargai tectonic slices.</td>
</tr>
<tr>
<td><strong>&gt; 40 Ma</strong></td>
<td>Deformation by N-S trending folds (e.g., Indus Synaxis).</td>
</tr>
<tr>
<td><strong>Oligocene-Early Miocene</strong></td>
<td>ESE-SE emplacement of the Kohistan Terrane onto the Indian plate and previously emplaced mélangé zones and tectonic slices along the Kohistan Fault.</td>
</tr>
<tr>
<td><strong>Miocene and Younger</strong></td>
<td>Development of N-S trending brittle faults in the Indus Synaxis region (e.g., Parau, Chakesar, Darband faults) as well as in the Nanga Parbat Synaxis (e.g., Rakot-Sassi Fault Zone).</td>
</tr>
</tbody>
</table>

Table 2.1 A detailed review of the MMT showing the tectonic history into following stages (after DiPierro et al. 2000)
2.3.2. Kamila-Jal Shear Zone

The contact between the Chilas Complex and the Kamila Amphibolites Belt was first mapped in detail by Khan (1988); Khan and Coward (1990). These workers reported a 30 meter wide shear zone demarcated by greenschist and mylonites at this contact, exposed in the valleys south of Chilas. Treloar et al. (1990) described a 28 km wide belt in the Indus Valley, mainly involving the Kamila amphibolite ductile shear zones, and is called Kamila Shear zone. In Fig. 2.9 the Jal and Kamila shear zones seem to be the different name of the same shear zone runs along the southern margin of the Chilas Complex (DPietro et al., 2000). The extension of the Kamila-Jal shear zone, to the west of the Indus valley (e.g., Swat and Dir region) has not so far been documented. Eastwards, the Kamila-Jal shear zone crosses the Indus River at Bunar-Indus confluence and to extend northwards as far as Thalichi. The Kamila-Jal shear zone is probably of Middle Cretaceous age (~90-80 Ma). No evidence of Quaternary re-activation is hitherto available. Khan and Coward (1990) described northward plunging lineation suggesting southward thrust displacement of the Jal Shear Zone. A similar kinematic sense of movement is reported in the Kamila Shear Zone (Khan and Coward 1990).

![Fig. 2.8. Schematic east-west cross section along the strike of the Main Mantle Thrust. All rock units are indicated by the Kohistan Fault, which merges with the indus Raikot Fault in the east at the western margin of the Nanga Parbat Synclines. 1. Sarna-Paria Swat fault, 2. Dargai-Khasora-Sheryar Fault, 3. Malakand Fault, 4. Nawagai Fault, 5. Kohistan and Aghigar Faults, 6. Puran, Chakshar and Dambband Faults, 7. Raikot Fault. The order of numbers indicates the tectonic activities from older to younger.](image-url)
2.3.2.3. Jaglot Syncline and associated Thrust Faults

The northern part of the Kohistan terrane, north of the Chilas Complex is extensively intruded by granitic rocks termed Kohistan Batholith (Jan et al., 1981; Pettersson and Windley, 1985). The region between the Kohistan Batholith and the Main Karakorams Thrust was previously considered to comprise solely of the Chalt Volcanics and the Yasin Sediments.
FIG. 2.10. Geological cross section across the Kohistan island arc terrane, and the southern part of the Karakoram block as exposed in the Hunza valley. Apart from the Main Mantle Thrust at the southern margin of the Kohistan terrane and the Main Karakoram Thrust at the Kohistan-Karakoram interface, two structures occur in the interior of the Kohistan terrane. One of these structures is the south-vergent Jal-Kamila Shear Zone at the southern contact of the Chilas Complex against the Kamil Amphibolite Belt. The other set of structures is north of the Chilas Complex and is defined by south-vergent Jaglot Syncline and north-vergent thrusts and folds around Gilgit. (After Searle and Khan, 1996)
Coward et al. (1987) for the first time reported a major structure in the form of a syncline in the Thelisch area, with a WNW-ESW trend. Khan et al. (1994; 1998) noticed a sedimentary succession in the Jaglot-Gilgit area, which they designated as the Jaglot Group. The Jaglot Group comprises, from base to the top, Gilgit Paragneiss, Gashu Metavolcanics and the Thalichi Formation (slates and marbles). As exposed on the Karakoram Highway near Thalichi, the Jaglot Group is involved in a major south-vergent syncline (the Jaglot Syncline) that involves Gashu Metavolcanics and the Thalichi Formation. The northern limb of this syncline is overturned, probably attenuated by a south-vergent thrust fault. Here the Gashu Metavolcanic Unit is overlain by the older Gilgit Paragneisses. The Gilgit area, though extensively intruded by the plutons belonging to the Kohistan Batholith, consists of Gilgit Paragneisses as the country rock. In the Hanzo area, the steeply south-dipping Chait Volcanics are overlain by the Gilgit Paragneisses, and are themselves underlain by vertical to steeply south-dipping Yasin sediments. This overturned sequence in the Hanzo valley could be due to overturning at the northern limb of the Gilgit anticline, or due to a set of north-verging thrust faults, or both (Searle and Khan, 1996). Therefore the Gilgit area defines a major antiform or a pop-up structure, with both its northern and southern limbs overturned (Fig. 2.10).

The structures in the Jaglot and Gilgit area are mapped in detail (Khan et al., 1994; 1998; Searle and Khan, 1996). However, all these structures are older than 60 Ma (Khan et al., 1998; Teleo et al., 1996). No signs of neotectonic activity related with these structures are reported.

2.4. Indian plate

The Himalayas, from purely geological and plate-tectonic point of view, represent the deformed northern part of the Indian plate involved in continent-continent collision. Thus the region to the south of the MMT is included in the Himalayas. The most northerly part of the Himalayas, in N. Pakistan is represented by the Nanga Parbat-Haramosh Synclise. The mountain ranges of Kashmir, Upper Kaghan (south of Baluasar), Upper Hazara (Alii Kohistan and to the south), Benham and Indus Synclise, lower Swat (south of Mingora), Chakkara, and Sajaur-Mohmand agencies define the northern parts of the Himalayas. The Salt Ranges and the Trans-Indus Ranges are the southern limits of the Himalaya in N. Pakistan.
2.4.1. Tectonic Subdivision

The Himalayas are regionally divisible into internal (hinterland) and external (foreland) zones (Coward et al., 1988). The internal zone occurs immediately to the south of the MMT and comprises crystalline rocks of Naran, Hazara, Besham and Swat areas (Fig. 2.11). The external zone, which, in essence, is a type foreland thrust-fold belt, comprises successions of stratified sedimentary rocks of Hill Ranges (e.g. Margala, Kalachiitra, and Kohat), Potwar-Kohat plateau, and Salt Range, Trans-Indus ranges. The tectonic boundary between the internal and external zones is marked by the Nathagallah-Khairabad thrust (NKT). Another classification, imported from the central and eastern Himalayas (Gansser, 1964), divides the Himalayas into Tethyan-, higher-, Lesser- and sub Himalayas (Fig. 2.12). The Tethyan Himalayas, comprising Precambrian- Eocene unmetamorphosed sedimentary rocks, are best developed in eastern and central Himalayas but are absent from the western Himalayas of N. Pakistan.

Fig. 2.11. Regional geological map of the NW Himalayas, N. Pakistan. Nathagallah Thrust marks the boundary between the Internal (metamorphic) and the External (non-metamorphic) zones (After Coward et al., 1988).
The higher Himalayas comprising crystalline rocks of Proterozoic age with imprints of Himalayan metamorphism are abundantly exposed just to the south of the MMT in Kaghan, Hazara, and Swat areas. The Main Central Thrust (MCT) demarcates the Higher Himalayas from the Lesser Himalayas. The MCT is well developed in eastern and central Himalayas but its extension beyond Kaghan is controversial in N. Pakistan, rendering the distinction of the Higher from Lesser Himalayas little problematic. The equivalents of the Lesser Himalayas in northern Pakistan have been tentatively divided into an inner or Abbottabad zone and an outer or Kalachitta zone.

The latter comprises unmetamorphosed sedimentary rocks ranging in age from Triassic to Eocene, and includes Kohat, Kalachitta, and Margala Hill ranges. The Abbottabad zone comprises unmetamorphosed fossiliferous rocks of early Palaeozoic age (Abbottabad Group), which overlies a sequence of variable metamorphosed rocks of imprecisely defined Late Proterozoic age (including Salkhala Formation, Tanawal, Hazara, Manki Formations and Landikotal and Dahirner Slate. The equivalent of the Early Palaeozoic Abbottabad Group in the Peshawar Plain is called Nowshera Group. This is overlain by a thick succession of fossiliferous Permian-Triassic rocks intercalated with basalts horizons. This is correlatable with Late Palaeozoic-Early Mesozoic Panjal Group of Kaghan and Kashmir. The Lesser Himalayas are demarcated from the Sub-Himalayas by the Main Boundary Thrust (MBT), which is a mountain front defined by a blind thrust, except for the west of the Indus river, where it becomes emergent. The Sub Himalayas of N. Pakistan are defined by the Potwar-Kohat Plateau comprising thick succession of Miocene-Recent molasse sediments (Rawalpindi and Siwalik Groups). Unlike the eastern Himalayas, the Lesser Himalayas are repeated twice in N. Pakistan. The Salt Range Formation and its overlying Palaeozoic strata, are equivalents of the Hazara Slates and overlying Abbottabad group in Hazara. The Salt Range lies at the southern edge of the Potwar plateau. The gently dipping detachment essentially running through the Salt Range Formation ramps along a basement normal fault and exposes the entire sequence from Precambrian to Recent in the Salt Range.

2.4.2. Major Structures:

The Himalaya of N. Pakistan is the structural manifestation of the Himalayan orogeny and thus comprise numerous major structures. According to Trechar et al. (1989), the internal zone of N. Pakistan comprises five major thrust sheets, which include; from
East to west, Upper Kaghan, lower Kaghan, Hazara, Besham and Swat. All these thrust sheets are bounded by fault structures. Their emplacement is considered to be post-peak metamorphism (post 45 Ma.) (Trelcar et al. 1989).

A traverse along the Kaghan River gives a representative picture of the major structures in the Himalayas of N. Pakistan. In this region, several major boundary faults separating thrust sheets of different tecto-stratigraphic make up can be distinguished (Fig. 2.12).

<table>
<thead>
<tr>
<th>Higher Himalaya Thrust Sheet</th>
<th>Paleozoic-Mesozoic Metasedimentary Cover Sequence Cambrian and older ortho- and Paragneisses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Central Thrust</td>
<td></td>
</tr>
<tr>
<td>Inner Lesser Himalaya Thrust Sheet</td>
<td>Precambrian Salkha Formation (metapelites, marbles, two-mica augen gneisses)</td>
</tr>
<tr>
<td>Panjtal thrust</td>
<td></td>
</tr>
<tr>
<td>Intermediate Lesser Himalaya Thrust Sheet</td>
<td>Carboniferous-Triassic Panjal Group (pelites, marbles, metavolcanics)</td>
</tr>
<tr>
<td>Thrust Fault</td>
<td></td>
</tr>
<tr>
<td>Outer Lesser Himalaya Thrust Sheet</td>
<td>Jurassic-Eocene Carbonate Platform</td>
</tr>
<tr>
<td>Main Boundary Thrust</td>
<td></td>
</tr>
<tr>
<td>Sub-Himalaya Thrust Sheet</td>
<td>Eocene-Miocene Balakot (Murree) Formation</td>
</tr>
</tbody>
</table>

Table 2.2. Showing major structural events in the Himalayas, N. Pakistan.

All the major thrusts in the Internal Zone of the Himalaya are affected by a later phase of N-S oriented fold structures such as the Nanga Parbat Synaxis, Hazara-Kashmir Synaxis, and Besham-Darband Synaxis. This phase of N-S folding post-dates the MBT and thus as young as < 5 Ma. Quaternary fault structures, mostly oriented N-S are commonly associated with margins of these N-S fold structures such as the Rakhot-Sassi Fault at the western margin of the Nanga Parbat Synaxis, Balakot Fault at the western margin of the Hazara-Kashmir Synaxis. The Besham Synaxis is cut across by several N-S faults including the Puran, Chakesar and Darband Faults.
Fig. 2.12. Geological map of NW Himalayas of (Hazara, Kaghan, Kashmir)N. Pakistan. Main Mantle Thrust (MMT), Main Central Thrust (MCT), Panjal Thrust (PT) and the Main Boundary Thrust (MBT). The north-vergent Hazara Kashmir Synclines refolds all the major thrusts except MMT, which is folded by the Nanga Parbat Synclines. (After Greco, 1989).
The Kohat-Potwar Plateau and the Sift range are bounded by Main Boundary thrust to the north and Main Frontal Thrust to the south.

2.5 SYNTHESIS OF REGIONAL TECTONICS

The geology and tectonics of Northern Pakistan is primarily governed by the Himalayan orogeny. Unlike the other concepts, the Himalayan orogeny is now believed to have started by Middle Cretaceous (~90 Ma ago), when the Kohistan Island Arc terrane collided with the southern margin of the Karakoram Plate (Hodges, 2000). This phase of the Himalayan orogeny termed the Protohimalayan phase is believed to continue to Early Eocene, just before the India-Eurasia collision. The orogenic phase marking the main India-Eurasia collision is termed the Eohimalayan phase that started around 55 Ma and continued to Oligocene. The latest part of the Himalayan orogeny covers the Early Miocene-Present time span and is termed the Neohimalayan orogeny. This phase includes the neotectonic activity such as that of the Nanga Parbat Synaxis. Table 2.2 classifies the structures in N. Pakistan into these three phases of the Himalayan orogeny in order to portray their relevance to neotectonics.

The oldest structures in the Karakoram Plate are the Tirich Mir Fault, which marks the southern Karakoram-Hindukush block with the Eastern Hindukush Block. This active zone is intruded by the middle Cretaceous Tirich Mir Pluton, suggesting a pre-Middle Cretaceous age for the active zone. The high-grade metamorphism is the Karakoram Plate is envisaged to have started soon after the collision with the Kohistan arc (i.e., ~80 Ma) with the Karakoram plate. Most of the major thrusts in the Karakoram plateau, including the Rishin Fault and the thrust stack in the Hunza valley probably formed between 52 and 35 Ma (Fraser et al. 2001). The Staurolite grade of metamorphism is in the Hunza Valley is dated to be 16 Ma (Fraser et al. 2001). The thrusts associated with this phase of metamorphism are intruded by 9 Ma granites, suggesting that the latest tectonic event in the Karakoram block occurred between 16 and 9 Ma. However, the Karakoram Strike Slip Fault along Kunjerab Pass-Siachen glacier is still active and is the youngest tectonic feature in the Karakoram plate.

According to Treloar et al., 1989 in the Kohistan terrane, the oldest structures are dated at middle Cretaceous 90-80 Ma. These include Jal-Kamia Shear zone in southern Kohistan and Jaglot-Gilgit fold structures and associated thrusts. The structures related with the MMT phase of deformation are not too common in Kohistan. The MMT itself has a wide span of tectonic development ranging from
<table>
<thead>
<tr>
<th>Years (in millions)</th>
<th>Karakoram Plate</th>
<th>Kohistan Island Arc Terrane</th>
<th>Indian Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Foreland</td>
<td>Hinterland</td>
</tr>
<tr>
<td>145</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>130</td>
<td></td>
<td>Initiation of the Kohistan-intraoceanic Subduction zone giving rise to Kohistan Arc. Separation of India and start of northward drift.</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td></td>
<td>Closure of Palaeo-Pilgrim, Karakoram-Indus already collided</td>
<td></td>
</tr>
<tr>
<td>110</td>
<td></td>
<td>Toltik Mir Fault</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Karakoram Axial batholith</td>
<td>Juvenile Arc Crust consisting of plutonic rocks of the Jijal Complex, karima</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Amphibolite belt and volcanic/volcanosedimentary rocks of the Chalt and Jagdal Groups formed</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>Sillimanite Grade</td>
<td>Metamorphism/denudation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Karima-Jal Shear Zone, Jagdal-Gilgit</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Syncline-anticline pair and associated thrusts</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Sillimanite-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Rock metamorphism and crustal shortening including MCT, Panga Thrust, Nangnag Thrust</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>Stilpnomelane-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>Stilpnomelane-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Stilpnomelane-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>Stilpnomelane-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Stilpnomelane-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Stilpnomelane-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Stilpnomelane-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>Stilpnomelane-Kyanite Grade</td>
<td>Metamorphism</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rock metamorphism and crustal shortening including MCT, Panga Thrust, Nangnag Thrust</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>India-Kohistan Collision Indus Suture (MIM) Closure</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3. Tectonic summary of the Himalaya-Kohistan-Karakoram terrane of N. Pakistan, showing major structures and deformation phases in each block in terms of their time history.
Middle Cretaceous to Early Miocene. The latest structures in the Kohistan terrane are related with the Quaternary Raikot Fault, which folded the Kohistan crust in the Bunar Gah area and rotates the MMT in an upright position all along the SW margin of the Nanga Parbat Synaxis.

In the Indian plate, the Himalayan phase of orogeny resulted in thrust stacking in the internal zone between 50 and 35 Ma and resulted in the formation of the MCT, Panjal and Nathiagali Fault (Fraser et al. 2001). The Main Boundary Thrust and structures in the footwall of the MBT formed after 8 Ma. All these structures are folded along crustal scale N-vergent fold structures such as the Indus Syntaxis, Hazara Kashmir Syntaxis and the Nanga Parbat Syntaxis in last 10 Ma. The youngest tectonic features in the Indian Plate include the Main frontal Thrust (i.e., the Salt Range Thrust) in the foreland and the Raikot Fault in the hinterland (khan et al. 1987).
CHAPTER 3
CHAPTER 3.

THE NANGA PARBAT SYNTAXIS

3.1. INTRODUCTION
The Nanga Parbat Syntaxis is a significant topographic, structural and lithologic entity exposed in the NW Himalayas, N. Pakistan. Structurally, the syntaxis is a crustal-scale antiform that strikes N-S and verges west/northwest. This contrasts with the dominant structural orientation of the Himalayas, which strike northwest-southeast and have a vergence of the Himalayan thrust front towards southwest (Fig. 3.1). As discussed in Chapter 2, the Nanga Parbat Syntaxis is a unique tectonic entity in the Himalayas for several of its attributes: 1) it is one of the biggest fold structures in the Himalayas. 2) it exposes deepest parts of the Indian plate crust in the form of ortho- and paragneisses, which are the oldest rocks encountered in the Himalayas (maxesum 2500 Ma; other ages from the gneisses include 1800, 406-500 Ma) (Zeitler et al. 1989). 3) The rocks have been exhumed from several tens of kilometers beneath the Kohistan-Ladakh island arc to their present-day exposures; 4) the peak of Nanga Parbat (8123m) sits at the NW terminus of the >2500 km Himalayan arc, away from main locus of high peaks, and represents one of the steepest pieces of topography above the sea; 5) it represents an area of exceedingly young plutonism, metamorphism and cooling (Zeitler et al., 1989; Chamberlain et al., 1989; Smith et al., 1992); 6) these young events demonstrate uplift/exhumation rates of 5-10 mm/yr (Craw et al., 1994).

In this chapter an overview of the lithostratigraphy, structure and geochronology is presented. These descriptions are used to construct a model for the tectonic evolution of the Nanga Parbat Syntaxis.

3.2. LITHOLOGIES
The Nanga Parbat Syntaxis comprises three major rock units: 1) the Iskere-Mushkin-Rupal Gneiss. 2) the Shangus-Harchu Gneiss, and 3) the Haramosh-Tashing Schists. A wide range of rocks including basic dykes and rocks intruding these major lithological units have been noticed in all parts of the Nanga Parbat Syntaxis (khan et al. 1997).
3.2.1 Iskere-Mushkin-Rupal Gneiss Unit

A broad homogeneous body of granite and augen gneisses occupies the west-central part of the Nanga Parbat Synclise all the way from north of the Indus valley through Mushkin-Daskin area of the Astor valley to the south in the region occupied by the summit area of Nanga Parbat Rupal valley area. Augen gneisses are dominant in the Rupal valley, while its exposures are found in the Indus and Astor valleys. Migmatization is common in the Iskere gneisses with abundant melt segregation. Gneissic banding and N-S oriented stretching lineation is common but selectively developed. Zeitler et al. (1989) reported 1850 Ma as the age of the protolith for the Iskere-Mushkin-Rupal Gneiss unit based on U/Pb on zircon dating.

3.2.2 Shengus-Harchu Gneiss

Maiden et al. (1989) first proposed the name Shengus Gneiss for the unit exposed east of Shengus in the east-central part of the Nanga Parbat Synclise. It comprises predominantly of paragneisses as exposed in the Indus Valley between Shengus and Stak. This unit differs from the Iskere-Mushkin-Rupal Gneiss Unit in terms of the abundance muscovite, staurolite, kyanite, sillimanite, and local intercalations of metasedimentary rocks including calc-silicates, marbles and quartzites. Sayab et al. (1997) mapped a similar unit in the east-central parts of the Astor Valley as the Harchu Gneiss and correlated with the Shengus Gneiss in the Indus valley. The pinkish coloured biotite-garnet rich gneisses also contain local occurrences of marbles, calc-silicates and quartzite.

According to Maiden et al. (1989), the Shengus-Harchu Gneiss was probably derived from a protolith of shale, with marl, arkosic sandstone, and limestone. Zeitler et al. (1989) reported a 400-500 Ma protolith age for the Shengus-Harchu Gneiss.
Fig. 3.1: Regional Geological Map of the Himalayas showing the structural relation of the Himalayas with the Nanga Parbat Syntaxis almost at right angle to the main Himalayan trend (after Hodges, 2000)
3.2.3 Haramosh-Tarshing Schists

A group of metasediments is exposed along the marginal parts of the Nanga Parbat Synaxis directly below the MMT. Different names depending upon their occurrence in different localities have been assigned for example Haramosh schists reported from the Indus valley section (Maiden et al., 1989) Rattu Formation, reported from the southern parts of the Astor valley (Tahirkheli, 1982) (Sayab et al., 1997) Tarshing metasediments reported from southern parts of the Rupal valley (Butler et al., 2000).

These schists are predominantly pelitic, comprising fine-grained two-micas, garnet schists. Other lithologies associated are marbles, calc-silicate gneisses, and subordinate amphibolite.

The age of the Haramosh-Tarshing Schists is not known, though these have been tentatively correlated with the Salkhala Formation of Precambrian (Wadia, 1961).

3.2.4 Intrusive Rocks

A variety of intrusive rocks predominantly granitic in composition with minor basic rocks, intrude the gneisses and schists already discussed. The basic rocks occur mostly in the form of dykes, intruding all the lithologies mentioned above are homogeneous and are metamorphosed to amphibolites. They are crosscutting the host lithologies, especially; they cross cut the gneissic banded. The basic dykes in the Nanga Parbat Synaxis are most probably Late Palaeozoic in age, and have correlated with the Permo-Carboniferous Panjal Group of the Lesser Himalayas (Tahirkheli, 1982). Their crosscutting relations with the gneisses of the Nanga Parbat Synaxis suggest that at least one phase of high-grade metamorphism is pre-Himalayan in age.

The granitic intrusions in the Nanga Parbat Synaxis are spread over wide area. A sheet like body occupies the eastern margin of the synaxis at the contact between the Harchu Gneiss and the Tarshing Metasedimentary unit, well exposed in the Astor valley. The granite is porphyritic comprising of large crystals of feldspar, enclosed in a matrix of muscovite-biotite and quartz. The biotite is highly mylonitized and has attained a distinct pink colour. Edwards et al. (2000) assigned the name Lath Unit to this porphyritic granite.

A large lenticular granitic body intrudes the metasediments at the western margin of the Synaxis, stretching from Dianmir Gah up to 30 km to the south at the eastern phase of the Bunar-Biari Gah. Ternmned Jahlari Granite, it is a biotite granite that locally develops
augen texture due to ductile deformation. The Jalhari granite yields 12-2 Ma age based on Th-Pb monazite dating (Schenider et al., 2000).
The central part of the Nanga Parbat Synaxis i.e., around the summit, contains several small bodies of leucogranite intruding the gneisses

3. 3. STRUCTURES IN NANGA PARBAT SYNAXIS

3. 3. 1. FOLD STRUCTURES

The Nanga Parbat Synaxis is defined by two upright crustal-scale fold structures, which extend from the Indus valley all the way to the south in the Rupal valley, where they are modified by the Rupal-Chhichi shear zone. These were termed as Iskere and Bulache antiforms by Maiden (1986). In the Indus valley, Maiden et al. (1989) suggested that northeast trending Baroloma fault separates these two antiforms (Fig.3.2), which are separated by tight syncline. These antiforms are also observed in the Astor Valley section (Fig. 3.3). Again a tight syncline with amphibolites in the core similar to the amphibolite of Kohistan-Ladakh arc terrane separate the two antiforms. This upright steep syncline, probably reworked by a steep fault is exposed in the northern face of the Astor River at the mouth of the Dichili Gah (Sayab et al., 1997).

![Diagram of fold and fault structures in the Nanga Parbat Synaxis and adjacent Kohistan Island Arc terrane](image)

Fig. 3. 2. 3-D representation of the fold and fault structures in the Nanga Parbat Synaxis and adjacent Kohistan Island Arc terrane (after Maiden et al., 1989).

The Iskere antiform trends north and plunges northward at 50°. The antiform has a steeply dipping western limb, which is reworked by the steep Raikot-Sassi Fault Zone. The
eastern limb dips 50° E and is truncated by the Baroluma fault. The Buluche antiform trends N30°E and plunging of 50° towards north. The western limb of the antiform is again steep, while the eastern limb is moderately dipping to the east and is truncated by the Stak fault of the MMT zone.

Interestingly, the Iskere antiform is cored by the Iskere-Mushkin-Rupal Gneiss, while the Bulache antiform, by the Shengus-Harchu Gneiss. The cover metasediments however occur at the limbs of both antiforms. This suggests that the pre-folding crustal set-up comprised a continuous sequence of cover sequence that was underlain by a basement that was predominated by the Iskere-Mushkin-Rupal Gneiss in the west and by the Shengus-Harchu Gneiss in the east. This is only possible if it is considered that there was imbrication of the basement beneath a roof thrust/ detachment at the basement-cover sequence contact. In this scenario, Iskere gneiss would have thrust on top of the Shengus gneiss, prior to the formation of the two large antiformal structures as portrayed in the Fig. (3.4).
Fig. 3.3. Geological map of the Ailor valley Nanga Parbat Syntaxis, showing major lithological units and structures (after Sayag et al., 1997).
In terms of sequence of structural evolution, the crustal-scale folding into the two antiformal structures is the latest folding phase in the Nanga Parbat Syntaxis. According to Maiden et al. (1989) two phases of folding preceded the large-antiformal folding stage, which therefore needs to be referred to as the Phase III folding. The Phase I folding stage is defined by tight isoclinal folds as noticed in the gneissic banding. The stage II folds are characterized by east-west oriented upright anticlinal and synclinal folds. Both Phase I & II folds are greatly modified by the Phase III large antiformal folds and thus are not significant.

![Diagram of structural evolution with labels and annotations]

Fig. 3.4 Simplified cross section (down plunge projection) of the syntaxial structure derived from structural data collection along the Indus gorge section. The inset shows a diagrammatic representation of the basement-cover imbrication that preceded the fold structures in the Nanga Parbat Syntaxis (Treloar et al., 1991).

3.3.2 FAULTS

The Nanga Parbat Syntaxis is characterized by a large number of large and small scale fault. Among them Main M mantle Thrust is the most important that bounds the massif on its northern, western and eastern side, forming a half window structure, with Kohistan terrane in the hangingwall and the Nanga Parbat massif in the footwall. Raikut-Sassi is an active fault zone that more or less coincides with the MMT at the western margin of the massif except for the in the Bunah Gah area where it is separated from the MMT and runs in a N-S orientation as the Dismir Shear Zone (Edwards et al., 2000; Khan et al.,
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![Simplified cross section](image)

**Fig. 3.4.** Simplified cross section (downplunge projection) of the syntactical structure derived from structural data collection along the Indus gorge section. The inset shows a diagrammatic representation of the basement-cover imbrication that preceded the fold structures in the Nanga Parbat Syntaxis (Treloar et al., 1991).

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39
The MMT at the eastern margin of the Nanga Parbat Syntaxis is delineated by Stak Fault Zone and the Subsar Thrust. The faults mapped in the interior of the Nanga Parbat Syntaxis include Shengus-Rupal-Chhichi shear zone, Churit fault and Baroloma fault (Edwards et al., 2000; Butler and Prior, 1988a; 1988b; Butler et al., 1989, 1992, 2000).

3.2.2.1. Main Mantle Thrust

The Main Mantle Thrust is also named as the Indus Suture Zone exposed in Pakistan, marking the suture zone between the Kohistan island arc terrane and the Indian plate. The MMT, for its most parts in N. Pakistan is trending mostly in an east-west direction, but in the Nanga Parbat region, it forms a northeasterly trending loop surrounding the Nanga Parbat Syntaxis. Mostly towards north, but in the Nanga Parbat region it is virtually vertical, and at places, it is even overturned.

The MMT in the Nanga Parbat Syntaxis marks the contact between the Cretaceous Kohistan arc rocks and the metasediments of the Nanga Parbat Group. In much of the region the contact is sharp, but locally it comprised more than one fault, as evidenced by tectonic slivers from both the Kohistan and Indian plate rocks. This is particularly true for part of the MMT exposed at the eastern margin of the Syntaxis at Stak (see later). At places lenses of ultramafics and amphibolites sometimes eclogite assemblages are found along MMT particularly at Stak (Indus Valley) making a mélangé (Edwards et al., 2000; Butler and Prior, 1988a; 1988b; Butler et al., 1989, 1992, 2000).

MMT AT THE WESTERN MARGIN OF NANDA PARBAT SYNTAXIS

The MMT is exposed and accessible at the western margin of the Nanga Parbat Syntaxis at several locations including Shahbatot-Sassi (Indus Valley), Bunji Gah, Astor-Indus Confluence, Raikot Bridge and around, and at Diamir-Bunar confluence.

The MMT at Raikot Bridge (Tath pani) and the Astor valley is an upright ductile structure marking contact between the amphibolites of the Kohistan terrace and the Indian plate metasediments (Fig. 3.5). Ductile planar and linear fabric developed under amphibolite conditions is preserved in rocks at the both sides of the contact. Kinematic indicators for the MMT related sense of movement are no more preserved, probably reworked by strains developed during the later stages of syntaxis development. Note that faults related with the active Raikot-Sassi fault zone rework the MMT contact at this margin.
In the Sassi-Shahbatot section, the MMT is defined by contact between Kamila Amphibolite in the west and the Haramosh-Tarshing-Rattu Schists in the east. A part from both these two lithologies, mylonite was found on either side of the contact, which was considered as the ductile deformation as a result of the MMT. Recent observations by Butler (2005) and this work suggest that since these mylonites are as young as 15 Ma they cannot be related with the MMT (that is ~50 old). The present study indicate that the kinematic features related with the MMT are very rarely preserved in this section.

To the south, in the Bunar Gah, the MMT is exposed at Diamir-Bunar Gah confluence. The contact between the Kamila Amphibolite in the west and the schistose rocks of Nanga Parbat is upright to steeply dipping towards west. In this region, the originally east-dipping MMT has been back-rotated to its present steep west-dipping orientation by the east-verging Diamir Shear Zone, which is the southern equivalent of the Raikot-Sassi Fault Zone (Fig. 3.6a,b).
Fig. 3.6a. Geological map of the SW margin of Nanga Parbat Synclise as exposed in the Buniar Gah area, east of Chulas. Note that in this area Diamir Shear Zone is the continuation of the Raikot-Sassi Shear Zone while the MMT in this area has a separate entity in its original form (after Edwards et al., 2000, Kahn et al., 2000).
Fig. 3.6b. Cross-sections across the Diamir Shear Zone, Bunur Gah. Note that original contact between the Kohistan terrane and the Indian Plate rocks of the Nanga Parbat Syntaxis marked by MMT is folded by the west-directed Diamir Shear Zone, which in this area is equivalent of the Raikot-Sassi fault Zone (after Edwards et al., 2000; Khan et al., 2000).
MMT AT THE EASTERN MARGIN OF NANGA PARBAT SYNTAXIS

The Indus Valley Section

STAK FAULT

The Stak fault marks the eastern contact of the Nanga Parbat Syntaxis, exposed on the Skardu road near Stak (Fig. 3.7). The fault zone overlaps the MMT and separates gneisses and metasediments of Nanga Parbat Syntaxis in the east from the Cretaceous Kohistan-Ladakh arc lithologies to the west. There is a 3-5 km broad zone comprising about half-a-dozen faults with tectonic slices derived both from the Nanga Parbat and Kohistan-Ladakh lithologies. Both ductile deformations as reflected in mylonite zones as well as the brittle deformation reflected by cataclasites have been recognized.

Following Verplank (1986), four major faults and numerous minor faults have been mapped in the Stak fault zone. From west to east the four major faults include 1) the Majupah Fault, 2) the Gainji Fault, 3) the Stak Fault, and 4) the Askore Fault (Fig. 3.7). Neotectonic feature associated with the Stak fault zone are described as under.

The western most of the faults making the Stak fault zone, termed Majupah fault is characterized by a 40 m wide mylonite zone in the Shengus Gneiss, of which about 6 meters are fault breccia. The simultaneous occurrence of mylonite and breccia implies a complex history for this fault. The mylonites formed earlier, during the deeper-seated activity of the fault. Rapid unroofing accompanied the fault producing breccia along the same fault zone.

The brittle fractures and brecciation always provided fluid pathways for extensive hydrothermal activities in this area. At least three splays of the fault can be observed crossing the ridge south of the river. These are marked by alteration and gouge zones. The Gainji fault crosses the road about 2.5 km east of the Majupah fault and is characterized by rusty schists. No mylonites and gouges have been recognized along this fault, although the Gainji nala follows the fault for about a km that could indicate neotectonic activity related with this fault. Third of the major faults is exposed about 50 m west of the bridge at Stack Nala. The fault is covered by glacial tills and landslide debris and thus could not be assessed for any neotectonic activity. The eastern most of the faults, termed Askore fault is exposed about 2 km west of the Stack Bridge immediately west of the Askore nala. A 50 m wide zone of chlorite-biotite schist with small inclusions of ultramafics marks the fault zone. This material is mostly fractured and brecciated to form a gouge zone. According to Verplank (1986), the Askore Fault is associated with fault scarps in
the glacial till that overlies the fault. There is no dating available for the glacial tills in this part of the Indus valley but a Holocene (0.1 Ma) or younger age is expected (Sbroder et al., 1993). Richards et al. (2000) have obtained a minimum age of 22,000 years for glacial deposits in the Nanga Parbat area. This reflects neotectonic activity along the Stak Fault.

Khattak et al. (1998) and LeFort et al., (1997a,b), have documented ultramafic and gabbroic rocks, with some metamorphosed to eclogite facies, along the Stak Fault and suggested a remnant of the Indus suture (MMT). Verplank (1986) suggested that the existing geological evidences suggest a transpressional sense of displacement with west side up and right lateral.

As far as the extension of the Stak Fault, north and south of the Indus valley is concerned, the high altitude ridges both to the north and south of the Indus valley exhibit physical observations of the Stak fault zone. Verplank (1986) marked the extension of the Stak Fault on the NW side of the Askere canyon. Zanettin (1964) mapped the contact along the canyon and the glaciated pass between the Stak and Tornak river valleys.
Fig. 3. 7. Geological map of the eastern margin of Nanga Parbat Synclasis exposed at Stak in the Indus Valley. Note that this contact is occupied by a 6 km wide zone comprising several fault structures. Presence of ultramafic rocks and eclogites confirms that the original trace of the MMT is preserved here (after Verma et al. 1988).
The Astor Valley Section

The MMT exposed in the Astor Valley is a steep and ductile zone of high strain. Synkinematic garnet in the adjacent metasediments yields Sm-Nd dating of 40-45 Ma (Foster et al., 1998), confirming the development of the fault zone in the main phase of the collision.

SUBSAR THRUST

Angles (2000) mapped a major thrust fault in the high-altitude region between the Indus and Astor valleys (Fig. 3.8). The main fault dips 23-30° SE. The thrust cross cuts and the MMT displaces in a dextral sense for at least 10 km. No evidence of neotectonic activity is found along this fault, the area has poor access that makes the assessment of neotectonic rather difficult. However, due to inaccessibility, the neotectonic activity in this remote area cannot be studied.

The Rupal Valley Section

CHURIT FAULT

In the upper reaches of the Astor valley, the eastern margin of the Nanga Parbat Synclines is marked by the mylonites related with the MMT. At lower elevations the dips tend to be vertical, but at higher elevations the dips become steeply westward (55° or more) giving a balloon-shape to the local cross-sectional contact geometry. Although the MMT zone in this area is devoid of brittle faults, about 200 meters west of the contact, a set of steeply dipping brittle fault strands is found within the metapelitic sediments of the Nanga Parbat Sequence (Fig. 3.9). This fault is named as Churit Fault (Edwards et al., 1996).

SHENGUS-RUPAL-CHHICHI SHEAR ZONE

Edwards et al. (1997) mapped a major shear zone in the Rupal valley, southwest of the Nanga Parbat (Fig. 3.10). This shear zone runs along the Chhichi valley, a southern tributary of the Rupal River, crossing the Rupal valley near Churit village. The shear zone runs northward and links with the east-directed thrust pinched syncline near Mushkin, separating the two major antiforms in Nanga Parbat (Astor valley).
Further north, the shear zone is considered to be extending across the Indus valley at Shergus, where it separates the Iskere and Bulacle antiforms.

Fig. 3. 8. Geological map of the Nanga Partial Synclines showing the position of the Subebr thrust at the eastern contact displacing the MMT (after Argles, 2000).
Fig. 3. A geological sketch map of the Churt Fault near the eastern margin of Nanga Parbat Synclise between Raŋgat and Rupal valleys (after Edwards et al., 1996).
The shear zone is mainly ductile, developed in a granitic protolith. The S/C mylonites of this shear zone show a clear and consistent shear sense of thrusting from the NW, along with a subordinate dextral strike-slip component. The thrust component has accommodated the rise of the core of the Nanga Parbat massif, including the area of the summit of Nanga Parbat, relative to the metasedimentary rocks of Indian cover provenance that occur to the southeast of this shear zone. The rocks of the shear zone show qualitatively moderate strains but these are maintained across a 5 km-wide zone dipping from 40°NW to subvertical. Discontinuous brittle faulting is associated with this shear zone. This shear zone is considered to be active for last about two millions years. No evidence of Quaternary rupturing is so far found, but considering the active exhumation of the Nanga Parbat Syntaxis, it is possible that the fault might have remained active in recent past, with a sound potential for future activity.

The Rupal Shear Zone is a wide belt of N-S trending orthogneiss showing a pervasive, west side up with dextral shear S-C fabric and overprinting lineation. Closer to the eastern margin, the Churit Fault in lower Tarshing valley juxtaposes sillimanite-grade orthogneiss in the west and over staurolite grade metapelites in the east. It lacks significant ductile overprinting of regional N-S lineation.

3.4. TECTONIC EVOLUTION OF THE NANGA PARBAT SYNTAXIS

The Nanga Parbat Syntaxis is a composite fold structure, which developed in the latest (F3) phase of deformation. The N-S orientation of this structure is at right angle to the trend of the Himalayas. Most probably, it occurs at the western end of the Himalayan arc. The southwest verging thrusts in the main Himalayan arc, east of the Nanga Parbat Syntaxis are markedly different from the southeast verging thrusts in the Himalayas west of the Nanga Parbat Syntaxis. It is believed that Nanga Parbat Syntaxis developed in response to these contrasting propagation directions of the these two portions of the Himalayan arc. Coward (1985) and Treloar et al. (1991) suggested that the thrusts in the eastern Himalayan arc converged at a pinning point at the site of the Nanga Parbat Syntaxis. Since the displacement at the eastern Himalayan thrusts was minimum at this point and increased eastwards, where a clockwise rotation scenario took place. This differential displacement generated a dextral shear couple at the pinning point. (Fig. 3.21). Treloar et al. (1991) suggested that this kinematic scenario resulted in 1)

50
overprinting of the marginal thrust (i.e., Liacher Thrust) by dextral strike-slip component (Shabbatot-Sassi Fault) 2) development of the large-scale antiformal folds at the pinning point, such as those in the Nanga Parbat Syntaxis.

![Map of Nanga Parbat-Haramosh Massif](image)

Fig. 3. 10. Geological map of Nanga Parbat Syntaxis showing major fault structures. The Raikot-Sassi Fault Zone runs along the western margin of the Syntaxis, and the Rupal-Chinchi Shear Zone occupies the central part of the Syntaxis (after Edwards et al., 1997).
Fig. 3. 11. Lateral termination of the Main Himalayan Thrusts at a pinning point. Differential displacement, rotation of the movement directions gives rise to dextral shearing and crustal scale folding such as those observed in the Nanga Parbat Syntaxis (after Tretow et al., 1991).

A comprehensive programme of dating and structural analyses recently concluded (see Khan et al., 2000 for details) has resulted in the following model for the evolution of the Nanga Parbat Syntaxis.

1) Nanga Parbat Syntaxis grew by a combination of folding and shearing at its margins.
2) The growth initiated probably through a regional scale buckling. These folds accommodated the initial uplift of the Nanga Parbat Syntaxis.
3) Once the ductile folding of the gneisses and the cover metasediments progressed and the limbs became steep, the uplift thereafter was accommodated by sub-vertical dip-slip shear zones along the margins of the large fold structures.

Thus the syntaxial growth largely took place as a result of a distributed ductile through a brittle sub-vertical shearing concentrated within the marginal shear zones that accommodated vertical uplift of the whole structure.

The evolution of the Nanga Parbat Syntaxis through crustal-scale buckling followed by steep shear zones is best explained by a pop-up model recently proposed by Edwards et
al. (2000). According to this model once these N-S crustal scale interference fold structures came into being, the W-NW verging Raikot-Sass Fault zone at the western margin of the Nanga Parbat Syntaxis and east-verging Chhichi-Rupai-Shengus together formed a major pop-up structure that facilitated the dramatic uplift and exhumation of the Nanga Parbat Syntaxis (Fig. 3.12).

Fig. 3. 12. A schematic NW-SE cross-section across the Nanga Parbat Syntaxis. The Aril Gail Shear Zone (equivalent of Raikot-Sass Fault Zone) in the NW represents the major active structure, supplemented by oppositely verging Shengus-Rupai-Chhichi Shear zone that provide the mechanism of Quaternary uplift and exhumation of the Nanga Parbat Syntaxis (after Edwards et al., 1997).
CHAPTER 4
CHAPTER 4. NEOTECTONICS

4.1. INTRODUCTION

Neotectonics is a branch of structural geology that refers to study of crustal movements which occurred in the earth's recent past and is continuing at the present day. These movements are driven directly or indirectly by global plate motions (plate tectonics), and result in the warping, folding or faulting.

The movement of plates, for the most part, gives rise to slow, progressive deformation of the earth’s crust, not detectable without high precision monitoring over periods of years and decades. For example, oceanic crust beneath all significant present-day oceans is under a continuous process of spreading (e.g., Atlantic Ocean, Red Sea) and contraction (e.g., Pacific). Crustal movements, however also occur abruptly, such as during the earthquakes or volcanic eruption, when they are readily detectable by human observers. Such abrupt movements are a major cause of anxiety amongst the human beings as they are not only hazardous to their property and resources but also directly threaten their existence. Neotectonics is thus an applied branch of geology that deals with natural hazards of earth movements.

Earth’s surface, based on geological and seismicity studies can be divided into stable and unstable zones, depending upon their susceptibility to earthquakes and volcanoes. It is a common practice in seismic hazard assessment to identify the active regions and subject them to detailed geological investigations to identify active faults and their attributes such as kinematics and slip rates. If a good seismicity record is available, these faults can then be related to seismicity. Such studies can lead to reasonable estimates for recurrence of movements on the faults and their related earthquakes, an information which is crucial for planning large infrastructures such as the hydropower dams, nuclear power plants, airports and highways.
4.2. Neotectonic Appraisal of the Nanga Parbat Syntaxis

The Himalaya and the associated mountains in N. Pakistan (Karakoram, Hindukush) are commonly graded as active as they are the youngest of the mountains on earth. Although they started growing about 90 Ma ago, the tectonic movements involved in their formation have continuously remained operative until today. In much of the Himalayas, the active deformation zone coincides with the mountain front, which in Pakistan is considered to be the region between the Main Boundary Thrust at the southern extremities of the Hill Ranges (Galiat-Marga-Kalachitta-Samana Ranges) and the Salt Range Frontal Thrust at the southern front of the Salt and Trans-Indus ranges, encompassing the Potwar and Kohat Plateaus (Fig. 4.1). It is notable that this region in Pakistan, despite having geological evidence of active displacement (e.g., thrusting of the Cambrian Salt Range Formation onto the alluvium and gravels of the Jhelum River), lacks major earthquakes, which is probably because of the thick ductile layer of salt underneath this region. In comparison, similar regions in the eastern Himalayas in India and Nepal have yielded at least four major earthquakes in the past 200 years, and are considered prone to future earthquakes of even greater magnitudes capable of casualties into millions rather than thousands (Bilham et al., 2000).

In northern Pakistan, apart from the mountain front, the Himalaya and associated mountains in their hinterland have several regions where signs of neotectonic activity have been reported. Amongst these, the most important region is Nanga Parbat (Fig. 3.10), where both records of seismicity and neotectonics are amply displayed. As outlined in the Chapter 2 & 3, the Nanga Parbat Syntaxis is a unique region in the Himalayas where tectonic activity started only about 10 my ago, that refolded the MMT and the combined crusts of the Indian plate and the Kohistan arc in its footwall and hangingwall, respectively. This huge crustal-scale fold termed Nanga Parbat Syntaxis not only refolded the MMT but also reactivated some of its segments especially at the NW margin into active faults.

In the past two decades, Nanga Parbat Syntaxial region has remained subject to international interest for its unique geological features such as the highest relief, the fastest uplift rates in the world, and the occurrence of the youngest leucogranites on earth (see Asif Khan et al., 2000 for references). Some of the salient geological and
geomorphological features that point to the recent tectonic activity of the Nanga Parbat Syntaxis are listed as below:

- The aerial distance between the summit of Nanga Parbat and the Indus River at the Raikot Bridge is 21 km and elevation difference between these two points is seven km. This amounts to be the highest relief on the surface of earth.

- The Nanga Parbat Syntaxis is characterized by the youngest radiometric age dates of < 2 Ma, compared to its surroundings. Zeitzer et al. (1985) has used these as basis to determine an uplift rate of 8-10 mm/year for the Nanga Parbat, which is the fastest uplift rate on the surface of earth for.

- The cordierite-bearing leucogranites exposed in the syntaxis area such as the as young as 0.75 million years support fast uplift and exhumation rates. have determined that the rocks now forming the summit of the Nanga Parbat Syntaxis have been uplifted to their present position from depths of a minimum of 15 km in last 3 million years (Winslow et al., 1994., Zeitzer et al. 1993).

- The horseshoe-shaped loop of the Indus River between the Shengus and Bunji villages is a product of neotectonic activity. The WNW flowing Indus River across the Nanga Parbat Syntaxis, while reaching west of the Shengus village, takes a sharp turn to the north towards the village of Sassi. The sharp turn in the course of the Indus River is attributed to a major active fault zone, which is locally termed Shabzoot-Sassi strike-slip fault (Tielour et al., 1991) but is a continuation of Raikot-Thrust in the south (Lawrence and Ghauri, 1983; Butler, 2000). In the Shabzoot-Sassi area the Indus River follows a distance of about fifteen km along this fault, before leaving the trace of the fault and turning west and then south towards the Indus confluence and Bunji.

- The course of the Indus River between the Liachar village and the Raikot Bridge for a distance of five km is again along of the same active fault.

- The Bunar Gah, a tributary of the Indus River follows the southward-directed part of the Raikot-Sassi Fault (Khan et., 2000; Edward et al. 2000)

- Near Liacher village, Precambrian gneisses belonging to Nanga Parbat Syntaxis are overthrust toward west onto the gravels of the Indus River and fan deposits of the Liacher stream.
- The 1841 Landslides, probably induced by a major earthquake, dammed the Indus River and triggered a lake outburst flood downstream as far away as Attock.

In the following, a detailed analysis of the neotectonic activity in the Nanga Parbat region is attempted. In this context all the principal neotectonic structures in the Nanga Parbat region are listed and described in terms of their segmentation, extent of rupturing and associated characteristics such as the kinematics and slip rates where deduced. Most of these structures are studied during the course of fieldwork associated with this study project, but all the relevant existing published data are incorporated for a complete picture.
Fig. 4.1. Regional tectonic sketch map of north Pakistan, showing principal tectonic zones and fault lineaments.
4.3. EASTERN MARGIN OF THE NANGA PARBAT SYNTAXIS

The eastern contact of the Nanga Parbat Syntaxis exposed in the Indus Valley is characterized by MMT. However, locally more than one faults and shear zones are superimposed on the MMT. So far three sets of these faults are recognized at various accessible points on this contact. In the Indus valley section a fault zone called Stak Fault has been described by Verplank (1986). Argles (2000) suggest that the area between the Indus gorge and Astor River is characterized by a set of thrust faults, which have a NE-SE trend and displace the original trace of the MMT/Stak Fault in a dextral sense of displacement. These thrust faults are named Subsar Thrust Zone. To the south of the Astor valley, while in the Rupal valley the Churit Fault overlaps the MMT.

A detailed appraisal of all the faults at the eastern margin of the Naaga Parbat Syntaxis is given in the Chapter 3. As far as the neotectonic activity is concerned, except for the Askore Fault, near Stak in the Indus Valley and to some extent the Churit Fault, exposed in the Rupal-Rama area, where brittle faults involve minor to subordinate amount of involvement of the Quaternary material, there is little evidence that the eastern margin of the Nanga Parbat has undergone any significant recent tectonic activity.

4.4. WESTERN MARGIN OF THE NANGA PARBAT SYNTAXIS

4.4.1. Raikot-Sassi Fault Zone (RSFZ)

The geology of the western margin of Nanga Parbat Syntaxis is also characterized by the Main Mantle Thrust (MMT) that separates Nanga Parbat Gneisses and metasediments from the Cretaceous Kohistan amphibolites and gabbroic rocks. The MMT is an extension of the Indus Suture zone that stretches along the entire length of the Himalayas from Burma, southern Tibet to India. The MMT crosses into Pakistan near Kargil and then extends throughout entire N. Pakistan all the way to western Dir, where it enters into northern Jalalabad region in Afghanistan. The MMT is considered to have formed some 55-58 Ma ago. There are evidences that some segments of the MMT have been reactivated at later stages. According to DiPietro et al. (2000) much of the MMT fault trace between Babusar and Malakand area is Oligocene-Early Miocene (35-20 Ma) in age that cuts out much of the ophiolites and melange sequences originally associated with the MMT. Vince and Treloar (1999) reported a Miocene extensional activity of the MMT in the Jijal area in District Kohistan. There is however, a unanimous view that segment of
the MMT that has most recently been activated is the one between the Bunar Gah in the southwest to the Khaltoro village in the north. This reactivated segment of the MMT is referred to by various names such as Raikot fault (Lawrence and Ghauri, 1983), Liacher Thrux (Butler and Prior, 1988a, b), Sassi or Sassi-Shahbatot Fault (Treloar et al., 1991).

In this report, the name Raikot-Sassi fault is used for the sake of simplicity, but it includes entire extent of the reactivated MMT from the Bunar Gah to Khaltoro (Plate 3). Further, the term fault zone will be used in this report. This is because, unlike the MMT, the Raikot-Sassi fault is not a sharp break between the Nanga Parbat and the Kohistan lithologies, rather consists of splay, which cut across both lithologies.

Before, a detailed description of the Raikot-Sassi Fault Zone (RSFZ) is carried out, it will be pertinent to discuss the issue of distinction between the MMT and its reactivated offspring i.e., RSFZ. Firstly it needs to be resolved that thick mylonites exposed at the Sassi-Shahbatot villages belong to the MMT or the RSFZ. These mylonites deform a set of felsic granite and pegmatite dykes and transposed them along their shear fabric. Similar dykes in the Hanuchal village and the road section to the Indus Confluence cross cut other lithologies exposed in this road section (Cretaceous Kamila Amphibolite and gabbric diorite belonging to the Tertiary Kohistan Batholith) without deformed. There are reliable radiometric ages of 34-15 Ma available for these dykes (Peterson and Windley, 1985).

This implies that the Sassi-Shahbatot mylonites belong to the post Early Oligocene reactivation stage of the MMT rather than being associated with the original Late Palaeocene-Early Eocene stage of the MMT formation. In this study, the Sassi-Shahbatot mylonites (and other mylonites zones to the south at Hapchal and Bunji) are therefore included as the fault rocks of the RSFZ.

4.4.1.1. SEGMENTATION

The Raikot-Sassi Fault Zone is generally considered as a continuous fault superimposed on the trace of the MMT from the Kaltoro village in the north to the Diamir-Bunar confluence in the south. There are several areas in between these two locations, either in the Indus valley or in the tributaries of the Indus River, where it is possible to physically check the continuity of this fault. At the same time, there are several points, where it is not possible to physically verify the continuity of this fault zone due to inaccessible high-altitude ridges.
The fieldwork during the course of this study, concurring with the findings of Butler et al. (1989), suggest that RSFZ can be divided into two separate fault segments, discontinuous from each other between the Bunji and Ramghat gorges. The ridge between these two E-W trending gorges is inaccessible, but two lines of evidence point to this discontinuity:

1) The principal strand in the Ramghat--Bunar segment is a moderately east-southeast dipping fault, while that in the Bunji-Shahbatot-Darchan segment it is either vertical or dips steeply to the east.

2) The Ramghat-Bunar segment is characterized by reverse faulting i.e., Nanga Parbat rocks overthrusting northwestwards onto Kohistan rocks. In contrast, the dominant displacement in the Bunji-Shahbatot-Darchan segment is a dextral strike slip.

3) The Diamir Shear Zone in Bunar Gah is related with the RSFZ (Edwards et al., 2000). However, because of its relatively different orientation, unusually great relative width and attributes such as the presence of a large fold closely associated and manifestation of the shear zone, this can be taken as a third segment.

However, since all these segments, otherwise closely follow the MMT and both have evidence of Quaternary activation, in much of the Raikot-Sassi Fault Zone (RSFZ) will be used in description of various attributes of the fault.

4.4.1.2. ACCESSIBILITY

The northern most segment of the fault zone between the Shahbatot and Khaltoro villages is mostly accessible through Indus valley and its northern Khaltoro and Dasu tributaries. The fault zone crosses over to the western slopes of the Indus valley at the river bend just to the south of the village Shahbatot. This segment of the fault zone was previously mapped only through the satellite images and aerial photographs. The present Bunji-Burchi traversing across the ridge enabled to study a part of the fault trace exposed on the western slopes of the Indus valley, just to the west of the Burchi village. However the inaccessible portion of the fault is based on analyses of the satellite images.

To the South of this ridge the fault follows the Unjal nala, a northern tributary of the Bunji Gah. The fault is exposed in the Bunji Gah at the Unjal Nala-Bunji Gah confluence. Southward the ridge between the Bunji Gah and the Ramghat Gah (Shaitan nala) is inaccessible and its mapping is based solely on satellite image analyses. The southward extension of the RSFZ is studied at many locations in the Astor valley,
Laicher village and Raikot. The southern termination of the fault zone has been studied in detail in the Bunar Gah and its northern tributary called Diamir Gah (Khan et al., 2000; Edward et al., 2000).

4.4.1.3. TERMINATIONS
The northern and southern terminations of the RSFZ have recently been identified during the course of this study. To the north of the Khaitoro village, the MMT extends northward and was cut across by the Shyok suture or MKT (Gansser, 1980). This indicates that MKT is younger than the MMT and the RSFZ, which is not realistic. Although Tahirkheli and Jan (1979), in their coloured map of N. Pakistan had shown that the MMT loops around the Nanga Parbat Syntaxis south of the MKT. This was further verified by Butler et al. (1992), Pêcher and LeFort (1999) and LeFort and Pêcher (2002). According to Pêcher and LeFort (1999), the RSFZ extends to the Darchan village where it dies out while the MMT is still well preserved.

Previously it was considered that southwards the RSFZ follow the MMT, beyond the Bunar Gah towards the Babusar. Searle and Khan (1996), in their regional map of N. Pakistan showed that the RSFZ splits from the MMT between the Raikot and the Bunar Gah, making a sharp bend turn towards south. This was later on proved the author of this report in the company of scientists from the SUNY Albany (USA) in 1997. This work shows that the RSFZ extends southwards along the Bunar Gah, but the displacement becomes minimum as one traverses towards the upper reaches of the Bunar Gah.

4.4.1.4. FIELD DESCRIPTION, KINEMATICS AND EVIDENCE FOR NEOTECTONIC ACTIVITY
As discussed above, the RSFZ is divisible into two major segments, one to the south of the Ramghat gorge and the other to the north of the Bashij gorge. In the following however, the RSFZ has been divided into five parts for convenience rather than for its actual physical discontinuity.

4.4.1.4.1. Darchan-Khaitoro-Shahbatot Segment
This is one of the most accessible parts of the RSFZ. The RSFZ in this area is defined by both ductile shear zones lined by mylonites as well as by the brittle reverse faults, which are commonly associated with fault gouges and cataclasites. RSFZ in this area varies in width from half to 3 km (Maiden et al. 1989).
Mylonite Zone

Mylonite is foliated (usually lineated) fine-grained metamorphic rock, which shows evidence for strong ductile deformation (Passchier and Trouw, 1996). Since it is a secondary rock produced by ductile deformation and can be derived from any type of pre-existing rock at the site of the shear zone. Mylonites are commonly comprising of minerals weak under moderate to high temperature-pressure conditions (quartz, calcite). Mylonites also contain relatively larger grains/crystals, called porphyroclasts. These are generally made of minerals, which are resistant to deformation even under moderate to high temperature-pressure conditions. According to Spry (1969), mylonites generally contain ~50% porphyroclasts surrounded by fine- to ultrafine-grained matrix. Mylonites inherently are strongly foliated rocks and often define a stretching mineral lineation that defines the sense of shearing/displacement.

A 300 m wide mylonites zone runs along the eastern edge of the river that follows the RSFZ in the Sassi-Shahbatot area. The best exposures of the mylonites are exposed at the tip of the Sassi river-bend between Khaltoro and Dasu canyons. Partially mylonitized rocks occur on the either side of the mylonites core for a distance of 500 m to 1.5 km on the either side of the core zone. The contact between the Nanga Parbat and Kohistan lithologies is marked by ductile deformation as the mylonites are derived from the both protoliths. South of the Shahbatot village (plates 4.1; 4.2; 4.9; 4.10; 4.11), the mylonites continue southwards and at the Shahbatot river-bend, they cross over to the western slopes of the Indus valley.
Strong mylonitic lineation has been noted by many previous workers (Maiden et al., 1989; Butler et al., 1992; Treloar et al., 1991), which is oriented N25°W/55°NW (plates 4.1; 4.2). Maiden et al (1989) have noticed a reverse dextral shear sense in these mylonites.

Brittle Faults

A broad zone of brittle faults characterizes the RSFZ in the Darchan-Khaltoro-Shahbatot segment. These are mostly trending north with steep easterly dips with reverse sense of displacement i.e., Nanga Parbat sequence thrusting onto the Kohistan sequence. Most of the brittle faults are localized east of the mylonites zone but some follow the mylonites zone and other occur to the west of the mylonites zone.

Three discrete strands define RSFZ in the Darchan-Khaltoro-Shahbatot segment. Of these, the westernmost follows the mylonites zone on its immediate eastern side and is named in this study as the Khaltoro fault. The other two fault strands occur to the east of the Khaltoro fault and are termed Dasu-Sassi fault and Harbus fault respectively (Maiden, 1986).
Khaltoro Fault

The Khaltoro fault strand can be observed between Shabhatot river-bend and upper reaches of the Khaltoro valley, but its best exposures are seen at the eastern slopes of the Khaltoro valley on the jeepable track. The fault scarp is clearly visible on satellite images including TM/ETM with 30 m resolution and SPOT 5 images with 2.5 m resolution. The fault is north trending with a vertical dip for the main strand. The main strand of the Khaltoro fault is lined by about two meters wide fault zone.

There are dozens of brittle fractures/faults on the either side of the main strand. The Khaltoro road gives access to those exposed to the west of the main strand, which were studied in detail than those exposed to the east of the main strand. A zone of about 3 km width along the eastern wall of the Khaltoro canyon is virtually a crush zone that represents mass movement along the western side of the RSFZ (plates 4.3-4.6). The whole zone is crisscrossed by fractures and rocks are highly dismembered into variable sizes ranging from tens of meter blocks to clays. The original lithology comprises basic rocks belonging to the Kamila amphibolite and granite/pegmatite dyke network of Kohistan batholith. Although these lithologies are disfigured completely or partially, but original network of dykes still persists suggesting a lack of internal displacement in the rock mass. Several large fractures have been noticed, which are associated with the gouge zones ranging from a few cm to 2 meters. Some of these fracture zones are parallel to the main strand and can be classified as splays of the RSFZ. Such fractures trend northward with steep easterly dips. There is another set of brittle fractures/faults, which is generally parallel to the main strand with steep westerly dips. Faults in this set appear to be controlled by gravity and may have formed subsequent to the main strand of the Khaltoro Fault (plate 4.5). Hangingwall of such faults are characterized by crush zones due to mass movement in response to gravity sliding. The 3 km crush/slide zone in the Khaltoro Canyon is probably product of such faults.

One of the western most brittle fractures is exposed on the western slopes of the Khaltoro valley (plates 4.7, 4.8). This is oriented NS and dips 70°E and cuts across the mylonites zone associated with the RSFZ. The fracture is associated with a one-meter thick gouge zone.
Plate 4. 3. A crushed zone lined by brittle faults with gouges, Khattoro Jeep able road.

Plate 4. 4. A view of the Khattoro Fault. The trace of the fault is associated with the fault gouge. The movement on the fault has triggered a 3-km wide zone landslide, where whole valley face has slipped into the gorge, probably together with the fault trace.

Plate 4. 5. Slipped valley face, Khattoro

Plate 4. 6. Principal strand, Khattoro Fault and associated gouge zone.
The next best exposures of the Khaltoro Fault can be observed at the Shahbatot river bend. The fault marks the contact between the mylonites zone and the Kohistan lithologies (amphibolites and marbles). The amphibolites (and marbles) immediately at the river bend are almost flat with 5-10° dips towards the west. These abut against the vertical mylonite zone with a knife-edge sharp contact (plate 4.9). It is seen from south side of the river bend, marked by a 2-meter vertical fault gouge zone at the skyline of the ridge (plate 4.12). Dozens of brittle fractures and faults with minor fault gouges are exposed on the either side of the main strand (Plates 4.9, 4.10).

Dasu-Sassi Fault
This fault splits from the main strand of the RSFZ at about the Shahbatot river bend and extends northward parallel to the main strand at a distance of about 500 m to 1 km east of the Indus River. This fault reworks through both the bedrock as well as the Quaternary glaciofluvial deposits. The fault cuts across the steeply east dipping mylonites zone, metasedimentary gneisses and schists belonging to Precambrian Nanga Parbat Group both to the south and north of the Shahbatot village. Midway between the Shahbatot and Sassi villages, the fault runs through the Quaternary deposits.
Plate 4.9 A view of the E-W oriented ridge at the Shahbatot river bend as viewed from north. The ridge is intersected by dozens of brittle faults and fractures, mostly associated with fault gouges. The western most fault (Khaltoro Fault) is obvious in this view marking a sharp boundary at the vertical western face of the mylonites against flat-lying Kohistan marbles and amphibolites. Faults with dips toward east are exposed further up on the ridge.

comprising glacial tills and alluvial fans (Plate 4.12). North of Sassi, the fault follows the eastern face of the Dasu valley, passing through the eastern side of the Dasu village crosses onto the western slopes of the Dasu valley at village Hanumal. From Hanumal it turns toward west and probably joins with the Khaltoor fault near Darchan. The fault was previously described by Maiden (1986) and has been further studied during the course of this work.

Maiden (1986) has described several examples of Quaternary deformation associated with the Dasu-Sassi fault. These and other examples studied during the present work include:

- Immediately to the south of Sumari nala, Quaternary deposits including glacial tills, fluvial sandstones and lacustrine silts, which overlie a tectonic sliver of Kohistan amphibolites. The contact between the Kohistan bedrock and the Quaternary deposits is reworked by the Sassi-Dasu Fault tilting the sediments with dips toward east.
Plate 4.11. A knife-edge sharp brittle fault cross-cutting west dipping Kohistan Amphibolites and marbles. Shahbatot River Bend viewed from south, displaying of the fault into two in the upper part of the ridge (1 & 2).

Plate 4.10. Prominent fault gouge zone on the Shahbatot River Bend (view from south) The gouge zone is about 2 meter thick but about 15 meter zone is all intersected by vertical brittle faults. The host lithologies are Kohistan Amphibolites.
- A broad terrace defined by the glacial till immediately east of the Sassi village is cut across by the Sassi-Dasu Fault forming a 100 m high scarp. The eastern side of the terrace is uplifted along this scarp relative to the western side. The fault scarp is traceable for about 2 km in this area.

- Between Sassi and Dasu villages, the Sassi-Dasu Fault passes through bedrocks and is mostly covered by fan deposits. The older fan deposits are commonly cut by the fault. The active fan deposits have a set of minor gullies, which is roughly in line with the fault trace.

- A large glacial till defines the plateau at the Dasu village. The eastern edge of the plateau against the bedrock is mostly covered by the fan deposits. The Sassi-Dasu Fault follows the eastern edge of the plateau and toes of the alluvial fans are offset in a series of discontinuous scarps, which range in height from 10-40 m. These scarps are preserved only in older fan deposits and are not visible in the younger active alluvial fans.

- At Hanumal village, a terrace defined by a glacial till deposit is offset by a 10-15 meter scarp that uplifts the eastern side of the terrace relative to the western side. Maiden (1956) has reported a 70-75° east dipping trace of the fault in the bedrock immediately beneath the scarp.
Plate 4.12. Aerial view of the Indus Valley as viewed towards south from Khaltoro valley. The eastern slopes of the Indus Valley have glacial tills, which are cut by traces of the Dasu-Sassi and Hurban faults, and the two eastern strands of the Rakot-Sassi Fault Zone.

Hurban Fault

The Hurban Fault is the easternmost principal strand related with the RSFZ. This fault splits from RSFZ at the Shabbatot river bend and trends towards NE up to the Ishkapai (Shabbatot) gorge, from where it turns NS and cuts across the Sunari, Sassi and Phutze tributaries in their lower middle reaches (Plate 4.12). It is not traceable beyond the Hanumal village north of Dasu.

In the Sassi area, the Hurban Fault crosses the Sassi till plateau, to the east of the Dasu-Sassi Fault. The scarp represented by the Hurban Fault shows east-side up displacement. The scarp is about 92 meter high, with a face slope of 35°. Considering that the till surface has an inherent slope of 16° west, the offset along the Hurban Fault is 58 m (Maiden, 1986).

Between Sassi and Hanumal, the Hurban Fault extends across a slope of undifferentiated bedrock and till deposits. The scarp on tills is composite, comprising of at least five steps, with an estimated total height of 50-75 meters. East of the Dasu village, the alluvial fans are dissected by the Hurban Fault at their heads.
Shabbatot Indus River Bend

About two kilometre south of the Shabbatot village, the Indus River makes a sharp bend. The east-west oriented ridge at this bend is the locus of all the three faults described above. The ridge is accessible both from the north and south of the bend and exposes traces of several sub-parallel vertical brittle faults. The Khahtoro Fault on this ridge marks the western boundary of the vertical mylonites zone, and is defined by dramatic juxtaposition of vertical western face of the mylonites against flat strata of amphibolites and marbles belonging to the Kohistan. The faulted contact is spectacularly exposed on the northern side of the ridge (Plate 4.11). Around the bend to the south, roadside exposures show dozens of vertical brittle faults all lined by fault gouges. One of the brittle faults exposed at the sky line of the ridge as viewed from south is vertical 2 meter thick fault gouge zone, which is related with one of the three faults described in the foregoing sections (Plate 4.10). A 200 m wide zone trend N-S this ridge is cut across by hundreds of brittle faults with gouge zones defines the RSFZ (Plate 4.11).

4.4.1.4.2. Shabbatot River Bend-Burchi-Unjal Nala Segment

This part of the RSFZ extends on the western slopes of the Indus River was previously least studied because of inaccessibility. During this work, a traverse was made starting from Bunji village across the 3800 m high Sarkund ridge to Burchi village on the western slopes of the Indus Valley (Plate 4). This traverse allowed to study a part of this segment of RSFZ immediately to the west of the upper Burchi village. Where observations of about 2 km part of the fault zone near Burchi were made, while the remaining part of the fault zone is inaccessible and the mapping of this inaccessible part of the fault zone has been carried out by the analyses of the satellite images.

Mylonite Zone

The Mylonite Zone, similar to that observed near Sassi-Shabbatot segment is accessible at two places on the Sarkund ridge. A mylonites zone was observed occupying the drainage divide area immediately east of the Hapchal village in the uppermost drainage area of the Hosi nala (Plate 4.13 A, B, C). The eastern contact of the mylonite zone could not be traced out as it appears to be involved in the crush/gouge zone defined by the brittle RSFZ on the eastern slopes of the ridge. The mylonite is developed in garnetiferrous amphibolites, which we include in the Cretaceous Kaila Amphibolite Unit of the Kohistan sequence. The original amphibolite foliation in this area is oriented
at N35-60°W/60-70°NE. The Mylonite zone cuts this fabric and has an orientation of
N10°W/30-35°NE. The mylonites are characterized by a matrix comprising tremolite,
biotite, chlorite and quartz, while garnet and plagioclase occur as porphyroclasts. A
dextral strike-slip motion is indicated by asymmetric porphyroclasts.
A similar zone of mylonites has been found on the western side of the fault gouge zone
(described below), midway on the eastern slopes of the Sarkund ridge west and up from
Burchi village (Plate 4.14; 4.15). The mylonites zone is 20-50 meter wide and has an
orientation NS/70-80° E. The continuation of the mylonites zone with that in the
Shabbatot-Sassi area or that east of Hapchal could not be observed/traced out.

Plate 4.13... A) Hapchal village near the top of the Sarkund ridge, N. of Bursii. B) Mylonite
outcrops above the Hapchal village. C) Feldspar porphyroclasts showing dextral sense of
deformation in mylonites.

73
Brittle Faults and Associate Crush/Gouge Zones

Unlike the Darchan-Sassi-Shahbatot area to the north, discrete faults with separate identities do not exist in this area. Rather a broad zone, 700-750 m wide, has been found that is equivalent to RSFZ in this area (Plate 4.14-4.16). The pre-existing lithologies are Kamila amphibolites, which at places contain lenses of ultramafic rocks. These amphibolites are locally mylonitized (Plate 4.17). Much of the eastern part of the crush/gouge zone consists of metasediments belonging to the Nanga Parbat group (the Haramosh Schists of Maiden et al., 1989). Both groups of pre-existing rocks are reworked by subparallel brittle faults, which are separated from each other by variable distances ranging from a few meters to tens of meters. The rocks involved in the brittle faults are converted to fault breccias and clayey gouge zones (Fig. 4.18). The rocks in the immediate vicinity of the brittle faults are traversed by fractures and are broken into blocks of different sizes. The principal brittle fault zone occurs to the west that defines the western boundary of the crush/gouge zone. This fault is associated with a gouge zone that is up to 4 meter wide at places. The eastern boundary of the crush/gouge zone is defined by the gneisses of the Nanga Parbat group, which themselves do not appear to be involved in the brittle deformation. This implies that it is essentially the Kamila amphibolites and the Nanga Parbat group, which are involved in the brittle deformation in this area.
Plate 4.14. An aerial panoramic view of the eastern slopes of the Sarkund ridge, showing transition from undeformed Kamila Amphibolite forming the ridge axis (left 2/3 of the photo), passing into sheared rocks related with the Raikot-Sasli Fault Zone (Centre middle).

Plate 4.15. Close up of the marked area in Fig. 4.17. Note the differences between the Kamila Amphibolite with granite pegmatite sheets on left, mylonites zone in the middle and the gouge zone on the right.
The gouge zone described above trends NS with steep dips towards east. The individual brittle faults within the gouge zone however, show a variable attitude ranging from N 60° E to N 40° W strike and 40-80° dips both in east and west directions.

Plate 4.16. A view of the ridge bounding the Indus River on the west near Bunji village. Note the brittle fault zone above the Burchi village with red and grey gouge zones.
Plate 4.17. Microphotograph showing a close up of gouge zone above the Burchi village, with variably spaced brittle faults with gouges separated by intact bedrock.

Plate 4.18. A view of the gouge zone associated with the Raikot-Sassi Fault Zone exposed on the eastern slope of the Sarkund ridge, above the
4.4.1.4.3. Bunji-Ramghat-Astor Segment

East-west oriented three tributaries of the Indus River, (Bunji, Ramghat, Astor) expose well Raikot fault and associated structures. Maiden (1986) and Butler et al. (1989) have described these structures, which have been supplemented by further data during the present studies.

Mylonite Zone

The mylonites zone observed in the northern part of the RSFZ, such as to the east of Hapchel (top of the Sarkund ridge) is continued southwards across the Bunji gorge. The zone crosses the Bunji gorge, immediately upstream of intersection between the Bunji and Unjial streams (Plate 4.19). The zone is at least 200 meter wide and separates Kohistan sequence from the Nanga Parbat group. The mylonite foliation is oriented N30-40°E/90° and a lineation with a plunge of 50-60° is NW direction is associated with the mylonites. Mylonites are mostly derived from Nanga Parbat Gneiss, but a part of the Kohistan sequence (Kamila amphibolite) is also mylonitized immediately at the contact. Metasediments belonging to the Nanga Parbat group are exposed mainly in the Ramghat and Astor sections, are involved in the mylonites zone.

Brittle Faults

This part of the RSFZ is characterized by a wide zone of brittle faults, which mostly occur to the western side of the mylonites. Whereas in the Bunji gorge, these are restricted to a kilometre wide zone west of the mylonites zone. In the Ramghat and Astor gorges, they are present in much broader zone that approaches three kilometre in width. A vertical brittle fault, associated with a 30-40 m wide gouge zone, is following the NE trending Unjial nala, reworks the western contact zone of the mylonites in the Bunji gorge. To the west at least 3 vertical brittle faults have been found on the northern face of the Bunji gorge (Plate 4.20). These faults are located within the Kamis Amphibolite Unit and are at a distance of few tens of meters apart from each other. Curvature of the foliation and displacement of white pegmatite dykes suggest east side up reverse sense of displacement (Plate 4.20). However, vertical orientation of the brittle faults and splays with both east and west vergence suggest a component of strike slip faulting associated with these brittle faults.

In the Shaitan Nala (Ramghat Gah), a broad zone (about 3 km) is involved in brittle faulting. On a 3 km long traverse along a water channel, at least thirty prominent brittle
faults were observed, all in the diorites belonging to the Kohistan Sequence (Plate 4.21). Most of the brittle faults are associated with fault gouges ranging in widths from a few centimetres to four meters (Plate 4.21 A,B). Most of the brittle faults in this area are steep with a NW trend. Divergent sulks from these vertical faults suggest a strike-slip component associated with these faults. There are many faults with westerly dips and a reverse sense of displacement i.e., hangingwall going up towards east. In the upper reaches of the Ramghat Gah, contact between Kohistan lithologies and Nanga Parbat metasediments is exposed. Foliated and banded basic rocks belonging to the Kamila Amphibolite are overlain by the Nanga Parbat metasediments with a sharp moderately east-dipping contact in much of the upper part of the ridge separating Ramghat from Astor canyons. The same contact at the valley floor level becomes vertical. Much of the contact is inaccessible but brittle nature of the contact and presence of a minor gouge zone indicates its equivalence with the Raikot thrust (Bulir and Prior, 1988a).

Plate 4.19. View of mylonites zone immediately east of the Urjal-Bunji intersection, upper Bunji Gorge. Plate 4.20. Northern face of the Bunji Gorge, showing two brittle fractures. These fractures occur about 200 m west of the main strand of the Raikot Fault at Urjal nala. Curvature of bedding in amphibolites and displacement of the pegmatite (white) dykes suggest east side up sense of displacement. The eastern fault is traversing the glacial till in the upper half of the ridge.

The Astor valley is separated from the Ramghat gorge by a narrow ridge < 500 m wide. The brittle structures observed in the Ramghat gorge, therefore extend into the Astor.
valley. Additionally, the structures related with the RSFZ can be studied east of the MMT within the Nanga Parbat gneisses, which is not possible in the Bunji and Ramghat canyons because of inaccessibility (Plate 4.23). The principal strand of the RSFZ is again a moderately east dipping brittle fault that brings Nanga Parbat gneisses in direct contact with the Kamila Amphibolite (Plates 4.24; 4.25). The original MMT contact between the Kamila Amphibolite and the Nanga Parbat metasediments is preserved in the footwall of this thrust at the valley-floor level but is truncated by a thrust in the upper reaches of the ridges (Plate 4.24). The Nanga Parbat gneisses in the hangingwall of the thrust are mylonitized for a distance of tens of meters to the east.

Again, the most prominent brittle faults are located west of the main strand, localized in the Kamila Amphibolite. The eastern flank of the Indus Valley in the Astor-Indus confluence area (between the new bridge at Thalichi and the old Ramghat bridge) shows main strand of the RSFZ (thrust) on the top of the ridge, which, verging to WNW, overrides a Quaternary valley fill deposit. At the road level, the bedrock comprising the Kamila Amphibolite is cut by at least two prominent fault gouge zones. One of these gouge zones is about 3 meters thick and is oriented at N10°W/65°SW (Plate 4.25 and Fig 4.3). This separates the bedrock in the east from the scree deposits. Splays from this fault cut across the scree and other recent deposits, which clearly indicate the recent activity associated with this fault. Another gouge zone to the north of the main one has clear indications of a dextral strike-slip motion as defined by curvature in the NE wall rock.
Plate 4.21. Downstream view of the northern face of the Ramghat (Shaitan) Gorge, Indus River in Background. The 3 km long water channel provides extensive exposures of dozens of brittle faults with gouge zones, mostly in the diorites belonging to Kohistan Terrane.
Plate 4.22. Two selected brittle fractures on the northern face of the Raengatut gorge. A) A west-dipping brittle fault with a 2 meter fault gouge zone. B) A major brittle fault that is steeply dipping towards west in its upper reaches and becomes less steepened at the base of the ridge. Several splays of brittle faults join this from west.
Plate 4.23. A photomicrograph showing panoramic view of the eastern Indus valley and its eastern face at Astore confluence. MMT (middle) and trace of the Raikot Thrust (upper right) are visible. 1. Nanga Parbat gneisses, 2. Nanga Parbat metasediments, 3. Kamila amphibolite, 4. Kohistan diorite
Plate 4.24. Photomicrograph showing panoramic view of the northern face of the Astor Valley. Three lithologic units Nanga Parbat Metasediments, Kamila Amphibolite and Kohistan Diorite make this section. The contact between the Nanga Parbat Metasediments and the Kamila Amphibolite defines the MMT that has a steep orientation. The Raikot Thrust, exposed in the upper reaches of the ridge cuts across the MMT and thrusts the Nanga Parbat metasediments onto the Kohistan diorites.

Fig. 4.2. Geology of the Astor (north) Ridge illustrating the relationship between MMT and the Liaochai Thrust (after Butler et al., 1989).
Plate 4. 25. Microphotograph showing large fault gouge zones exposed on the eastern face of the Indus Valley near the Astor-Indus confluence.

Fig. 4. 3 Sketch (after Butler et al., 1986).
4.4.1.4.4. Liacher-Raikot Segment

The ridges south of the Astor valley are inaccessible for studies of the RSFZ. However, three south-southeast directed tributaries of the Indus River, in this area expose some most spectacular features of the RSFZ. These include Liacher, Buldar and Raikot canyons. This part of the RSFZ is well documented in literature. Lawrence and Ghauri (1984) first described presence of an active fault in the Raikot area. Butler and Prior (1988 a,b) documented extension of the same fault at Liacher and Astor-Ramghat confluence, while Butler et al. (1989) and Butler (2000) gave additional accounts of the RSFZ in this area.

Mylonite Zone

Butler and Prior (1988) describe a 2 km wide shear zone in the Nanga Parbat Gneisses in the immediate hanging wall of the MMT, exposed at the western flanks of the Raikot valley. This ductile shear zone has a variety of mylonites types but is dominated by blastomylonites. Asymmetric feldspar porphyroclast as well as the offset of the granitic sheets coupled with stretching alienations indicate reverse sense of movement i.e., north-westward over thrusting of the Nanga Parbat sequence the Kohistan sequence.

Brittle Faulting

About 500 meter above the Indus River on the ridge bounding the Raikot valley in the west, Butler and Prior (1988a) describe a 20 meter fault zone marked by microbrecciation, and gouges. This fault is oriented NS and dips to the SE. A zone of about 500 m in the footwall of this fault is characterized by both NW and SE directed brittle faults lined by cataclasites and gouges. The ENE-WSW oriented linear zone of hot springs along the KKH, SW of the Raikot Bridge is associated with one of the northernmost active faults of this zone.

At the village, the ridge facing the Indus River flanking the Gah exposes three major gouge zones (Plate 4.26 A). The lowestmost major gouge zone is oriented at N20°E/60°SE and overthrusts Indus River alluvium (Plate 4.26 B). The fault shows NW thrust displacement of over 200 m onto the older alluvial fan deposit belonging to the stream. The two major gouge zones in the hangingwall of the lowestmost gouge zone are oriented in the same general orientation. Whereas the gouge zones have strong internal deformation resulting in mechanical disintegration of the original competent lithologies into microbrecciation and fine-grained clayey gouges, the wall rocks of the shear zones
are not involved in deformation. There are hundreds of sub-faults and fractures in between the major gouge zones, which show displacements of less than a meter but result in pervasive crushing.

Plate 4. 28. Photomicrograph showing an active thrust fault at Liacher. A) Panoramic view 1. Indus River Alluvium. 2. Gouge/Crush Zone derived from Kohistan diorites. 3) Kohistan diorites with pegmatic dykes. 4) Nanga Parbat metasediments. 5) Nanga Parbat Gneisses. 6) Close up of the Liacher Thrust. Note bedrock comprising tens of meter gouge/crush zone overthrusting onto the Indus River Alluvium comprising pebbly sand with cobbles and clay.
Fig. 4. Sketch map of slope failure/mass movement in the Indus Valley in the area between the Raikot Bridge and Bunji. 1. The Tatta Pani debris falls and slides (1841 to recent); 2. The Prehistoric rockslides; 3. The rockslide of 1841; 4. The Gor Gali debris slide of 1841; 5. The Prehistoric Hattu Pir rockslide, reactivated 1841; 6. The Prehistoric Thalichi debris slide; 7. The Bunji rockslide of 1841. (After Shroder, 1969).
Plate 4.27. Microphotograph showing features indirectly related with the Raikot-Lischer Thrust. A) The Hattu Pir landslide 1841, eastern face of the Indus valley. The buildings in the foreground occur to the north of the river verifying that the landslide blocked the river. B) The major landslide zone on the eastern face of the Indus Valley between Lischer and Raikot where the Nanga Parbat gneisses thrust onto alluvium. C) The Linear array of hot springs at Tatta Pani along the adius fault, southern bank of the Indus River.
The Raikut-Laicher portion of the RSFZ in particular, and Raikut-Bunji area in general has remained subject of substantial mass movement in terms of slope failures and landslides. Although the steepness of the slopes bounding the Indus Valley in this area is sufficient to yield failures as a consequence of factors other than neotectonics. The presence of more than one slope failures/landslides belonging to the same event points to role of neotectonics and associated earthquakes. As shown in (Fig. 4.4), there are seven major landslips/landslides in the Indus Valley between Raikut Bridge and Bunji, of which four belong to an event in 1841 (Shroder, 1993). Of these Hattu Pir landslide, midway between Laicher and Astor confluences on the left bank of the Indus River is one of the major landslide directly related with the RSFZ. This landslide is characterized by a large scarp and a huge body of the landslide material that is found not only on the left bank of the river but also across the river on the right bank (Plate 4.27 A). Obviously this landslide blocked the river for which there is an account in the literature. Just downstream of the confluence, again on the left bank of the river, there is a huge mass of rock that slipped from the adjacent ridge by a vertical distance of hundreds of meters. This landslide has intact rocks including the trace of the Raikut thrust whereby Kohistan Amphibolites are thrust on top of river alluvium (Plate 4.27 B). Downstream near the Raikut Bridge, the left bank of the river is lined by one of the plays of the RSFZ that is associated with a linear array of hot springs (Plate 4.27C).

4.4.1.4.5 Jalipur-Bunar Gah Segment

This segment of the RSFZ is least studied. As a general practice, previous workers have tentatively mapped the RSFZ and MMT as one fault all the way from Raikut to Babusar Pass area. Khan et al. (2000) and Edwards et al. (2000), for the first time distinguished these two faults in the Bunar Gah area. According to these works, the MMT crosses Bunar Gah at Diamir-Bunar confluence and extends SW towards Niat and Babusar close to village Halala. Between Raikut Bridge area and Gunar Farm, RSFZ probably follows the MMT on its southern side. In the ridges south of the Gunar Farm area however, the RSFZ takes a sharp turn towards the south and runs along the eastern flanks of the Bunar-Bij Valley. Locally termed Diamir Shear Zone (Edwards et al., 2000). It is characterized by both ductile and brittle shearing, which is characteristic of the RSFZ.

The Diamir Gah, an eastern tributary of the Bunar Gah exposes full extent of the DSZ. Footwall of the MMT contains metasediments, which are intruded by a NS oriented 5 km
Wide body of granite. Three kinds of structures have been mapped (see Khan et al., 2000, Edwards et al., 2000). Ductile structures defined by shear zones lined by mylonites are abundantly present in the Jhalari granite. There are high strain zones, which range in thickness from a cm to hundreds of meters. Zones where the granite has escaped deformation separate the shear zones from each other. The shear zones are consistently oriented NS with variable but mostly steep dips to the east. Shear sense criteria such as S-C porphyroclastic fabric clearly show a reverse sense of displacement i.e., eastside up. Second types of structures are defined by the brittle faults. These are steeply E-dipping and parallel to sub-parallel with the gneissic layers and ductile shear zones (Plate 4.29). Late strain is often indicated by narrow (metre scale) zones where hydrothermal flux has developed thick biotite accumulations. Overall the granite gneiss belt defines a steep N-S trending, W-vergent, reverse sense shear zone 5 km in width. The third structure recognized in this area is folding of the MMT together with its hangingwall and footwall. (Plate 4.28) shows the view of this large-scale fold. Note that MMT and fabric in the rocks dip to the west in the lower parts of the view. Midway through the ridge these take a turn and attain dips towards the east, forming a recumbent fold structures. All these three structures are closely linked and define the kinematics of the RSFZ in the Bunar Gah area (Fig. 3.6 A & 3.6 B). Khan et al. (2000) and Edwards et al. (2000) interpret that NS directed shear zones and brittle fault structures with steep easterly dips are characterised by west-verging overthrust of the core of the Nanga Parbat Syntaxis in the 5 km wide DSZ. The same overthrusting results in the folding of the originally west-dipping MMT and its hangingwall into east dipping upper limb.

The neotectonic effect of the RSFZ in Raikot-Chilas area are indirectly reflected in deformation in Quaternary Jalipur sediments which are considered to be tillite deposit related with 27 thousand years old ice age recorded in Indus valley. These sediments show deformation at three locations between Jalipur village and Chilas along the Karakoram highway (Plates 4.30 to4.32)
Fig. 4. A Geological map of NW margin of Nanga Parbat Syntaxis. Note that Palkot-Sassi Fault in Bunar Gah area is represented by the Jahari-Air Gah-Diamir Shear Zone that runs on the eastern flank of the Bunar-Bilij valley.
Fig. 3. Cross sections of the southwestern margin of the Nanga Parbat structure.

Fig. 4. 6. Geological cross section across the Diamir Shear Zone, the equivalent of the Rakot-Sasai Fault Zone at Bunar Gah.
Plate 4.2b. Photomicrograph showing the Gashat fold structure exposed at the western margin of Nanga Parbat Synclise at the eastern flank of Bunar Gah. This structure is key to structural geology of the area. The lower limb, dipping west represents structural manifestation at MMT phase. The Nanga Parbat tectonic phases characterized by ballooning out of rocks from the core of the synclise upturned the originally west-dipping structure to east-dipping structures at the Raikot fault, which is responsible for the development of this remnant fold structure.
Plate 4. 29 Photomicrograph showing the Northern face of the Diamir gorge showing steep east dipping brittle faults. These again relate to the Raikot-Sassi neocenoic phase.
Plate 4.30. Microphotograph showing Jalljpur shales (27 ky old) deformed to form a tight syncline on the right flank of the Injus River, near Kar Gas.

Plate 4.31. Photomicrograph showing Jalljpur shales with steep dips towards south.

Plate 4.32. Photomicrograph showing close up of Plate 4.31. Note that cross-beds show younging towards north, implying overturning of the sequence.
CHAPTER 5
CHAPTER 5

SYNTHESIS AND DISCUSSIONS
Detailed description of the various fault zones in the Nanga Parbat region presented in Chapters 3 & 4 allows discussions on several attributes of the Raikut-Sassi Fault Zone (RSFZ), which will be incorporated in the future studies on Seismic Hazard Assessment.

5.1. RUPTURING
The net length of trace of the RSFZ exceeds 80 km from Darchan village in the upper reaches of the Khahtoro valley to the south at Biji-Barai confluence in Bunar Gah. According to Pecher and LeFort (1999), the RSFZ dies out in the upper Khahtoro valley by gradual loss of displacement. The southern termination of the fault in the Bunar Gah is accommodated in a fold structure that rotates the MMT, together with its footwall and hangingwall from its originally west-dipping orientations to west-verging structures with easterly dips (Khas et al., 2000; Edwards et al., 2000). Further there is a consensus that RSFZ is characterized by maximum displacement at Raikut-Liacher-Astor segment. This draws an analogy with a pair of scissors facing each other with their pins at the termination points of the fault zone, and their open mouths meeting at Raikut-Astor segment.

The length of the RSFZ between the two termination points listed above is not unusual for a fault structure. However, it is unrealistic to imagine that the entire length of the RSFZ ruptured in one go. According to educated estimates, an earthquake of 8 M will rupture an area not exceeding 15-25 meters, while moderate earthquakes of magnitude 6 will not produce ruptures exceeding 1m, even that if the earthquake was focussed at depths shallower than 10 km. Therefore, it is realistic to believe that the length of the RSFZ is a product of rupturing during hundreds and thousands of earthquakes in past 10 million years, rather than related with a few major/great earthquakes. As pointed out by Buder and Prior (1989), several segments of the RSFZ have 2-3 meter wide gouge zones with sharp boundaries against surrounding wall rock, showing little or no deformation. Such fault gouges zones are generally believed to have formed as a product of an aseismic creep associated with low magnitude earthquakes rather than moderate or major earthquakes.
5.2. SEGMENTATION

Fault and fault zones along their length are divisible into segments, if they show gaps in their continuity, change in amount and sense of displacement, nature of seismicity or any other attribute. Since the RSFZ spatially overlaps the trace of the MMT, it has remained a common practice to show it as a single continuous fault from north of Sassi to Raikot and further southwest. It was recognized that dextral strike-slip movement characterizes Sassi-Shahbatot segment of the RSFZ (Maiden et al., 1985; Treloar et al., 1991), while the Raikot-Liacher segment is dominated by NW directed reverse-displacement. It is noticed during this study that the vertical to steeply east-dipping brittle faults, mostly concentrated in the Kohistan sequence west of the MMT, continue from north of Sassi through Bunji to Ramghat Astor area. In comparison, the E-dipping thrust faults with shallow to moderate dips observed between Ramghat Astor-Liacher-Raikot area are not observed in the Bunji canyon and to the north. Additionally, the Damin Shear Zone in the Bunar Gah area has several characteristics, which suggest that it can be considered as a separate segment of the RSFZ. These characteristics include a N-S orientation virtually at right-angle to the dominant orientation of the RSFZ, presence of a major fold structure accommodating the deformation and a width of the shear zone exceeding 5 km. These facts have made basis to propose division of the RSFZ into three segments; the Sassi-Bunji segment, Ramghat-Liacher-Raikot segment and Bunar segment. This would not imply presence of three separate faults. Rather his segmentation indicates a discontinuity or break in the RSFZ. Thus a three-fold segmentation of the RSFZ can be used in the subsequent seismic hazard analyses.

In essence, it is more appropriate to divide all the major faults surrounding the area of interest into appropriate segments to facilitate the seismic hazard analyses. This strategy has been adopted in the subsequent report on seismic risk analyses.

5.3. SPLATING

Presently in the Nanga Parbat region, the RSFZ can be considered as a single fault trace. One or more strands commonly define the RSFZ, with dozens of subordinate to minor faults occurring in the surroundings of the main strands. When the main strands are more than one they run sub-parallel to each other, eventually uniting to form one main strand. Between the Shabband river bend and Darchan (Khaltoor valley), there are three principal strands of the RSFZ recognized, with dozens of subordinate to minor faults noticed west of the main strand. The three strands unite to define a fault zone of about 700 m width at
the eastern slopes of Sarkund ridge near Burchi. Several vertical faces noticed on the
either side of the Indus valley around the Asmani Mor area are considered to be spills of
the main fault zone as suggested by their subvertical attitude and parallelism with the
main strand of the RSFZ at Burchi. Southwards in the Bunji, Ramghat and Astor areas,
two patterns are noticed. In the eastern parts of the fault zone (almost at the site of the
former MMT), NW vergent thrust faults are predominant, and include one or more spills.
To the west of this main fault strand, a zone of up to 3 km width has dozens of brittle
faults. Two types of faults are found in the footwall of the main strand in this zone: 1)
vertical faults with gouge zones and a dextral strike-slip component, and 2) east-verging
thrust faults, opposite to the main strand.

5.4. SUBSURFACE GEOMETRIES
The lack of microseismicity data especially for the area between Shengus and Sassi
makes it difficult to predict the subsurface geometry and behaviour of the RSFZ.
Presently there is now good database of microseismicity data available for the area
immediately to the south of Bunji (Lehigh University-University of Peshawar 1996-1998
Nanga Parbat project, funded by National Science Foundation, USA) (Fig. 5.1A,B).
The earth's crust is divisible into an upper brittle and a lower ductile regime. Seismicity is
normally restricted to brittle regime where a movements in rocks under temperatures
between or lower than 300-450 °C result in rupturing, which give rise to seismic waves. A
similar movement in rocks in the ductile regime does not produce earthquakes because
the deformation is accommodated by plastic adjustment rather than by rupturing, as is the
case in the brittle deformation regime. One of the important implications of new
microseismicity data from Nanga Parbat is to determine the depth of the brittle-ductile
transition in the crust underlying the Nanga Parbat Syntaxis. A careful analyses of the
seismicity record of 1996-1997 NSF experiment suggests that seismic events from Nanga
Parbat are divisible into two sets, one at very shallow crustal depths (< 5 km), and second
at depths ranging between 5 and 8 km. The base of seismicity (5-8 km depth events)
forms a prominent antiformal shape beneath the syntaxis and exhibits considerable
structural relief, approximately 3 km in a lateral distance of 12 km (Fig. 5.1C). The apex
of this antiform occurs at 5 km depth below sea level and is offset approximately 10 km
northwest of the topographic ridge crest. The base of seismicity deepens to 8 km below
sea level to the NW and SE mapping a thermal boundary and a transition between brittle
and plastic deformation that takes place over ~3km thick zone (Meltzer et al., 2001). Thus
maximum depth of earthquake events in the Nanga Parbat Syntaxis is ~ 5 km and in the marginal parts of 8 km. This implies that Raikot-Sassi Fault can be seismic at the maximum depths of 8 km, most probably only up to 5 km. Second information that comes from the NSF Seismic Experiment (1996-1997) is about the subsurface geometry of the Raikot Fault. As shown in Fig. (5.1C), the events shallower than 5 km are concentrated at the NW and SE margins of the syntaxes, with higher concentration at the NW margin than that at the SE margin. Furthermore, the events at the NW margin suggest presence of a fault zone dipping to the SE (Fig. 5.1D), which minimise the trace of the SE dipping RSFZ at Raikot-Liacher section, which compliment the field observations. This observation is significant as the first record of subsurface behaviour of the RSFZ based on a precise local recording of seismic events in Nanga Parbat region. If this information were exported to the segment of the RSFZ north of Bunji, it would be expected that the field observations regarding the vertical nature of the fault would also be applicable to the subsurface.
Fig. 5.1. A) Broadband and short-period array (triangles), regional and local events from four month recording window. B) Detail of Nanga Parbat short period array and epicentres of local events. Base is topography. Seismometers were deployed in an ~60x80 km area at elevations from 1000-4500 m. Access west and east of massif was obtained along valleys. Access to massif interior was obtained by trekking along glacial valleys. Abrupt cutoff in seismicity west of massif is associated with the Rakhot fault; cutoff toward east is bounded by crest of massif. C) The base of seismicity forms a prominent antiformal shape beneath the massif and exhibits considerable structural relief, approximately 3 km in a lateral distance of 12 km. The apex of this antiform occurs at 5 km depth below sea level and is offset approximately 10 km northwest of the topographic ridge crest. The base of seismicity deepens to 8 km below sea level off the NW and SE mapping a thermal boundary and a transition between brittle and plastic deformation that takes place over ~3km thick zone. D) Close-up of <5 km depth events near the NW margin of the Nanga Parbat Synaxis, showing subsurface geometry of the Rakhot Fault (Meltzer et al., 2001).
5.5. EVIDENCE FOR NEOTECTONIC ACTIVITY

Activity on faults can be reliably dated provided age data is available for the rocks involved in faulting. In Nanga Parbat region, especially near the RSFZ, the rocks can be grouped into six age groups (Table 5.1):

Table 5.1 showing tectonic activity along faults based on age data of rocks involved in faulting.

<table>
<thead>
<tr>
<th>1</th>
<th>Late Archean</th>
<th>2700 Ma and older</th>
<th>Nanga Parbat Gneisess and Metasediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Cretaceous</td>
<td>~100-120 Ma</td>
<td>Kohistan Sequence (Kamila Amphibolite Unit)</td>
</tr>
<tr>
<td>3</td>
<td>Palaeocene</td>
<td>~60 Ma</td>
<td>Kohistan Batholith diorites/gabbros</td>
</tr>
<tr>
<td>4</td>
<td>Oligocene</td>
<td>34-25 Ma</td>
<td>Pegmatite dykes in Kohistan sequence, such as near the Indus confluence</td>
</tr>
<tr>
<td>5</td>
<td>Late Miocene</td>
<td>~10 Ma</td>
<td>Granite/pegmatite sheets in Nanga Parbat e.g., Shengus</td>
</tr>
<tr>
<td>6</td>
<td>Quaternary</td>
<td>27,000-3000 Years</td>
<td>Glacial tills, Indus River alluvium, alluvial fans</td>
</tr>
</tbody>
</table>

Additionally the age of the MMT is known to be 55-58 Ma. This implies that structures related with MMT will deform all rocks older than Early Eocene, and the fabric related with the MMT would be intersected by the Oligocene-Miocene pegmatite dykes and will be unconformably covered by the Quaternary glacial and fluvial sediments. As described earlier mylonites zones and brittle faults now occupy much of the original site of the MMT. The pervasive fabric in the vicinity of the MMT developed under amphibolite-facies of metamorphism and mylonites zone developed under greenschist facies conditions were initially considered to be related with the MMT (Butler and Prior, 1988a, b; Butler et al., 1992). RSFZ was considered to represent only the brittle faults. These studies ignored the relationship between the mylonites and the pegmatite sheets. The traverse from the Indus confluence to Sassi exposes excellent field relations between the various phases of deformation and the Kohistan pegmatite dykes of 34-25 Ma age (Fig. 5.2). The Early Eocene Kohistan batholith gabbros exposed between the Indus confluence and the Hanuchal village are predominantly undeformed and are cut across by a network of pegmatite sheets/dykes. At Hanuchal village, a suite of strongly foliated basic rocks (Cretaceous Kamila Amphibolite Unit) occupies western vicinity of the RSFZ. The fabric is again cut across by a network of Kohistan pegmatite dykes, suggesting that the fabric in
the amphibolites is older than 34-25 Ma. There is a possibility that this fabric could be related with the MMT, but existing knowledge of the Kohistan tectonics from elsewhere suggests that fabric in the Kamila Amphibolite Unit is middle Cretaceous in age rather than Eocene (Treloar et al., 1990). The same 34-26 Ma pegmatite sheets are present in the mylonites at Sassi and Shahbatot, but these are strongly deformed, folded and in most cases transposed along the mylonites fabric. This clearly suggests that the mylonites formed during a deformation phase that post-dated 34-26 Ma. This implies that the mylonites at the NW contact of the Nanga Parbat Synaxis are not related with the MMT.

Question arises that do they relate with the RSFZ? It is not uncommon to find a fault manifested in brittle faulting when ruptured at shallow crustal depths and in mylonites, when activated at depths (Ramsay, 1964). The close association of the brittle faults and the mylonites zones in RSFZ and the resemblance of kinematics favours the possibility that onset of deformation on the western margin of the Nanga Parbat Synaxis resulted in the formation of ductile shear zones with mylonites at depths and brittle faults at surface to shallow depths (Butler, 2000). There is an ample evidence based on hundreds of fission track K/Ar, Ar$^{40}$/Ar$^{39}$ dating (see Zeitler et al., 1985, 2001; Treloar et al., 2000) that the tectonic activity in the Nanga Parbat region started about 16 Ma ago and is continued at present. This tectonic activity has not only reflected in the formation of the ductile and brittle fault zones but has resulted in the dramatic uplift and exhumation of the rocks in the Nanga Parbat Synaxis. According to estimates based on radiometric dating and geomorphologic studies, rocks located at depths of > 7 km depths have been mechanically transported to surface during the last 3 Ma. This implies that mylonites at the deeper parts of the RSFZ, formed 3-7 Ma ago were uplifted and exposed to their present position during the last about 1 Ma. The brittle faults in the RSFZ observed at present are manifestation of the most recent tectonic activity as they reworked the mylonites, and must be associated with mylonites currently residing at depths greater than 5-10 km.

What evidence is there regarding the neotectonic nature of the RSFZ? Several lines of geological evidences are used to decipher active tectonic nature of faults. The active faults

- commonly displace drainage patterns.
- produce fault scarps.
- deform the recent sediments such as alluvial fans, river alluvium and glacial tills.
- are associated with recent seismicity.

Evidences for all these attributes have been found in the RSFZ.
Plate 5.1. Photomicrographs showing relationship between 34-15 Ma old pegmatite dykes and deformation associated with the Raikot-Sassi Fault Zone exposed on Indus Confluence-Sassi Road. A) Kohistan diorites cut across by an irregular netowrk of dykes. The host rock as well as the dykes show no signs of deformation; B) Karmla Amphibolites at Hanuchal village show strong vertical foliation in the amphibolite cross cut by pegmatite dykes which remain undeformed. C) Sassi mylonites. The 34-15 Ma year old pegmatite are deformed and transposed along the shearing. Field relations suggest that mylonites and brittle faults in the Sassi-Shabbatot area are younger than the 34-15 Ma dykes and not related with the MMT phase of deformation. The the mylonites are rather related with the Raikot-Sassi Fault Zone

5.5.1. Drainage Pattern Displacements

Ample proof of stream offset associated with the RSFZ is found in The Bunji-Shengus area in the north and the Raikot-Astor area in the south. The Indus River displays the most dramatic offset caused by the neotectonic activity. From Skardu downstream the Indus River flows in a general W-NW direction. At Asmani Mor, ~5 km downstream from Shengus, the river takes a 90° sharp turn and starts flowing northwards towards Sassi along the general trend of the RSFZ. In details, part of the river between Shabbatot bend and tip of the Sassi bend follows the Khaltoro-Sassi fault (the westernmost active strand of the RSFZ). In the south, between the Shabbatot river bend and Asmani Mor, the river flows at a distance of 500-800 m east of the main fault strand. In this area, the river offset to north is associated with N-S oriented vertical fractures, which run parallel to and closely related with the main fault strand (Fig. 5:2).
In Bunji gorge, a NNE oriented tributary, termed Unjal Nala follows the RSFZ. Southwards, the zigzag course of the Astor River in an area of about 2 km from its confluence with the Indus River is considered to be induced by the N-S oriented fault strands associated with the RSFZ. Further south, the Indus River is again induced by neotectonic activity associated with the RSFZ to follow the active fault zone for a distance of at least 5 km between Liacher and the Raikot Bridge.

It is worth mentioning that neotectonic activity associated with the RSFZ has not only produced lateral stream offsets but has also caused abrupt changes in river/stream gradient. The existing topographic data do not have sufficient resolution to notice these
effects on maps. Madin (1986) however has listed marked kink points in gradients of the Indus, Ranghat, Bunji, Ishkapal, Dasu and Khaltoro streams rivers at places where they cross the strands and splays associated with the RSFZ.

5.5.2 Fault Scarps
Displacements along faults ruptured on the earth’s surface are commonly manifested in abrupt changes in topography across the fault trace. Planar surfaces at the site of trace of the fault separating these topographic breaks are called fault scarps. Fault scarps associated with various strands and splay of the RSFZ are found at a number of places. These are particularly well exposed on the eastern flank of the Shabtato-Sassi segment of the Indus Valley and on the ridges bounding the Dasu and Khaltoro canyons. Fault scarps are also visible on satellite images at eastern slopes of the Sarkund ridge opposite the Arsnani Mor are exposed in the Liacher and Raikot area to the south also exposes several fault scarps, which have been listed in Chapter 4.

5.5.3. Deformation in Quaternary Sediments
One of the most compelling evidence for neotectonic activity of a fault is its interaction with Quaternary and younger sediments. Quaternary sediments in northern Pakistan include glacial tills, ranging in age from 1.8 million years to < 10,000 years. Sediments younger than these include alluvium related with Indus River while the alluvial fans related with the tributaries of the Indus River are the youngest among these sediments. These sediments are not dated with any precision but their involvement in deformation can be taken as the most compelling proof of neotectonic activity of a fault zone. This study therefore, specially focussed on this aspect. As described above, there are several places where Quaternary sediments ranging from glacial tills to river sediments and alluvial fans were found involved in the RSFZ.

- Glacial till plateaus in the vicinity of the Sassi village are dissected by two easterly strands of the RSFZ (Hutson and Sunari fault strands) associated with east-side up offsets in the terraces with development of scarps at the traces of the faults.
- Glacial tills as well as alluvial fans are dissected by these two fault strands in the vicinity of village Dasu (north of Sassi).
- At the Astor-Indus confluence a 3 meter wide fault gouge zone has splay which cut across a valley fill deposit.
- At Liacher, the main strand of the RSFZ, termed Liacher Thrust (Butler and Prior, 1988a,b) thrusts Nanga Parbat gneisses directly onto alluvial deposits (sandstone, siltstone, gravelly) belonging to the Indus River.
- A linear array of hot springs follows an active strand of the RSFZ, near Raikot Bridge along the southern flanks of the Indus River.
- Jalipur mollase, a Quaternary glaciofluvial deposit is deformed and overturned at least three locations between Jalipur village and Ke Gas village in the lower Indus valley between Raikot and Chilas.

5.5.4. Seismicity

The geological evidence for recent seismicity is adequately reflected in active faults in Nanga Parbat region; instrumental record for seismicity is virtually negligible. Two explanations are possible, either the Nanga Parbat region is seismically quiet, which is unlikely. The second possibility is that the lack of a local seismic station network in northern areas in Pakistan is the main cause for this discrepancy.

A temporary regional array deployed as part of the Karakoram Project (1980) recorded only three events near the Nanga Parbat Syntaxis in a six-week recording window (Yielding et al., 1984). In 1996-1997, a National Science Foundation Project conducted by Lehigh University, USA in collaboration with the National Centre of Excellence in Geology, University of Pashawar deployed 60 IRIS PASSCAL instruments, (10 broadband and 50 short period stations), in the Nanga Parbat region to record local and regional events. Over a period of 4 months recording in 1997, this seismic experiment identified ~2000 seismic events. These included source locations in the region including the Pamirs and Hindu Kush to the northwest, the Karakoram and NE terminus of the Kohistan arc to the north and northeast, the Himalayan arc to the southwest, the Hazara and Kashmir syntaxis to the south and southeast. Most significantly, this network recorded as many as 5-8 small magnitude local events per day.

Figure 5.1 portrays the seismicity recorded from the 1996-1997 NSF project giving some very useful clues about the pattern of seismicity in the Nanga Parbat Syntaxis (Meltzer et al., 2001). This experiment has negated the perception that Nanga Parbat is aseismic as reflected in catalogues of instrumental record derived from far off seismic stations.
effects on maps, Madin (1986) however has listed marked kink points in gradients of the Indus, Ramghat, Bunji, Ishkapal, Dasu and Khaltoro stream/river at places where they cross the strands and splays associated with the RSFZ.

5.5.2 Fault Scarsps
Displacements along faults ruptured on the earth’s surface are commonly manifested in abrupt changes in topography across the fault trace. Planar surfaces at the site of trace of the fault separating these topographic breaks are called fault scarpDs. Fault scarpDs associated with various strands and splays of the RSFZ are found at a number of places. These are particularly well exposed on the eastern flank of the Shabbatot-Sassi segment of the Indus Valley and on the ridges bounding the Dasu and Khaltoro canyons. Fault scarpDs are also visible on satellite images at eastern slopes of the Sarkund ridge opposite the Asmani Mor are exposed in the Lischer and Raikut area to the south also exposes several fault scarpDs, which have been listed in Chapter 4.

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- Glacial till plateaus in the vicinity of the Sassi village are dissected by two easterly strands of the RSFZ (Hurbon and Sumari fault strands) associated with east-side up offsets in the terraces with development of scarpDs at the traces of the faults.
- Glacial tills as well as alluvial fans are dissected by these two fault strands in the vicinity of village Dasu (north of Sassi).
- At the Astor-Indus confluence a 3 meter wide fault gouge zone has splayDs which cut across a valley fill deposit.
The historical record as well as the two events, which occurred most recently in November 2002, provides further clues about the seismic activity of the Nanga Parbat region.

The historical record of a major earthquake in the Nanga Parbat region in 1841 is documented in many publications (Lawrence and Ghauri, 1983; Shroder, 1993; Shroder et al., 1989, 1993; Cornwall, 1994). The 1841 earthquake caused a major landslide (termed Liacher rockslide), still well preserved on the eastern bank of the Indus River between Raikot and Liacher Drew (1875). Another major landslide related to the same event termed Hattu Pir landslide is exposed on the eastern bank of the Indus River, between Astor and Liacher rivers. Two more rockslides, one at Tatta Pani and other opposite to the Bunji confluence are found. All these landslides, especially the Hattu Pir and Liacher were large enough to completely block the Indus River for at least six months developing a natural dam that was at least 160 meter high and 60 km long upstream from the site of blockade. When ultimately the natural dam failed, it flooded the entire Indus valley to the south. According to a documented in Journal of Asiatic Society, Bengal (Vol. XVII, p. 231), a 500 strong army persons of Raja Gulab Singh camped 3 km upstream from Tarbela was completely swept away by this flood. Waves as high as 28 m were observed near Attock where the Peshawar Basin was temporarily flooded. The number of landslides between Raikot and Bunji and the amount of displacement of the rock material was sufficient to block the Indus River for six months suggest that the earthquake that triggered this disaster was at least 7.8 M.

The earthquake of November 20, 2002 is the recent most manifestation of active tectonics of Nanga Parbat Syntaxis and as reported by Tariq et al. (2002), the hypocentral parameters of the main shock are:

Origin time : 21:32:29.85
Epicenter : 35.52°N, 74.68°E
Depth : 21.5 km
Magnitude (Mb) : 6.2

From the most affected villages the epicentral location was at Doian and Tatto just off the Indus Valley at the confluence with the River Astor. The main shock was preceded by 20 days of significant numbers of foreshocks ranging from magnitudes 3.3 to 5.5. There was
a intensive phase of seismic activity 2nd to 8th November when 53 events were
documented (Hughes, 2003). The foci of the earthquakes were widely spread but with a
NNE -SSW trend covering 60km along the Indus Valley from Chilas to Dohan and below
the 25km wide west flank of the Nanga Parbat mountain range. More than 5 villages in
Raikot, Budar and Astor valley were completely or partially destroyed killing 27 people
and injuring hundreds.

5.6. NEOTECTONIC ACTIVITY AND SEISMIC HAZARDS FOR THE PROPOSED
DAMSITE AREA

The preceding description and discussions raise the obvious question that what is the
neotectonic vulnerability level for the proposed site for the Bunji Hydroelectric Project
i.e., Asmati Mot, which is proposed to host the dam, reservoir and the tunnel inlet, the
axis of the proposed tunnel across the Sarkund ridge and the site of the tunnel outlet and
Power Station near Hoshi village (Bunji-Indus confluence area)? The detailed seismic
hazard assessment is beyond the scope of this study; rather this study is aimed at
providing a base for seismic hazard assessment to be immediately followed. This section
addresses the neotectonic and seismic hazard vulnerability of this specific area as
compared to other parts of the Nanga Parbat Synclise.

As noted in the previous sections, the NS oriented, vertical RSFZ passes on the eastern
slopes of the Sarkund ridge and attains a width of about ~700 m, with fault gouges,
breccias and crush zones. Before we go into this discussion, it is appropriate to say that
the Hoshi area west of the Sarkund ridge hosting tunnel outlet and the Power House is not
only sound in terms of engineering properties but also has no trace of faults, active or
dormant in closer vicinity, and hence is most suitable for the proposed engineering
structures.

As noted above, a part of the RSFZ that occurs north of the Shabbatot river bend
displaces glacial till and alluvial fans. Recent dating of these sediments suggests that
these range in age from 3,000 to 27,000 years (Richards et al., 2002). So there is definite
geological evidence that at least until 3000 years ago this part of the RSFZ was active and
must have caused devastating earthquakes. The same scenario is expected for the part of
the fault zone near D2a/D2b site, as the glacial tills and debris on the ridge immediately
south of the Shabbatot bend (opposite to the Kholola confluence) are cut across by the
fault zone. Compared to the Raikot-Astor segment of the RSFZ, where both historical and
instrumental seismic data point to occurrence of major to moderate earthquakes (1841

109
there is no such record available for the part of the RSFZ in the northern segment (north of Bunji). The lack of documented historic or instrumental record may point out that whereas the Raikot-Astor segment is still active with a recurrence period of ~150 years, the Bunji-Shabatot-Sassi segment is seismically quite for the last 3000 years. Does this imply that this part of the RSFZ has become dormant and is not susceptible to future earthquakes? Although there is no evidence to dispel this interpretation, the existing knowledge from active zones such as San Andreas Fault, California and Chaman fault zone, NW Pakistan suggests that lack of seismicity along a part of the active fault is indicative of a greater potential for seismic hazard than its presence. According to the advocates of “seismic gap” theory, the segments of active faults with greater number of small magnitude earthquakes keep releasing the elastic strain and thus loose potential for major earthquakes. In comparison, parts of the faults, which keep storing the elastic strain without releasing it through small magnitude earthquakes, remain quite over hundreds and thousands of years before ultimately resulting in major earthquakes. Thus the knowledge that 1) the RSFZ was active until 3000 years ago, 2) is continuous with seismically active Astor-Raikot segment and above all 3) passes close to the proposed critical engineering structures is enough to explore most sophisticated engineering solutions and design parameters if this project has to go ahead.
CONCLUSIONS

The review of the geology of the western margin of the Nanga Parbat Syntaxis and detailed study of the neotectonic features allows drawing several conclusions:

1) The rocks constituting the area are mainly metamorphosed igneous rocks. These include orthogneisses and schists, belonging to the Nanga Parbat Syntaxis, and amphibolites and gabbro-diorite-granite-granitic pegmatites belonging to the Kohistan Terrane. The determination of engineering properties of these rocks is out of scope of this study, but it may be relevant to state that all these rocks are highly competent and are suitable for foundation of engineering structures.

2) This study substantiates the presence of a major fault zone (Raikot-Sassi Fault Zone).

3) The RSFZ is associated with several neotectonic features suggesting that the fault zone is active. These include displacement of the drainage including the Indus River, deformation of glacial tills and alluvial fans, fault scarps and the presence of hot springs. The historical and instrumental record of seismicity shows that the southern segment of the RSFZ (Bunji-Lachher-Raikot segment) was a source of at least two major/intermediate (6-8 M) events during the past 160 years, and is the subject of active microseismicity at present. The activity of the northern segment (Bunji-Shahbatot-Sassi-Khaltoro segment) is only based on geological evidence. The lack of historical and instrumental seismicity record for the northern segment may be due to a lack of knowledge. There are no local seismic stations in the northern areas of Pakistan, while the historical record is equally poor. Alternatively, if it is assumed that the lack of seismicity is true, it may imply that either 1) the northern segment of the RSFZ is dormant in historical times and might have lost its activity, or 2) the northern segment is locked and accumulating elastic strain. The knowledge that Nanga Parbat Syntaxis is actively growing, it is unlikely to favour the former possibility. There is a greater possibility of a seismic gap related with the northern segment of the RSFZ. This would imply that active growth of the Nanga Parbat Syntaxis is resulting in storage of elastic strain in the northern segment of the RSFZ, which would warrant occurrence of intermediate to major earthquakes at this segment in future. Therefore, the entire trace of the RSFZ should be considered as an active fault with potential for future seismic activity.
4) The steepness of the slopes in the Indus, together with the presence of vertical fractures parallel to RSFZ on the both sides of the valley warrants special attention for landslide hazards. Such potential mass movement can cause direct damage.
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113


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121


