Geomorphometric features and tectonic activities in sub-Himalayan thrust belt, Pakistan, from satellite data

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A B S T R A C T

The sub-Himalayan thrust belt is an active thrust wedge which progresses southward over the north-dipping Indian plate. The north-south compression resulted in severe deformation of sedimentary rocks in this belt. Distinct thrust geometries and topography have evolved under the interaction between tectonic and erosional environments. To better understand the relationship between tectonics and topography, a Digital Elevation Model (DEM) derived from Shuttle Radar Topography Mission (SRTM) data was used to extract the geomorphic and drainage features. Based on comprehensive analyses of topographic relief, drainage density, and drainage patterns, nine topographic units were identified. The thrust wedge was divided into three physiographic assemblages with apparent lateral variations. These units match up with the interpreted main structures from the Landsat Enhanced Thematic Mapper Plus (ETM+) images and published geological maps. The relationship between geomorphometric features and tectonics indicates that structural activities primarily control the topography in the sub-Himalayan thrust belt. Topographic features are indicative of tectonics in the young tectonic regions with low elevation.

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1. Introduction

Topography is the result of complex interactions between tectonics and erosion. Mountain belts are the most conspicuous topographic features on the continents. If there were no erosional processes, the surface geometry of a mountain belt would reflect the sum result of tectonic processes. Generally, the surface processes controlled by climate and surface properties start to shape the topography when a mountain belt is built. These processes result in mass redistribution followed by isostatic compensation. Tectonics, surface processes, and topography interact with each other. In the last two decades, a large amount of work has examined the influence of surface processes on topography (e.g. Beaumont et al., 1992, 1994; Tucker and Slingerland, 1994, 1996; Burbank et al., 1996; Brozovik et al., 1997; Brocklehurst, 2002; Finlayson et al., 2002; Wobus et al., 2003). Further explorations of the interactions between landscape evolution and tectonic processes have been made using numerical modeling (e.g. Koons, 1989; Tucker and Slingerland, 1994; Kühni and Pfiffner, 2001). Most of the work is concentrated on large mountain belts such as Alps and Himalayas.

The Himalayas are the youngest and the most spectacular topographic features on Earth. As a consequence of the collision between the Indian plate and Eurasian plate, the Himalayan orogenic belt built a series of north-dipping Cenozoic faults in southern Tibet (Hodges, 2000; Yin and Harrison, 2000; Yin, 2006). The sub-Himalayan thrust belt in Pakistan, bounded by the Main Frontal Thrust (MFT) and the Main Boundary Thrust (MBT), is a particular part of the system with distinct topography (Fig. 1). Crustal shortening, due to northward under-thrusting of the Indian plate beneath Eurasia, continues to create active tectonic features on the northwestern fringes of the Indian craton since the onset of continental collision (Jaswal et al., 1997). Due to the same compression, thin-skinned tectonic features developed in this area and overthrusted southward along a decollement in evaporite beds. Intense deformation occurred in the thrust wedge. From east to west, the Salt Range, the Surghar Range and the Trans-Indus Salt Range, stand over the Punjab Foreland Basin of Pakistan with abrupt relief (McDougall and Khan, 1990). The ranges, interconnected by transfer zones, are still growing by progressive folding and thrusting (Blisniuk et al., 1998). The MFT fault lies along the southern piedmont of the distorted ranges, and separates them from the Punjab Foreland Basin (Fig. 1). Extensive research has been carried out in the sub-Himalayan thrust belt in an effort to understand Himalayan evolution (e.g. Farah et al., 1977; Yeats et al., 1984; Lillie et al., 1987; Baker et al., 1988; McDougall and Khan, 1990; McDougall and Hussain, 1991; Blisniuk et al.,...
However, little attention has been paid to the topography in the sub-Himalayan thrust belt, especially the relationship between the tectonic processes and topography. The purpose of this paper is to investigate the relationship between tectonic processes and topography in the sub-Himalayan thrust belt using the extracted geomorphometric features from a Digital Elevation Model (DEM) and interpreted structures from Landsat Enhanced Thematic Mapper Plus (ETM+). Drainage analysis is the main focus here, because it provides useful information about the structural units and evolution history of faulting (Jackson and Leeder, 1994; Jackson et al., 1996; Boudiaf et al., 1998; Goldsworthy and Jackson, 2000). Also, the lateral variation of topography along the thrust front is explained based on the geomorphic and structural data.

2. Datasets and methods

2.1. Datasets

Two datasets were used to extract the structural and geomorphometric features. Linear structures and lithologic features were interpreted from twelve Landsat-7 ETM+ scenes. Statistical and spatial analyses were carried out on Shuttle Radar Topography Mission (SRTM) DEM data to describe the geomorphometric features including drainage density, slope, drainage pattern, and relief.

2.2. Landsat and DEM data processing

To get a whole map view for the study area, twelve scenes of ETM+ data were mosaicked together. The mosaic quality of Landsat data was enhanced by georeferencing, fine adjustment, color balancing and brightness matching, thereby helping to identify structures and lithologies. According to physiographic landscape and spectral reflectance signatures in the study area, a color composite scheme of short-wave infrared (SWIR) image was prepared for structural interpretation in Environment for Visualizing Images (ENVI) software package (Fig. 1). The image was obtained by combining ETM bands 7, 4, and 3 as red, green, and blue, respectively. This procedure was found useful for extracting the features of interest for this study from the Landsat images.

DEM data (90 m spatial resolution) was used for automatic extraction of the drainage system. Because the SRTM cannot collect data at some places with rough relief, there are certain holes with no data which can be a problem for stream extraction to be used in drainage analysis. Therefore, areas without data were fixed through inverse distance weight (IDW) which produced location-dependent values for the holes in DEM technique (Philip and Watson, 1982; Watson and Philip, 1985).

2.3. Drainage analysis

For drainage analysis, the stream network was extracted from the DEM data as a first step. Flow directions from each pixel to its
steepest downslope and flow accumulation, corresponding to the number of upslope pixels that flow into each cell along the flow direction, were determined using the ArcGIS software. The results were used to extract the stream network by applying a threshold value to selected pixels (Tarboton et al., 1991).

A threshold value of 500 was used in this study, which means that if a stream starts at a pixel to which 500 upslope pixels flow into. The total area for 500 pixels is ~4 km² which is about 1/6 of the area of the 5 km × 5 km grid used for density analysis. This confirms that there are certain river segments in each grid and that following statistics for drainage density in the grid are meaningful. Lakes in the study area were considered as channels along their center lines. The extracted stream networks are shown in Fig. 2. To describe the configuration of the streams, drainage density, and drainage patterns were investigated. Further analyses were conducted based on these two parameters.

Drainage density is the total length of all the streams and rivers in a drainage basin divided by the total area of the drainage basin, being represented by the following equation:

\[ \rho = \frac{1}{S} \sum_i L_i \]

where, \( \rho \) is drainage density; \( S \) the area of drainage basin; \( L_i \) the length of the \( i \)th river in the basin. The drainage density provides a hydrologist or geomorphologist with a numerical measure of landscape dissection and runoff potential. There are many factors, including climate, soil infiltration capacity, vegetation, topography, and geology, etc., that influence the stream density. The stream density calculated in this study only reflects the topology and geology, because the streams are extracted directly from the DEM data which only includes the topology and some geological information. Instead of calculating the density in selected drainage basins for drainage basin analysis, we created 3’ × 3’ (~5 km × 5 km) grids stochastically to cover the entire study area and collected statistical data for the stream density in each grid (Fig. 3). The grid size was selected by considering the range of the study area and the stream network.

To better understand the geomorphic elements in the study area, especially in the highland areas where the topographic units are hard to identify based on density analysis; percentage slope was calculated to express the maximum change in elevation over the distance between a pixel and its eight neighbors (Fig. 4). The slope identifies the steepest downhill descent from a pixel in the DEM data. Streams usually flow along the direction of the steepest slope. In this study, we averaged the DEM data from 90 m to 5 km spatial resolution, which is the same size as the grid used in density analysis, to obtain a smoothed slope map in concordance with the density map. The slope map indicates that the lower the slope value, the flatter the terrain; the higher the slope value, the steeper the terrain. Topographic units were delineated from the slope and density map.

Finally, the channel segments were counted and the azimuths of the segments were calculated for every topographic unit. Rose diagram was employed to display statistical data of stream segments that fall within a specific angular region, because it can show semi-variogram values in all directions at once rather than showing only one at a time (Fig. 5). The different

Fig. 2. Stream network extracted from the DEM data for drainage density and pattern analysis using ArcGIS. Lakes are considered as streams along their center lines.
combinations of stream orientation revealed specific drainage patterns and flow directions that are usually governed by the rock properties, structures and gradient of surface in different topographic units.

3. Results

3.1. Drainage and topographic units

The distribution of the stream channels is not uniform, because of the different relief and progressive tectonic activities. The extracted drainage densities and patterns present the variations of channel space and configurations in the sub-Himalayan thrust belt. In the statistical density map (Fig. 3), four locations with high drainage density were identified, which correspond to four tectonic basins: (1) Punjab Foreland Basin; (2) Bannu Basin; (3) Peshawar Basin; (4) Jalalabad Basin. The average drainage density in the four basins is much higher than that in the entire study area (Table 1). Combining with the slope map, we further divided highland areas into five topographic units: Lesser Himalaya and Kohat Plateau with steep slope, Khost Plateau and frontal thrust ranges with intermediate slope, and Potwar Plateau with gentle slope (Fig. 4). The topographic unit boundaries are placed at locations where slope changes abruptly. Rose diagrams are powerful to present stream orientations in different topographic units (Fig. 5). The irregular flow directions in the rose diagram indicate that the pattern seems not to be fully developed in the frontal thrust ranges because of the rapid uplift along the front of the MFT (Fig. 5h). A dendritic pattern has tributaries that branch like the limbs of a tree. This pattern is well developed in four basins where no strong tectonic control exists except at their boundaries (Fig. 5a–d). The rose diagram for the Kohat Plateau shows that the streams mainly distribute in two directions at a right angle, indicative of a trellised pattern (Fig. 5f). In the Potwar Plateau, streams form a dendritic pattern and flow westwards (Fig. 5e). In summary, the drainage patterns revealed by rose diagrams have remarkable differences among the ranges, plateaus, and basins. The difference in stream patterns supports the division of topographic units based on the stream density and slope analysis.

Three relief profiles were drawn to examine the trend of elevation change in different topographic assemblages in the sub-Himalayan thrust belt (Fig. 6). Profile (a) crosses the following topographic units from north to south: the Lesser Himalayas, the Jalalabad Basin, the Bannu Basin, the Trans-Indus range, and the Punjab Basin. Profile (b) crosses southwards the Lesser Himalayas, the Jalalabad Basin, the Kohat Plateau, the Surghar range, and the Punjab Basin. Profile (c) crosses southwards the Lesser Himalaya, the Peshawar Basin, the Potwar Plateau, the Salt range, and the Punjab Basin. In general, the profiles have a similar trend. They start from the flat foreland basin at the south, pass through alternating mountains and basins northwards, end in the Lesser Himalayas with high elevation.

The Punjab Foreland Basin is flat and its elevation is less than 200 m. To the north Trans-Indus Range, Surghar Range, and Salt
Range from west to east, rise up abruptly to an average elevation of 1000 m. The ranges present large lateral variation of topography. MFT lies along the south piedmont of the ranges. North of the MFT, the topography is rugged and the average elevation is much higher (700 m). The Bannu Basin is situated north of the Trans-Indus Range. The Kohat Plateau is located north of the Surghar Range. The Potwar Plateau is north of the Salt Range. The Bannu Basin has the lowest elevation in these three geological units. The Kohat Plateau has a highest elevation with rugged relief. The Potwar has a reduced elevation and gentle relief compared with the Kohat Plateau. The Bannu Basin has the lowest elevation in these three geological units. The Kohat Plateau has a highest elevation with rugged relief. The Potwar has a reduced elevation and gentle relief compared with the Kohat Plateau. The Bannu Basin has the lowest elevation in these three geological units. The Kohat Plateau has a highest elevation with rugged relief. The Potwar has a reduced elevation and gentle relief compared with the Kohat Plateau. The Bannu Basin has the lowest elevation in these three geological units.

3.2. Interpretation of structures

The linear structures derived from the interpretation of Landsat images in the northwestern Himalayan area are depicted in Fig. 7. In comparison to the 1:650,000 geological map (Searle and Khan, 1996), the Landsat image provides more detailed mapping of main faults and folds. Some of the small faults and folds presented in the 1:50,000 geological map for the Salt Range (Gee, 1980), were difficult to extract from Landsat ETM+ images. However, 1:50,000 geological maps covering the entire study area are not available. The Landsat images provide a clear picture of most of the linear structures. The geological map and our interpretation results show that the structures between MFT and MBT comprise mainly south-verging folds and thrust faults. The youngest thrusting is concentrated on the frontal thrust system with the Salt Range in the east, the Surghar Range in the middle, and the Trans-Indus Ranges in the west. Strike-slip faults interconnect the adjacent ranges. In the Kohat Plateau, the parallel folds and faults are tightly aligned. The Potwar Plateau is comprised of the northern folded zone and southern platform. The folds in the Kohat Plateau have longer wavelengths than those in the Potwar Plateau.

4. Discussion

4.1. Topographic units and tectonics

The topographic units and the distribution of the structures indicate that the boundary of the topographic units match up with the main structures interpreted from Landsat data and published...
geological maps (Fig. 7). The MFT fault is consistent with the northern edge of the Punjab Foreland Basin. The MBT separates the Peshawar Basin and the Jalalabad Basin from the Potwar Plateau and the Kohat Plateau. Three elevation profiles crossing different topographic assemblages reveal that the changes in the trend of elevation are similar among three profiles, which starts at high elevation, crosses the rugged relief area, and reaches the flat foreland basin. The topographic units are constrained by the imbricate thrust faults whose upthrown blocks form high elevation. The crust shortening leads to the rugged relief in the thrust wedge. This indicates that the regional tectonics built the foundation for the topography with minor shaping by erosion.

The different reliefs in the topographic units are controlled by the tectonic activities. In the thrust front ranges, because of the rapid uplift, the streams are very short, and the patterns are not fully developed. In the basins, dendritic patterns are common because of no strong structural activities. Tributaries run on the uniform Quaternary alluvium. In the plateau regions, various patterns exist. The trellis pattern in the Kohat Plateau indicates strong control of structures on streams. East–west striking anticlines and synclines line up parallel, which resulted in alternating valleys and ridges. Channels align themselves parallel to structures in the bedrock with minor tributaries coming at right angles. Although the structural patterns are similar, streams in the Potwar Plateau present a dendritic pattern because the structural control on the streams is not so strong as that in the Kohat Plateau. The folds in Potwar Plateau open wider and faults are spaced out, which resulted in lower elevation and gentle relief. A dendritic pattern tends to develop in this environment, but

Table 1

<table>
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<th>Tectonic units</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Other</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (km/km²)</td>
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<td>0.5937</td>
<td>0.5746</td>
<td>0.5771</td>
<td>0.4144</td>
<td>0.4484</td>
</tr>
</tbody>
</table>

Fig. 5. Rose diagrams showing the streams orientation frequency at 5° interval in nine topographic units. The diagram letters (a–i) correspond to topographic units (1–9) in order (See Figs. 4 and 7).
structures have some effects on the development of the channels in the Potwar Plateau. The Soan River flows along the axis of Soan syncline westwards into the Indus River.

Based on different geomorphic features, drainage patterns, and structures, the sub-Himalayan thrust belt is divided from west to east into three structural assemblages: Bannu-Trans-Indus thrust sheet, Kohat-Surghar thrust sheet, and Potwar-Salt thrust sheet. The Kohat-Surghar thrust sheet was resisted more at the north, compared to the other two sheets during their southward propagation. The apparent inconsistency among these thrust sheets is expressed by the Kalabagh reentrant. Our work is supported by studies based on other datasets. For example, Farah et al. (1977) used gravity data and suggested that the thrust wedge move at the top of the Indian plate’s basement and the thrust front is wrenched. Lillie et al. (1987) and Baker et al. (1988) defined the geometry of the thrust based on the interpretation from seismic profiles. Balanced cross sections show that thrust propagation is dominated by layer-parallel slip, and taper-preserving deformations, which increase the wedge thickness and results in the uplifted elevation (McDougall and Hussain, 1991).

4.2. Lateral variation of structural geometry

There are three models that explain the spatial variation of topography along the thrust front: (1) Chaman transform fault zone: according to this model the wrench zones are en-echelon arranged branches of the Chaman fault (Treloar et al., 1992); (2) normal faults in the foreland basin: Blisniuk et al. (1998) suggest that the normal faults in the foreland control the development of the thrust front; (3) the viscosity model: this model indicates that the rheologically weak layers of the thrust base dictate the geometry of the thrust front (Butle, et al., 1987). Cotton and Koyi (2000), and Schreurs et al. (2002) modeled the transfer zones in fold and thrust belts and suggested that the viscosity of the basal detachment control the variations of structural geometry.

Our work supports the idea that thrust sheets have been elevated from the Punjab Foreland Basin, because they thrust over the basin. Due to the resistance from the basement, severe deformation occurred in the upthrown block, which resulted in the rugged topography. In the Kohat Plateau, east-west striking anticlines are separated by narrow synclinal valleys, which are expressed with rough relief. The Potwar Plateau has a reduced elevation and relief than the Kohat Plateau. This indicates that the shortening is different, because of the inconsistent resistance at the base. The Kohat-Surghar thrust sheet was resisted at the north of the Bannu-Trans-Indus thrust sheet and the Potwar-Salt thrust sheet, in absence of ductile flow during the southward overthrusting. A narrow and high fold and thrust belt were formed by closely spaced and dominantly forward propagating thrusts. The other sheets progressed along an evaporitic base with high viscosity. Folds and thrusts opened wider because of the low resistance, which resulted in low relief. Due to the inconsistent movement, transfer zones perpendicular to the strike of the folds and thrusts formed between two adjacent sheets.

Fig. 6. Three topographic profiles across the (a) eastern, (b) central, (c) western sub-Himalayan thrust belt showing the variations of elevation. Traces of profiles are shown on the DEM map (d).
5. Conclusions

1. Nine topographic units are identified in the northwestern Himalayas of Pakistan using slope, drainage density, and drainage patterns extracted from DEM. The topographic units are consistent with the structures interpreted from Landsat images and published geological maps.

2. Combining topographic and structural data, three thrust sheets are recognized in the sub-Himalayan thrust belt, which is important to understand the lateral variation of structural geometry.

3. The viscosity model is favored to explain the formation of the lateral variation of topography at the thrust front. The southward thrusting caused by the Indo-Asian collision primarily controlled the trend of elevation variation.

4. The geomorphometric features identifying the topographic units are effective indicators for tectonic studies in the young tectonic regions with low elevation.

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