InSAR observation of the strike-slip faults in the northwest Himalayan frontal thrust system

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ABSTRACT

The Indo-Asian collision formed a series of north-dipping Cenozoic thrust faults in the Himalayan region, some of which are still active. The frontal thrust system in the northwest Himalayas has significant lateral variation, with the appearance of a reentrant along the thrust front. In the transfer zone of the structural reentrant, strike-slip faults dominate the deformation. To better understand the activities of the strike-slip faults in the northwest Himalayan frontal thrust system, interferometric synthetic aperture radar (InSAR) was used to measure the slip rate and direction. Radar image pairs with long time intervals are preferred to monitor the cumulative displacement caused by a low slip rate along the faults. The measurement across the Kalabagh fault zone indicates that ongoing slip rates are lower than those previously measured by conventional methods. The activities along the Kalabagh fault have segmental characteristics. Current deformation at the north segment mainly concentrates on the splay faults east of the Kalabagh fault. The southward decrease of displacement in the eastern fault block suggests that active deformation is mostly accumulated within the Potwar Plateau–Salt Range thrust wedge instead of at the thrust front. This work indicates that the Kalabagh fault zone linking the thrust fronts of the Salt Range and the Surghar Range plays an important role in accommodating the deformation in the Himalayan frontal thrust system caused by the Indo-Asian convergence.

INTRODUCTION

The Himalayas created by the Indo-Asian collision are a spectacular natural laboratory for studying various geologic processes related to mountain building (Yin, 2006). Since the major collision began in the latest Cretaceous—early Tertiary (Wells, 1984; Yeats and Hussain, 1987; Smith et al., 1994; Beck et al., 1995; Jaswal et al., 1997), the northward underthrusting of the Indian plate has built a series of thrust structures south of the suture zone between the Indian and Asian plates (Yin and Harrison, 2000). In the northwest Himalayas, thrusting and folding dominate the deformation. Strike-slip motion (McDougall and Khan, 1990; Khan and Glenn, 2006) makes the structures in this area complicated. Along the northwest Himalayan frontal thrust system, the Salt Range, the Surghar Range, and the Trans-Indus Range were uplifted abruptly over the Punjab foreland basin by progressive deformation associated with the continent-continent collision (Fig. 1). Pronounced structural reentrants indicate significant lateral variation of deformation along the ranges, which are still growing by progressive folding and thrusting (Blisniuk et al., 1998). Previous studies provided a detailed understanding of the stratigraphy, structure, and tectonic evolution of the frontal thrust system (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., 1998; Ahmad et al., 2005), but little is known about the faults that offset the frontal thrust system. Yeats et al. (1984) reported Quaternary deformation at Ghundi. McDougall and Khan (1990) estimated the average slip rate along the Kalabagh fault from the cumulative displacement of piercing points. Ahmad et al. (2005) studied the stratigraphy and structures.

Figure 1. Shaded topographic map of the northwest Himalayan frontal thrust system showing major structures. MMT—Main Mantle Thrust; MBT—Main Boundary thrust; MFT—Main Frontal thrust. The rhombus frame at the lower center of the map is the footprint of ERS-1/2 (European Remote Sensing) scene. DEM—digital elevation model.

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of the Kalabagh fault. However, the current slip rate and direction along the Kalabagh fault, important to understand the deformation pattern and fault activities, are not known.

Interferometric synthetic aperture radar (InSAR) is a powerful geodetic tool to monitor the surface deformation, and has been proven by numerous successful applications (Gens and Van Gendreren, 1996; Massonnet and Feigl, 1998). Although measuring creep on the faults is difficult using InSAR because of the small displacement signal, a few studies have proved that it is possible to observe the low rate of slip. Peltzer et al. (2001) studied the transient strain accumulation and fault interaction in the Eastern California shear zone using the InSAR measurement. Rosen et al. (1998) and Lyons and Sandwell (2003) measured the creep along the San Andreas fault using the InSAR technique. Wright et al. (2004) observed the slip rate on the major faults of western Tibet by InSAR. Taylor and Peltzer (2006) estimated the current slip rate on active conjugate faults in central Tibet. However, all of the applications focused on large scale, highly active strike-slip faults.

In this paper the InSAR technique is extended to observe the slip rate on the Kalabagh fault, a smaller fault that acts as an important transfer zone to adopt the lateral variations of structures in the northwest Himalayan frontal thrust system. By taking advantage of the previous geological studies together with the InSAR observations, the evolution model of the strike-slip faults in front thrust system is improved, and its significance for the thrust system is recognized and discussed.

DATA AND METHODS

Data Sets

We used 22 scenes of radar images acquired by ERS-1/2 (European Remote Sensing) satellites between 1992 and 1999 in this study (Table 1). These data cover the entire Kalabagh fault zone, western margin of the Potwar Plateau, southern part of the Kohat Plateau, and Kalabagh reentrant of the Punjab foreland basin (Fig. 1). An interferogram can be computed for any combination of two images named as an image pair; its quality is dominated by the coherence between the master image (reference image) and the slave image. Image pairs with low correlation were excluded from the candidate list based on the coherence evaluation. The image pairs showing good coherence may include large atmospheric variation, which can lead to misinterpretation. Although there are some algorithms to reduce the atmospheric variation in InSAR processing, it is difficult to completely remove atmospheric noise from the interferogram. A straightforward approach is to remove those images with large atmospheric variation at the beginning of InSAR processing by pair-wise comparison of interferograms, assessing the atmospheric variations for a specific radar acquisition without much quantitative analysis (Massonnet and Feigl, 1995). From the comparisons of highly correlated and short-time-interval interferograms, the images with large atmospheric variation were removed from the candidate list. To obtain an accurate unwrapped phase from the complex interferogram, a small perpendicular baseline (<500 m) is needed. At the same time, a long time interval of the image pair is preferred to measure the cumulative displacement caused by the low slip rate along the faults. Considering all these factors, two images acquired on 28 November 1992 and 20 April 1999 were chosen to generate an image pair with good coherence, a small perpendicular baseline (86.8 m), and a long time interval (~6.4 yr).

Radar Interferometry

SAR beams microwaves and collects the reflected signal from the surface. Recorded data include both magnitude and phase information of the radar echo. Range distance information is encoded in phase. If we know the accurate geometry between satellite and surface, and topography, the range displacement of the surface can be deciphered from two SAR images. SAR interferometry uses the phase information to calculate the differential distance from satellite to ground surface between two repeat-pass acquisitions over the same region. The resulting difference of phase is an interferogram, which is a pattern of fringes containing information about differential range distance. This technique is also called differential interferometric synthetic aperture radar (DInSAR); a differential interferogram is computed at the same scene over two repeat-pass acquisitions. DInSAR techniques are classified based on the numbers of repeat passes, as 2-pass, 3-pass, and 4-pass DInSAR. We use the 2-pass DInSAR technique with a digital elevation model (DEM) acquired by the Shuttle Radar Terrain Mission (SRTM) to monitor the location and the magnitude of ground deformations resulting from fault activities. The basic idea of 2-pass differential interferometry is that a reference interferogram corresponding to surface topography is simulated based on the DEM and is subtracted from the complex interferogram of an image pair. The use of a DEM to derive the topographic phase reduces phase unwrapping problems. In addition, 2-pass DInSAR has fewer limitations on the data selection compared to 3-pass and 4-pass techniques. It is very robust in generating complex differential interferograms.

Interferometry Processing

Radar interferometry processing was performed with the GAMMA software package developed by GAMMA Remote Sensing and Consulting AG. In 2-pass DInSAR processing, DEM data are needed to simulate the topographic phase. In this study, a DEM was used not only to remove the topographic phase from

TABLE 1. ERS-1/ERS-2 SATELLITE IMAGES IN THE KALABAGH AREA USED FOR INTERFEROMETRIC PROCESSING

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Acquired date</th>
<th>Orbit (descending)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS-1</td>
<td>2 May 1992</td>
<td>4158</td>
</tr>
<tr>
<td>ERS-1</td>
<td>6 June 1992</td>
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<td>ERS-1</td>
<td>19 September 1992</td>
<td>6162</td>
</tr>
<tr>
<td>ERS-1</td>
<td>26 November 1992</td>
<td>7164</td>
</tr>
<tr>
<td>ERS-1</td>
<td>2 January 1993</td>
<td>7665</td>
</tr>
<tr>
<td>ERS-1</td>
<td>22 May 1993</td>
<td>9669</td>
</tr>
<tr>
<td>ERS-1</td>
<td>26 June 1993</td>
<td>10170</td>
</tr>
<tr>
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<td>25 March 1996</td>
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</tr>
<tr>
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</tr>
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<tr>
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<td>21 September 1996</td>
<td>37568</td>
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<td>22 September 1998</td>
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<td>41576</td>
</tr>
<tr>
<td>ERS-2</td>
<td>29 June 1999</td>
<td>21903</td>
</tr>
</tbody>
</table>

Note: The Track for each image is Track 5, and the Frame for each image is Frame 2934, ERS—European Remote Sensing.
the complex interferogram, but also to reduce the coregistration errors in the rugged area. The complex interferogram was calculated from the registered image pair. To unwrap the interferogram and reduce noise, the following processes were adopted: (1) estimate the baseline with highly precise Delft orbit parameters, obtained from the Delft Institute for Earth-Oriented Space Research; (2) simulate the topography phase in SAR geometry based on baseline information and DEM data; (3) remove the topographic phase from the complex interferogram; (4) reduce random noise using an adaptive filter (Goldstein and Werner, 1998); (5) unwrap the interferogram with a minimum cost flow (MCF) and triangulation algorithm (Costantini, 1998; Eineder et al., 1998); and (6) perform linear regression of atmospheric phase with respect to height because of the vertical stratification of the troposphere. The unwrapped differential phases in the interferogram correspond to the displacement along the SAR look vector (line of sight, LOS). It can be converted to ground displacement by multiplying by 4πr, then dividing by the wavelength of the ERS-1/2 radar satellites (5.6 cm).

The ground displacement map generated from 2-pass InSAR was geocoded into the Universal Transverse Mercator (UTM) projection system by assigning pixels within the map to ground coordinates. The look-up table, which is a byproduct of the transferring of a DEM from map coordinates to radar coordinates in the InSAR processing, was used to allocate the pixels. In this process, the interferogram pixels were resampled with a bilinear interpolator and projected to the corresponding output map coordinate system. Further analyses of the displacement in the projected geographic coordinate system were conducted on the geocoded interferogram.

RESULTS AND ANALYSIS

Two images used to generate the interferogram were acquired on 28 November 1992 and 20 April 1999. The result represents the cumulative displacement during this period along the Kalabagh fault zone in the radar LOS reference (Fig. 2). In this figure, blue indicates 40 mm LOS motion (away from the satellite or northwest), and red indicates 40 mm LOS motion (toward the satellite or southeast). The lack of a sharp jump across the fault indicates that the creep rate is low. To look quantitatively at the spatial distribution of slip along the faults, we created four swaths across the Kalabagh fault zone at four different places. The northernmost swath is located at the northern extension of the Kalabagh fault, and is divided into two polygons by the fault. North of the Indus River, the Kalabagh fault zone is composed of four branch faults: the Cemetery fault, the Kalabagh fault, the Ainwan fault, and Dinghot fault from west to east. The main fault, the Kalabagh fault, is located along the straight Chisal Algd River, which flows southward into the Indus River at a right angle. The swath across the northern part was divided into five polygons by the four faults. Each polygon represents one block in the fault zone. The other two swaths across the middle and southern parts were divided into two polygons on two blocks along the fault. Some places, especially in the foreland basin, have low coherence because of the long time span of the image pair used in this study, and agriculture. Simple profiles across the fault cannot reflect the variations of displacement along the fault. We calculated the average displacement in the polygons to represent the motion in the corresponding fault blocks; this process can reduce some irregular variations among the pixels in each polygon. The mean displacement in each polygon (Fig. 3) is in the direction along the LOS.

Since the displacement measurement is in the radar LOS reference, we can project it to Cartesian coordinate system on the horizontal surface based on the satellite orbit geometry:

\[
D_{\text{LOS}} = \begin{bmatrix} D_x \\ D_y \\ D_z \end{bmatrix} = \begin{bmatrix} \cos \alpha \sin \theta \\ \sin \alpha \sin \theta \cos \theta \end{bmatrix},
\]

where \(D_{\text{LOS}}\) is the displacement toward the satellite along LOS, \(\theta\) is the incidence angle, which is 23º from vertical at the center of the SAR frame and perpendicular to ERS flight direction, and \(\alpha\) is the azimuth of the LOS vector (from the origin point to the satellite), which is \(-103^\circ\) for descending ERS tracks. \(D_x, D_y, D_z\) are component vectors of the

Figure 2. Interferogram showing the displacement in line of sight (LOS) in the Kalabagh area from 28 November 1992 to 20 April 1999. Blue indicates 4 cm LOS motion (away from the satellite or northwest), and red indicates 4 cm LOS motion (toward the satellite or southeast). Main faults in the Kalabagh fault system: F1—Cemetery fault; F2—Kalabagh fault; F3—Ainwan fault; F4—Dinghot fault.
deformation in the north, east, and vertical directions, respectively.

To restore the three components to the natural deformation along the fault plane, fault geometry must be considered to calculate strike-slip and/or dip-slip values. North of the Indus River, the strike of the Kalabagh fault is N15°W (McDougall and Khan, 1990). Field observations have provided evidence that the Kalabagh fault is nearly vertical (Yeats et al., 1984). The elevation of two blocks is almost the same along the Chisal Algard River, where the northern segment of the Kalabagh fault is located. Thus, the creep along the northern segment of the Kalabagh fault can be assumed as purely strike-slip motion.

The relationship between the LOS and strike-slip motion is:

$$D_{LOS} = D_s (\sin \alpha \sin \theta \sin \phi + \cos \alpha \sin \theta \cos \phi) = 0.1834D_y,$$  \hspace{1cm} (2)

where $\phi$ is the azimuth of the horizontal displacement parallel to Kalabagh fault (165°), and $D_s$ is the magnitude of horizontal strike-slip motion.

To compare the displacement in different fault blocks, we converted the LOS displacement of all blocks into strike-slip motion along the Kalabagh fault. The slip rate was calculated by cumulative horizontal strike-slip motion ($D_s$) divided by the time interval (6.4 yr). Figure 4 shows the different slip rate of the fault blocks at the northern Kalabagh fault zone. The western block of the Kalabagh fault moved southeastward at a rate of 5.3 mm/yr from 28 November 1992 to 20 April 1999. The eastern block of the Kalabagh fault moved southeastward at a rate of 3.4 mm/yr. The movement of the fault blocks increases eastward, except the western block of the Kalabagh fault, which moves on a salt diapir. It indicates that the Potwar Plateau at the east side of the fault zone moved southward faster than the west side. The entire fault zone shows right-lateral strike-slip motion. At the northern end of the fault zone, the interferogram has uniform color, indicating no differential displacement there. The quantitative analysis results suggested that the average displacements of two polygons separated by the extension line of the Kalabagh fault are almost the same.

The Kalabagh fault extends southward from the Indus River to the front of the Salt Range thrust. The west block is the Punjab foreland basin, with low elevation (<200 m) and gentle relief. Across the fault, the elevation jumps abruptly to 700 m (Chen and Khan, 2009). This part is divided into two segments by a small step of the thrust fault near Ghundi. The fault from Khairabad to Ghundi is the middle segment of the Kalabagh fault, and south of Ghundi is the southern segment. These two segments are not pure dextral strike-slip faults. Along the middle segment, field observations near Khairabad have shown that the fault plane dips 40°E. On the southern segment, the fault has been subjected to compressional deformation (Yeats et al., 1984; Ahmad et al., 2005). The relationship between the LOS displacement and strike-slip motion is much more complicated because the slip direction is not clear along the fault plane.

If we simply convert the LOS deformation to pure strike-slip motion, the computed value will be larger than the real value. The displacement value in the LOS reference (Fig. 3) shows that the displacement is decreasing at the east side of the Kalabagh fault.

**DISCUSSION**

Previous studies of the Kalabagh fault by McDougall and Khan (1990) indicated a minimum average displacement rate of 7–10 mm/year near the Indus River since 2 Ma; they also noticed that the total displacement is reduced northward in the Kalabagh fault zone, where strike-slip faults merge with the north dipping thrust faults. Our results show that the current displacement rate is lower than that suggested in McDougall and Khan (1990). In addition, the magnitude of displacement varies in the fault zone. In the north part, the fault zone consists of four splay faults. The blocks along the Aminwan and Dinghot faults move faster than other blocks, indicating that the current deformation is mainly accumulated on these branch faults, which may be caused by the internal deformation in the Potwar Plateau after the development of the Kalabagh fault. The activity along the Kalabagh fault decreased after the formation of splay faults east of it. The LOS interferogram (Fig. 2) shows no offset along the northward extension of the Kalabagh fault. This suggests that the faults die out in the north. From Khairabad to Ghundi, the displacement in LOS is 5.7 mm; this is lower than the northern segment. It may be caused by the small thrust step east of Ghundi, which acts as an obstruction to slow down the southward movement. The southern segment extends from Ghundi to the Salt Range thrust. Its displacement in LOS decreases to 3.7 mm, similar to the global positioning system observations in the Salt Range (R. Bilham, 2008, personal commun.). The southward decrease in displacement along the eastern fault block of the Kalabagh fault suggests that current deformation at the front of the Main Frontal Thrust is smaller than the internal deformation in the Potwar Plateau.

The factors influencing the evolution of the Kalabagh fault and northwest Himalayan frontal thrust system have been long argued. Butler et al. (1987) pointed out the importance of the salt in the development of the thrust geometry and structural style in the frontal thrust system. McDougall and Khan (1990) suggested that the configuration of the basement was the primary structural control on the Kalabagh fault zone. Blisniuk et al. (1998) suggested the foreland normal fault control on the thrust front development. Cotton and Koyi (2000), Costa and

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**Figure 3. Average displacement for different fault blocks.** The displacement is in line of sight toward the satellite. The fault block numbers are shown in Figure 2.

**Figure 4. Rate of movement for different fault blocks in the northern segment of the Kalabagh fault system.** The direction of movement is 165° on the ground surface. See Figure 2 for the fault block numbers.
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Vendeville (2002), and Schreurs et al. (2002) modeled the thrusting and folding over a viscous evaporitic décollement and brittle detachment, and found that the thrusting propagated in a forward sequence on brittle detachment. The thrust front was the youngest structure. In contrast, the thrusting did not systematically propagate forward in a viscous décollement. The thrust front reached to the region missing a viscous décollement soon, and was followed by folding or thrusting within the thrust wedge. Our observations are in concordance with the analog modeling results. The InSAR measurement indicates that the current internal deformation is larger than the frontal deformation within the Potwar Plateau–Salt Range thrust wedge, which is moving on a thick salt décollement. The Kohat-Surghar thrust wedge has less southward propagation of thrusting due to the large resistance from the brittle detachment. The different deformation styles are supported by the results of geomorphic and tectonic analyses (Chen and Khan, 2009).

Several models explain the responses of major collision events between the Indian and Asian plates. For example, thin viscous models emphasize crustal thickening and shortening (England and Houseman, 1989), and extrusion tectonics models explain shortening along continental-scale transform faults (Molnar and Tapponnier, 1975; Tapponnier et al., 1990; Harrison et al., 1992). However, the detailed internal kinematics and geometry of extrusions are poorly documented because the configurations of many structures, including strike-slip faults that accommodate the extrusions, have not been recognized or adequately mapped. In addition, variations of structural geometry are widespread along the Himalayan orogen. This geometry has important implications for the deformation, exhumation, and sedimentary history of the entire orogen (Yin, 2006). This work on the strike-slip fault in the northwest Himalayan Frontal thrust system is helpful to understand its evolution and will contribute to understanding the three-dimensional deformation history of Himalayan collision. Our estimated rate of displacement along one of the major strike-slip faults in the sub-Himalayan thrust belt of Pakistan can be compared with data on other strike-slip faults to evaluate their overall tectonic significance in accommodating the shortening in Indo-Asian collision.

**CONCLUSIONS**

According to the variations of slip rate, the Kalabagh fault can be divided into three segments with different structure activities: northern, middle, and southern segments.

Strike-slip motion dominates the style of deformation at the northern segment. The current deformation is concentrated on the splay faults in the northern segment of the Kalabagh fault.

Unlike previous work, which suggested the thrust front as the most active unit, our work suggests that internal deformation is greater than that at the thrust front. Salt is the primary factor controlling the styles of deformation.

This work indicates that the Kalabagh fault zone, linking the thrust fronts of the Salt Range and the Surghar Range, plays an important role in accommodating the deformation in the Himalayan frontal thrust system caused by the Indo-Asian convergence.

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