

Geomorphic response to an active transpressive regime: a case study along the Chaman strike-slip fault, western Pakistan

Shams Ul-Hadi,^{1*} Shuhab D. Khan,¹ Lewis A. Owen² and Abdul S. Khan³

¹ Earth and Atmospheric Sciences, University of Houston, Houston, TX, USA

² Department of Geology, University of Cincinnati, Cincinnati, OH, USA

³ Center of Excellence in Mineralogy, University of Balochistan, Quetta, Pakistan

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*Correspondence to: Shams Ul-Hadi, Earth and Atmospheric Sciences, University of Houston, Houston, TX 77004, USA. E-mail: sulhadi@mail.uh.edu

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ABSTRACT: The Chaman left-lateral strike-slip fault bounds the rigid Indian plate boundary at the western end of the Himalayan-Tibetan orogen and is marked by contrasting topographic relief. Deformed landforms along the fault provide an excellent record for understanding this actively evolving intra-continental strike-slip fault. The geomorphic response of an active transpressional stretch of the Chaman fault was studied using digital elevation model (DEM) data integrated with Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Visible and Near Infrared/Short Wave Infrared (VNIR/SWIR) and images from GeoEye-1. Geologic and geomorphic mapping helped in reconstructing the Late Quaternary landscape history of this transpressional strand of the Chaman strike-slip fault and the associated Spinatizha thrust fault in western Pakistan. Topographic analysis of a part of the transpression (the thrust bounded Roghani ridge) revealed northward growth of the Spinatizha fault with the presence of three water gaps and two corresponding wind gaps. Geomorphic indices including stream length-gradient index, mountain front sinuosity, valley floor width to valley height ratios, and entrenchment of recent alluvial fan deposits were used to define the lateral growth and direction of propagation of the Spinatizha fault. Left-lateral displacement along Chaman fault and uplift along the Spinatizha fault was defined using topographic analysis of the Roghani ridge and geomorphic mapping of an impressive alluvial fan, the Bostankaul fan. The landforms and structures record slip partitioning along the Indian plate boundary, and account for the convergence resulting from the difference in the Chaman fault azimuth and orientation of the velocity vector of the Indian plate. Copyright © 2012 John Wiley & Sons, Ltd.

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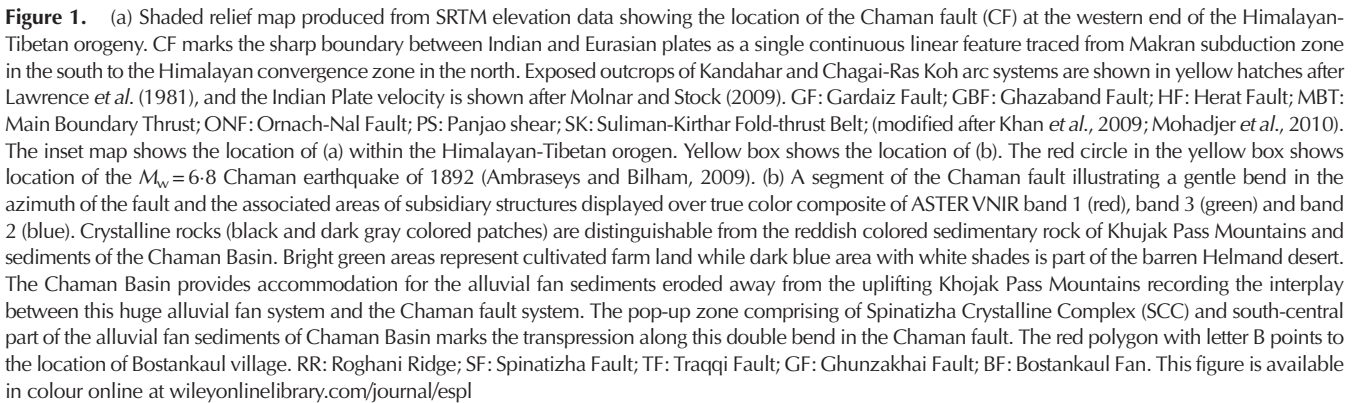
KEYWORDS: Chaman fault; transpression; ASTER; geomorphic indices; remote; sensing

Introduction

The interaction between active tectonics and fluvial systems is a key element for understanding Earth's dynamic surface. How evolving thrusts and folds affect co-evolving fluvial systems and how fluvial systems influence uplifting blocks have been studied both in the field and modeled in laboratories (Bernal *et al.*, 2004; Pearce *et al.*, 2004; Miller and Slingerland, 2006; Hilley and Arrowsmith, 2008). These studies are helpful for understanding the kinematics and mechanical evolution of active structures and regional tectonics. Furthermore, study of the characteristic landforms and drainage patterns around evolving geologic structures such as faults and folds has been used to infer direction and lateral growth of the geologic structures (e.g. Jackson *et al.*, 1996; Keller *et al.*, 1999; Azor *et al.*, 2002). The geometry and growth rate of geologic structures, interaction of multiple geologic structures, inherited topography, and characteristics of the fluvial system are the main variables that reflect this interplay (Burbank *et al.*, 1996). With lateral fault propagation, the fault lengthens in the direction of growth by lateral tip propagation

and/or fault linkage (Densmore *et al.*, 2007), which are expressed by the development of distinct topography and landforms (Cowie and Scholz, 1992; Jackson *et al.*, 1996). The geomorphology in tectonically active regimes is therefore a powerful tool to assist in differentiating more active segments of geologic structures and can help in establishing the structural evolution of a region. The distinction between active and more passive geologic structures can be achieved through detailed studies of geomorphic indices such as stream length-gradient index, mountain front sinuosity, valley floor width to height ratios and entrenchment of Quaternary deposits, and coeval drainage pattern that encompass a fault or fold (Keller and Pinter, 2002; Keller and DeVecchio, in press).

Yet, there are few geomorphic studies of evolving thrusts and folds (Cox *et al.*, 2001; Francesco and Marta, 2011). We therefore examine the geomorphic development of actively evolving thrusts within a restraining bend along the left-lateral Chaman strike-slip fault system in western Pakistan (Figure 1) to understand the geomorphic and structural evolution of a zone of transpression within an active plate boundary, which in this case



constrained slip rate of 24 to 35 mm/yr accounts for a total displacement of 460 ± 10 km along the Chaman fault system since the inception of strike-slip movement at $\sim 20\text{--}25$ Ma along the western collision boundary between Indian and Eurasian plates (Beun *et al.*, 1979; Lawrence *et al.*, 1992). Recent sporadic global positioning system (GPS) studies reveal 18 ± 1 mm/yr slip rate along the fault (Mohadjer *et al.*, 2010), while Interferometric Synthetic Aperture Radar (InSAR) analysis along a part of the fault suggests slower movement at ~ 8 mm/yr (Furuya and Satyabala, 2008). Historical and recent instrumental seismic record along the northern segment of the Chaman fault that runs through Pakistan (Figure 1a) shows a gap in major seismic activity, with the exception of 1892 where the moment

magnitude scale (M_w) was 6.8 for the Chaman earthquake. Ambraseys and Bilham (2003) argue that this seismic gap is not representative of the long-term activity for the region and have forecasted an overdue $M_w = 7$ event where Late Quaternary deformation along the Chaman fault system is evident from the deformed alluvial fan deposits, deflected drainage patterns and pressure ridges (Lawrence *et al.*, 1992).

The geomorphic expression of the Chaman fault system is evident throughout its entire length. This is most apparent at the contact between the Quaternary deposits to the west and the meta-sediments of the Late Eocene to Oligocene Katawaz Basin (Carter *et al.*, 2010) to the east of the fault (Ruleman *et al.*, 2007); exceptions are where the fault brings slivers of the Late Jurassic to Cretaceous arc rocks west of the fault zone in contact with the meta-sediments (Lawrence *et al.*, 1981). The segment of the Chaman fault that runs through western Pakistan represents the southern subsidiary system of the main shear zone (Figure 1b). This segment is represented by linear zones that are < 1 km wide to about 20 km wide zones of multiple strands with conjugate Riedel shears and thrust fault systems that merge with the main fault (Lawrence and Yeats, 1979; Wheeler *et al.*, 2005). The overall trend of the fault varies from N10°E to N35°E throughout its length due to the presence of many double bends in the fault (Lawrence *et al.*, 1992). An example of a restraining bend is present between 30–50° N and 30–75° N where the main Chaman fault is joined by the Traqqi and Ghunzakhai faults, which are two subsidiary faults west of the main trace of the Chaman fault (Lawrence and Yeats, 1979). The trace of the main stretch of the Chaman fault in this area changes from ~N17°E to ~N28°E north of the village of Bostan-kaul (Figure 1b, 30–75° N/66–48° E). The Chaman fault continues along that trend until ~30–35° N, where the trend then becomes ~N15°E. An incipient transpression, smaller in size, but similar in geometry to the restraining bends reported elsewhere along the fault (Ruleman *et al.*, 2007), is present to the west of this curved segment of the Chaman fault.

The transpressional bend has resulted in a pop-up block composed mostly of crystalline basement complex, and represents a N30°E trending ridge that is > 50 km long and ~10 km wide, but tapers out to the north. The crystalline basement complex is in contact with the Katawaz Basin sediments on its eastern side and is emerging from below the Quaternary alluvial fan sediments of the Chaman Basin. This uplifted block is unusual because the long-term sense of vertical displacement is east side up (Lawrence *et al.*, 1992), resulting in the uplift of the eastern side Katawaz Basin sediment against the Quaternary alluvium along the western side of the fault. The present landscape is a consequence of the time-integrated interactions between the Chaman fault system and its associated structures, and the extensive bajada that originates from the Khojak Pass Mountains.

The Spinatizha Crystalline Complex, which comprises a part of the study area, is in the northern part of the pop-up zone and is composed of crystalline basement rocks that are not seen anywhere else in Pakistan west of the Chaman fault. This was mapped by Lawrence *et al.* (1981; see Supplementary Data, Figure s1) who divided it into: (1) the Spinatizha Metamorphic Complex; (2) the Bazai Ghar Volcanics; (3) the Khawja Amran Intrusive Series; and (4) a sedimentary sequence of unknown affinity. A wide range of rock types mostly west of the Chaman fault, similar to the widespread Late Jurassic to Cretaceous arc rocks present elsewhere in the region, were characterized on the basis of geochemical and petrographic analysis by Lawrence *et al.* (1981). Lawrence *et al.* (1981) interpreted the Spinatizha Crystalline Complex to be a sliver detached either from the Kandahar or Chagai arcs, and subsequently uplifted along the Chaman fault (Figure 1a). The Kandahar and Chagai arcs are composed of pre-Indo-Eurasian collision granitic and andesitic

rocks that formed on the southern edge of the central Iran, Lut and Afghan micro-continents extending to northeast as an oceanic arc (Lawrence *et al.*, 1981; Treloar and Izatt, 1993). This study provides insights into the evolution of this transpression along the Chaman fault and its impact on the associated evolving landscape.

Datasets and Methods

DEM data extracted from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument were used for topographic analysis, to calculate geomorphic indices and for geological/geomorphic mapping. In addition, high resolution GeoEye-1 image data covering ~50 km² of the study area was used to help confirm the results derived through ASTER data. High-resolution images from Google Earth database were also utilized for geomorphic analysis.

The ASTER instrument, developed by National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy Trade and Industry (METI) formerly known as Ministry of International Trade and Industry (MITI), is onboard the Earth Observing System (EOS) TERRA satellite launched in December 1999, and it records Visible and Near Infrared (VNIR), Short-wave Infrared (SWIR) and Thermal Infrared (TIR) portion of the solar radiation in 15 spectral bands with wavelength ranges 0.53–0.86 µm, 1.60–2.43 µm, and 8.13–11.65 µm, respectively (Yamaguchi *et al.*, 1998; Abrams *et al.*, 2004; Table s1). Four VNIR bands at 15 m resolution (including the backward-looking telescope in band 3 providing data as band 3b for digital stereo-pair/DEM generation), six SWIR bands at 30 m resolution, and five TIR bands at 90 m resolution record spectral data with swath widths of 60 km. ASTER data were selected for use in this study because of its relatively high spectral (15 m in the VNIR bands) and comprehensive (15 bands covering 0.52 to 11.65 µm) resolution.

GeoEye-1 is a commercial satellite launched on September 6, 2008 that can image Earth's surface in any direction in panchromatic mode with a ground resolution of 0.41 m and multi-spectral mode with a ground resolution of 1.65 m (<http://www.geoeye.com>). Although the spectral resolution of 450 to 800 nm (panchromatic one band) and 450 to 920 nm (multi-spectral including three visible and one near infrared) is restricted to VNIR, however, the high ground resolution favors large-scale geomorphic mapping. The ground accuracy of 4 to 6 m makes the GeoEye-1 data as one of the most accurate sub-meter sized imagery available (Table s3).

Geological/geomorphic mapping

ASTER bands combinations, ratios, and principal component analysis (PCA) applied to two ASTER granules (L1B data) acquired on June 14, 2007 were used for lithological discrimination and structural interpretation within the study area (please see Supplementary Data for scenes details; Table s2 for ASTER data products). We selected these scenes because of the absence of clouds and the absence of snow on mountains when they were acquired. Further, the study area is a part of the Helmand Desert with little vegetation cover. ASTER data product L1B (abbreviated as AST_L1B) is registered radiance at the sensor, with surface reflectance as VNIR and SWIR, and thermal emissivity as TIR (Abrams *et al.*, 2004). Log residual algorithm, which reduces noise from topography, instrument and sun (Khan and Mahmood, 2008) was applied to the AST_L1B to account for any impacts of the topography on the data quality. The Darkest Pixel (DP) atmospheric correction method, which is useful for VNIR and SWIR ASTER data

(Hadjimitsis, *et al.*, 2010) was applied to the data in this study using DARK_SUB_DOIT extension of ITT Envi-4.8. However, no apparent deviation from the original data was encountered after DP correction and we preferred to use the original data to avoid any undesired changes to the original image data as a consequence of making this correction.

Among the several band combinations that were considered, it was found that VNIR band 1, band 3, and band 2 combination displayed as red-green-blue (RGB) color composite was better suited to examine the general geologic and land cover overview of the area (Figures 1b and s2). This bands combination reflects a close to true ground color combination and is helpful in defining regional scale rock suites, landforms, and lineaments (Kalinowski and Oliver, 2004).

Band ratios enhance the spectral differences between bands, reduce the effects of topography by dividing one spectral band by another, and produce an image with relative band intensities. Each ratio displays spectral contrast of specific absorption features (Rowan and Mars, 2003). When displayed as color composites these combinations of different band ratios provide useful information about the surface features and materials. ASTER band ratios have proved useful to suppress brightness differences related to grain size variations (Khan and Glenn, 2006) and the mineral/rock content of a surface (Kalinowski and Oliver, 2004). We examined several band ratios, among which the combination of 5/7-5/1-5/4, 4/5-6/7-3/4, and 3/4-4/5-6/7 were found to be most useful for broad mapping and differentiating sediments and sedimentary rocks from metamorphic and intrusive igneous rocks (Figures 2 and s3).

Multi-spectral data bands are normally highly correlated to each other, which reduces contrast in output images. PCA transforms multi-spectral data bands to produce uncorrelated output bands by finding a new set of orthogonal axes that have their origin at the data mean and that are rotated to maximize the data variance. The output data bands have segregated noise components and reduced data dimensionality (Kalinowski and Oliver, 2004). The percentage of data variance decreases from first PCA bands towards the last PCA bands, which are noisier and have little variance. PCA bands produce more colorful composite images than the uncorrelated spectral color composite images (Richards, 1999).

The ASTER VNIR and SWIR data (the first nine bands) from two scenes were transformed using PCA tool of ITT Envi-4.8 software. The PCA VNIR bands transformation was most useful in classifying lithology throughout the study area because of the higher values of data variance. The PCA first forward transformation combinations of RGB 1-3-2 and 3-2-1 were used in the final classification (Figures 3b and s4). The ASTER PCA allowed Quaternary deposits to be differentiated into four major alluvial fan units, and to map the sharp contacts between alluvial fan sediments and crystalline bedrock. The PCA was also helpful in differentiating alluvial fan sediments from sedimentary bedrock. The surface expression of the loose sediments as compared to the lithified bedrock and the presence of hydroxyl (OH⁻) content of the weathered clays and presence of water content (Kalinowski and Oliver, 2004) in the alluvial deposits in the study area provide a possible explanation for the contrast on the PCA images (Figure 3b). These two PCA bands combinations were specifically useful in mapping the individual rock units within the Spinatizha Crystalline Complex.

We were able to refine the rock units mapped by Lawrence *et al.* (1981, Figure s1) using the remote sensing. This helped us identify and map several additional structural strands of the Chaman fault that had not previously been recognized (Figure 4). PCA was especially effective in differentiating the previously undifferentiated metamorphic and intrusive rock units in the central part of the mapped area. The ASTER band ratios

and PCA were also helpful in examining the drainage pattern and mapping offset drainages within the study area. That in turn helped in mapping the Spinatizha fault and strike-slip lineaments present between the Spinatizha and Chaman faults.

DEM extraction and geomorphic indices

A DEM was extracted using OrthoEngine Module of Geomatica 10 from a single ASTER image (L1A granule, Table s2) acquired on June 14, 2007 that covered the northern part of the study area (please see Supplementary Data for details of individual scenes). Occasional holes within the dataset in the DEM were filled through interpolation of the surrounding data. The DEM was exported as Geotiff into the ESRI ArcGIS software package for topographic analysis, for drainage extraction (Figures 3a and s4) and to calculate geomorphic indices.

Stream length (SL)-gradient index

The SL index provides a measure of the erosional resistance of the rocks involved and relative intensity of active tectonics (Azor *et al.*, 2002; Keller and Pinter, 2002) and is defined as:

$$SL = (\Delta H / \Delta L) * L \quad (1)$$

where L is the total length of the channel calculated upstream from the drainage divide to the midpoint of the reach to where the index is calculated and $\Delta H / \Delta L$ is the channel gradient of that particular reach of the stream (with ΔH being the change in elevation and ΔL the length of the reach). SL is sensitive to channel slope, which is a result of tectonic activity, stream power and/or rock resistance in an area. SL values for and around the Roghani ridge were calculated using ASTER DEM for major streams identified during field visits and from ASTER PCA.

Valley floor width to valley height ratio (V_f)

The valley floor width to valley height (V_f) ratio is a measure of the valley floor width (V_{fw}) to the elevation divides at the right (E_{rd}) and left (E_{ld}) of the valley at a set distance from the mountain front (Keller and Pinter, 2002), and is calculated as:

$$V_f = 2 V_{fw} / [(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})] \quad (2)$$

where E_{sc} is the average elevation of the valley floor. Higher V_f values correspond to flat-floored valleys representing low tectonic activity in contrast to low V_f values for V-shaped valleys, which are related to rapidly uplifting mountain ranges with higher valley incision (Azor *et al.*, 2002). The V_f values for three antecedent streams across the Roghani ridge were measured using the DEM generated from the ASTER data.

Mountain-front sinuosity (S_{mf})

Mountain-front sinuosity (S_{mf}) essentially relates to the interaction between erosion and tectonics (Azor *et al.*, 2002; Keller and Pinter, 2002). Active tectonics tends to generate a straight mountain front while erosional processes cut embayments into a mountain front that increases the sinuosity. The S_{mf} values were calculated as the ratio between the length of the mountain front (L_{mf}) and the straight-line length (L_s) approximately parallel to the mountain front such that:

$$S_{mf} = L_{mf} / L_s \quad (3)$$

More active tectonics results in lower S_{mf} values. ArcGIS was used in measuring the mountain front and the corresponding front parallel line.

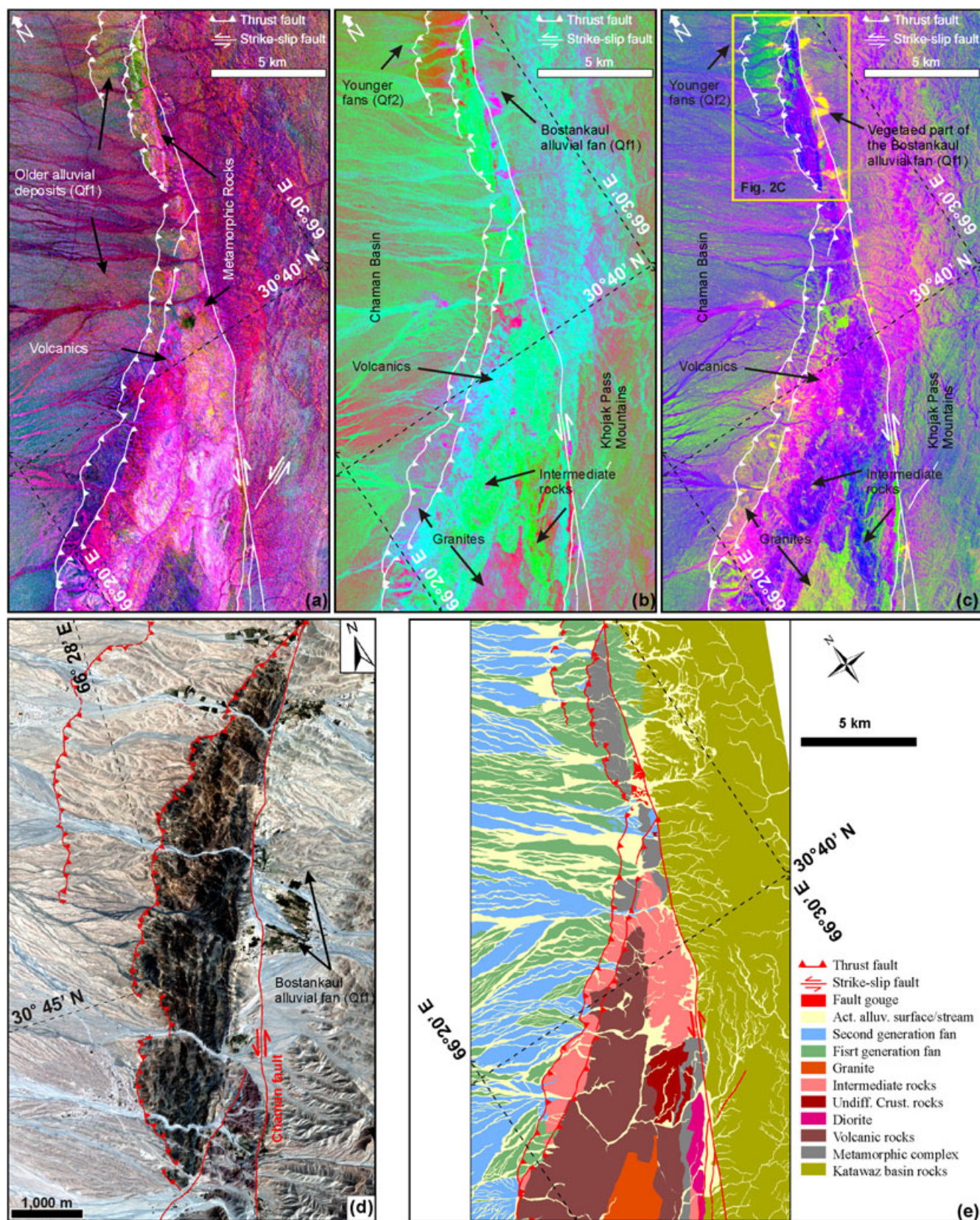


Figure 2. ASTER band ratios (a) 5/7-5/1-5/4, (b) 4/5-6/7-3/4, and (c) 3/2-4/5-6/7 displayed as RGB to delineate different rock types and structural lineaments. The interpreted rock units match closely with the previously mapped lithologies (Figure s1). The band ratios in (a) differentiate among different alluvial fan generations based on presence of water content (OH^-) in the younger surfaces from the older dry surfaces, while band ratios in (b) and (c) use clay content and texture of the surfaces. In (b) weathered crystalline rocks and younger fans (dark green colors) stands out different from the intact granitic bodies (pink), bluish colored volcanic and sedimentary bedrock of the Khojak Pass Mountains. Band ratios in (c) differentiate among weathered (pale green with purple shades) and intact granitic (yellowish green) rocks, volcanic (pink) and intermediate (dark blue with slight purple mixing) rocks, and vegetated (yellow) from non-vegetated (a whole range from dark purple to pinkish) alluvial surfaces. For the location see Figure 1b. (d) GeoEye-1 multi-spectral bands 1 (red), 2 (green), and 3 (blue) (with ground resolution of 1.65 m) are displayed as color composite RGB image of the Roghani ridge and Bostankaul alluvial fan. A part of the Bostankaul alluvial fan has displaced left-laterally $\sim 1150 \pm 55$ m along a strand of the Chaman fault. The evolving Roghani ridge records stream deflection and quenching as wind and water gaps. (e) A part of the map in Figure 4 showing structural and geological interpretations based on analyses of images shown in (a)–(d), geological map of Lawrence *et al.* (1981), and field data from this study. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

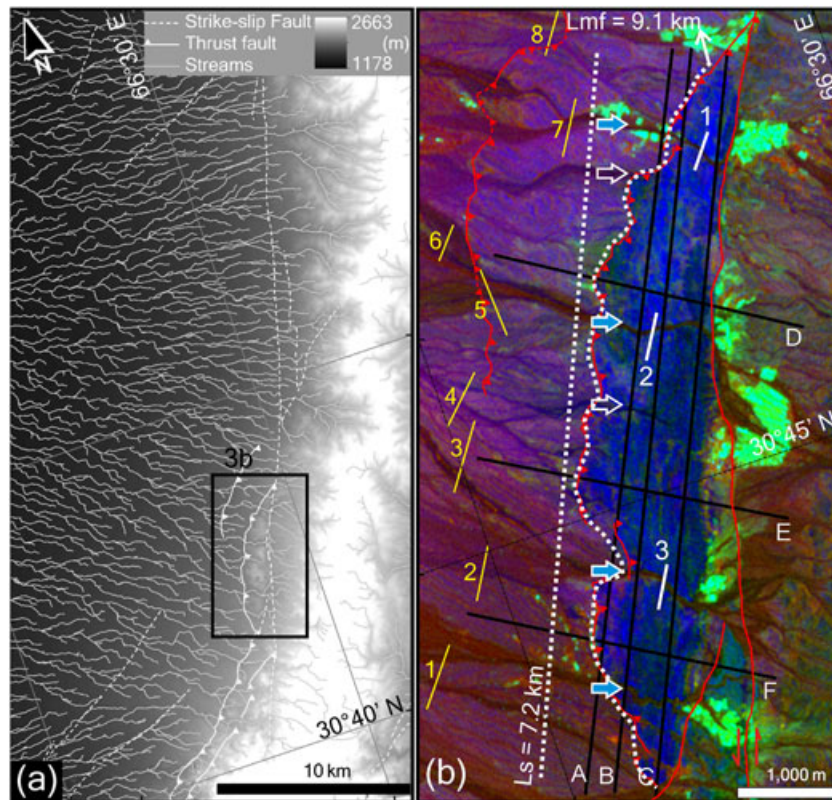


Figure 3. (a) Absolute DEM derived from 15 m ASTER VNIR 3 N and 3B stereo images using 19 Ground Control Points (12 GPS ground points and five points from the topographic maps) and 15 Tie Points (mostly in parts of the image area where no elevation data was available) with average root mean square (RMS) error of 9 to 11 m horizontal and ~ 9 m vertical, displayed with drainage extracted from DEM data of the study area. The abrupt increase in topographic relief at the eastern side of the Chaman fault provides vast amount of sediment supply to the low-lying area of the Chaman Basin. Note the almost parallel, linear and transverse streams orthogonal to the Chaman fault in their proximity to the fault trace. The drainage pattern becomes oblique to almost longitudinal (north-western part of the map) in a medial position in the basin. See Figure 1b for the location of (a). (b) First forward PCA of ASTER VNIR and SWIR displayed as 1-3-2 (RGB) used in geologic/geomorphic mapping. Notice the lenticular Raghani ridge (dark blue colored rock body) flanked by alluvial fan deposits (pink to dark pink colored on west of the ridge) with position of wind (white hollow arrows) and water gaps (blue filled white arrows). Green-colored patches are vegetated areas. The central water gap and the corresponding wind gap are 1348 ± 15 m apart. Black lines A–F are the topographic profile lines shown in Figure 8. Numbered white lines are the stream profiles used in Figure 10 while numbered yellow lines are stream profile lines used in Figure 11. Dashed white curved line (L_{mf}) is the measured length of mountain front of the Raghani ridge while dashed white straight line (L_s) is the equivalent parallel straight line used in mountain front sinuosity calculation ($S_{mf} = L_{mf}/L_s = 1.27$). The Spinatizha thrust and Chaman strike-slip faults tend to maintain a straight front of the ridge that is dissected by the local drainage system. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Entrenchment (E) of Quaternary deposits

Recent river entrenchment (E) is calculated as the difference in elevation between a channel bed and the alluvial plain that is being incised (Azor *et al.*, 2002). Higher E values reflect longer uplift histories while lower E values reflect relatively recent uplift. With lateral fault propagation, values of E are expected to decrease in the direction of fault growth. Transverse stream profiles based on ASTER DEM were measured using Spatial Analyst extension of ArcGIS at a constant distance from the mountain front.

Field datasets

The Raghani ridge and Bostankaul alluvial fan were chosen for detailed field study (Figure 2). This was mainly because of their position at the northern end within the zone of transpression and their accessibility. Topographic maps based on DEM derived from 15 m ASTER VNIR stereo-pairs together with 1:50 000 scale topographic maps of the survey of Pakistan were used as base maps for geomorphic mapping of the Quaternary landforms, drainage patterns, and sediments. In addition, we measured stratigraphic sections along stream cuttings within alluvial fans of different ages and their lateral extents. Soil development, vegetation type and cover, rock weathering, and

degree of rock varnishing development were used to develop a morphostratigraphy for the Quaternary alluvial fans. Widths and depths of the three antecedent streams across the Raghani ridge were measured across several reaches. Stream terraces and bars present along these streams and within the valleys were mapped by walking along the boundaries of the individual landforms using a GPS with an approximate ± 5 m horizontal and an approximate ± 10 m vertical uncertainty. The map units (field-based polygons) were exported to ESRI ArcGIS and compared with the landforms classified from the ASTER datasets to confirm their locations and sizes, and in particular the width and length of the streams within the study area. The width of the mapped streams and terraces matched within < 5 m of those polygons derived from ASTER data.

Results

We extended the structural mapping of Lawrence *et al.* (1981, Figure s1) to the south of their study area. Emphasis was placed on understanding the interaction between the structural evolution of the pop-up zone, which comprises of the Spinatizha Crystalline Complex in the north and the Quaternary sediments and landforms in the south, together with the surrounding alluvial fan system.

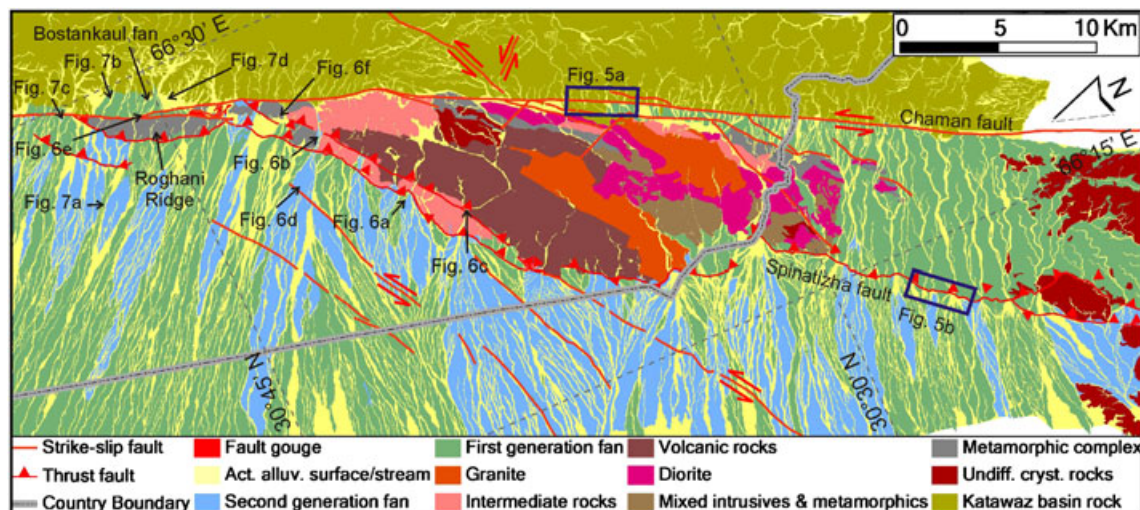


Figure 4. Geology of the Chaman and Spinatizha faults, and surrounding areas. The strike-slip strands of the Chaman fault system in the left half of the map form a complex shear zone incorporating rocks from both the meta-sediments of Katawaz Basin and rocks of the Spinatizha Crystalline Complex, which is considered to be fragments of the Cretaceous arc rocks exposed west of the Chaman fault. The arc-shaped southeast directed Spinatizha fault is an active frontal thrust that resulted from the combination of compression and strike-slip motion on the Chaman fault. The resultant topographic high along this thrust has strongly influenced the alluvial fan system of the Chaman Basin with deep stream entrenchment, deflection and quenching. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

The north and central part of the mapped area is the most structurally complex, with a comparatively wider Chaman fault zone comprising of a major fault trace with multiple converging synthetic faults and two antithetic faults (Figure 4). The shear system is more evident either within the Spinatizha Crystalline Complex on the west or the meta-sediments of the Katawaz Basin to the east. At the contact between the crystalline and sedimentary rocks in the fault zone, the alluvial fan deposits are either eroded away or are highly deformed and were present only as small outliers. The wide fault zone converges into a more continuous and linear fault trace along the southern part of the Chaman fault. Here the Chaman fault left-laterally displaces transverse streams along the contact of the Quaternary alluvial fan deposits and sedimentary bedrock (Figure 5). Fault gouge is locally present in small patches along the fault trace, and is mainly composed of reddish to dark gray colored mylonitized clay-rich material with occasional sandstone/shale blocks that have been incorporated from the sedimentary rock of the Katawaz Basin.

A significant finding of this study was the discovery of a southeast-dipping thrust fault, which we call the Spinatizha fault. The Spanatizha fault thrusts crystalline bedrock over Quaternary alluvium. In addition, a bajada is present that records progressive propagation of the Spintizha thrust fault into the foreland. Below, we first describe and discuss the consequences of the actively interacting strike-slip and thrust faults on the coeval bajada of the Chaman Basin. Then we discuss the nature of the Spinatizha thrust fault.

Chaman Basin

The Chaman Basin, in which the study area is located, is an elongated, arc-shaped, and asymmetrical accommodation zone for sediment derived from the eastern Khojak Pass Mountains. The Chaman Basin was created as a flexure within the eastern Eurasian Plate margin crust, which most probably is composed of Cretaceous arc rocks (Treloar and Izatt, 1993; Jadoon and Khurshid, 1996), in response to the uplifting eastern block of the Chaman fault. The rising Khojak Pass Mountains, which borders the Chaman Basin to the east, is composed of Oligocene

to Recent Katawaz Basin sedimentary rocks that are mainly shale and sandstone, some of which have experienced low-grade metamorphism. The Helmand Desert flanks the western side of the basin, and two unnamed basins similar to the Chaman Basin flank the northern and southern ends of the basin (Figure 1b). The Chaman Basin is ~80 km long and ~20 km wide in its central part at an average elevation of ~1350 m above mean sea level. The ephemeral streams network that feeds the basins is mainly composed of moderate to highly incised discontinuous channels occasionally transforming into deep gorges (Figure 6a). These streams are unstable and shift across the valley floor continuously producing terrace risers and mid-channel bars (Figure 6b).

Two major streams patterns are common within the basin: (1) linear, almost parallel channels with well-defined channel banks, and (2) anastomosing channel systems that are developing a semi-dendritic pattern with less defined and migrating stream channels. In the mapped area, these two patterns are interchanging irrespective of the channel bed lithology (Figure 4). The dominant control on this drainage pattern is the actively evolving structures associated with the Chaman fault system within the basin. Other factors including, bedrock lithology, vegetation and climate are constant in the study area and cannot explain the change in drainage pattern.

Stream density within the basin is almost constant, except in the area underlain by crystalline bedrock, which is characterized by a less dense and deeply incised narrow network of antecedent streams (Figure 6c). However, these streams commonly flow along the crosscutting splays of the Chaman fault (Figure 6d; Lawrence *et al.*, 1981).

The Khojak Pass Mountains are the main source of sediment for the alluvial fans sediment (Figure 7a). Although the Khojak Pass Mountains provide the bulk of the sediment in central part of the basin, numerous boulders and finer sediments are sourced from the Spinatizha Crystalline Complex (Figure 1b). Consequently either the crystalline rocks are the younger part of the transpression or these rocks are very resistant to erosion, and are not contributing to the sediment budget of the Chaman basin.

Based on our fieldwork and ASTER image interpretation we were able to differentiate four major generations of alluvial fan development (Figures 4 and 6e). The oldest alluvial fan deposits (green colored polygons in Figure 4) underlie most of

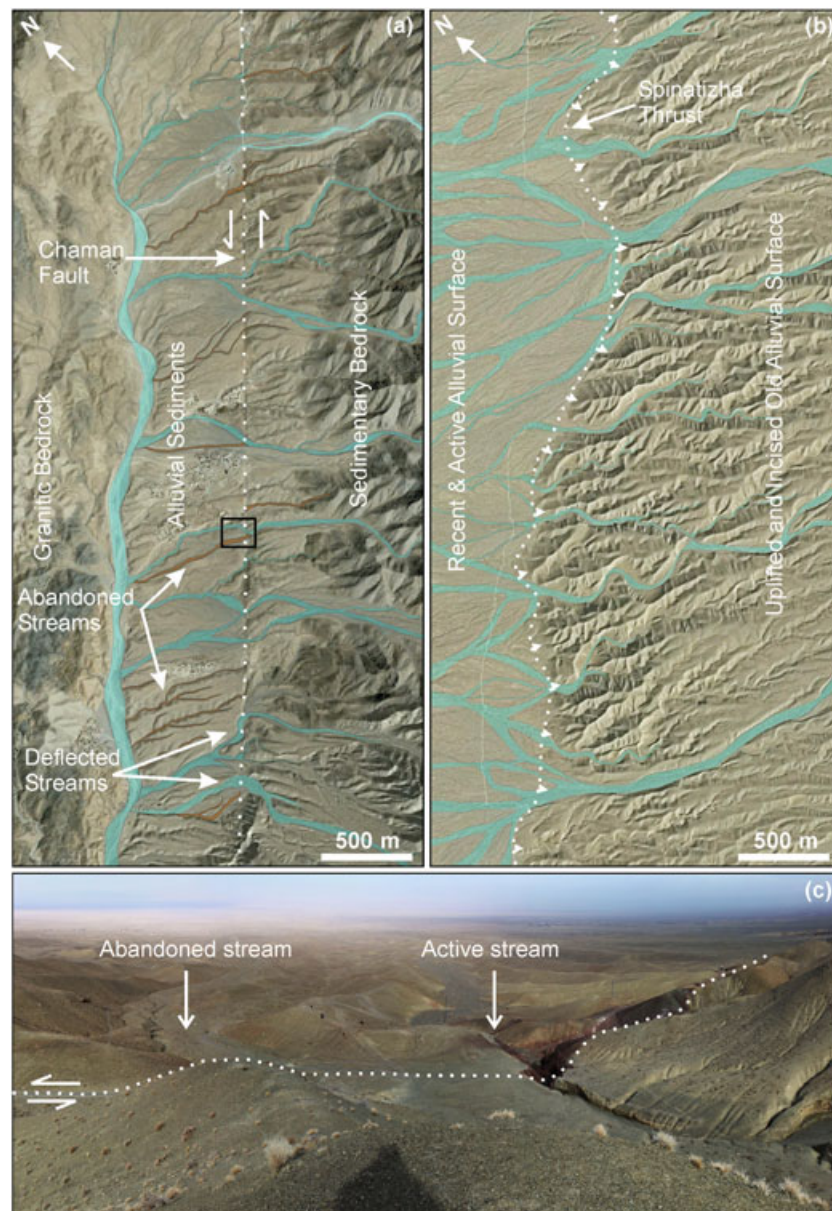


Figure 5. Geomorphic expressions of the thrust and strike-slip faults shown on Google Earth high-resolution images (for the location see Figure 4). (a) Single trace of the Chaman fault along which the drainage system and old alluvial fan surfaces have been abandoned and left laterally displaced. Black rectangle shows location of (c). (b) The Spinatizha fault thrusts up the alluvial fan surface, which is incised by a laterally migrating, almost parallel stream network. In the footwall of the fault the drainage pattern braids away from a single source point reworking the abandoned surface. (c) Field photograph showing a typical abandoned stream in association with an active stream along a strike-slip fault segment. Active stream show rapid incision through the abandoned alluvial surface. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

the Chaman Basin and are proximal to the major structures within and around the basin. The alluvial fan sediments are mainly flashflood deposits comprising monotonous successions of fanglomerate that reach thicknesses of as much as 40 m and are present along both sides of the main Chaman fault (Figure 7b). Particle sizes range from meter-sized boulders to silt and clay matrix showing little or no sorting. Boulders frequency, however, decreases down alluvial fan. Most of the alluvial fans coalesce to form bajada; however, isolated inliers of fanglomerate are present where streams have incised into the alluvial fans and/or where active faulting has uplifted them. The fanglomerates are unconsolidated, but carbonate cement is present at some locations resulting in partial lithification of the fanglomerates (Figure 7c). Soil has developed to a depth of about 1 m on most of the oldest alluvial fan surfaces.

The second generation of alluvial fans (blue polygons in Figure 4) is incised within the oldest alluvial fans, and covers most of the older landscape within the basin. With continued

uplift and the consequent shift of the depositional center of the basin much of the previously deposited sediments have been eroded away and re-deposited downstream. The fanglomerates are comparatively rounded, polymictic and have particle sizes ranging from the occasional meter-sized boulders to clay-rich matrix. These fanglomerates are unconsolidated and massive, typical of flashflood deposits.

The third generation of alluvial fans (yellow polygons in Figure 4) are much more localized and are deposited along the margins of individual older alluvial fans within active drainage systems. Most of these alluvial fans have experienced little or no erosion and their surfaces are very flat, and are composed of sediment up to a few meters thick. These alluvial fan deposits are not faulted and overly tectonic structures within the study area (Figure 7d). The fourth generation of alluvial fans (mapped as yellow polygons with the third generations of fans in Figure 4) are geomorphically active, representing current streams beds and channel deposits.

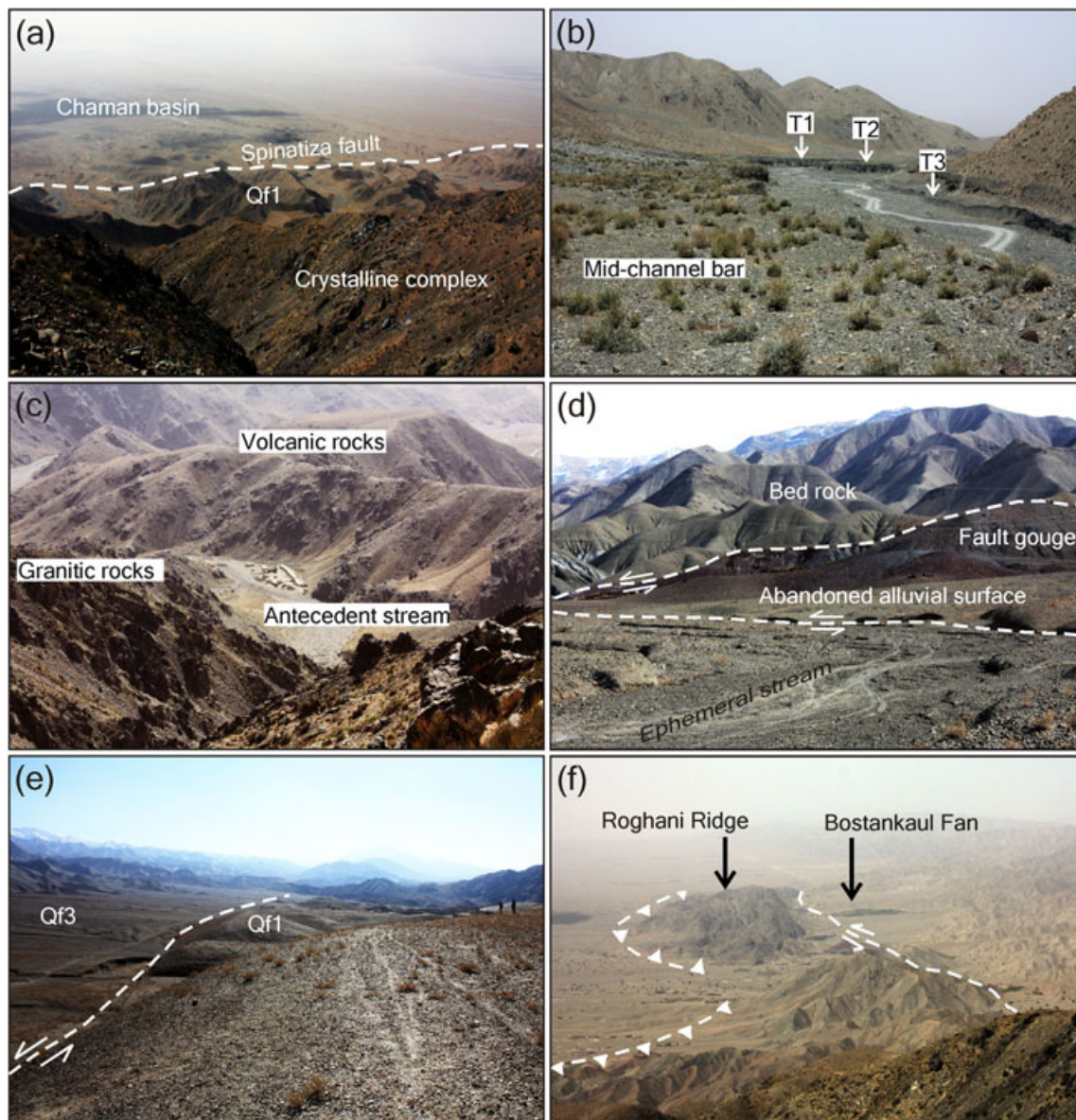


Figure 6. Typical geomorphic settings in the study areas. The location of each field photograph is shown in Figure 4. (a) View looking west at the ephemeral streams network at the foothills of the pop-up zone. These highly incised discontinuous channels in the high ground drop their load as these cross the probable location of the Spinatizha fault to becoming dispersed from a single source point occasionally transforming into deep gorges. (b) River terraces and active bars west of the main Chaman fault. Terraces and bars reflect degradational and aggradational phases during the life span of a stream respectively and are the result of tectonic uplift and consequent erosional processes. (c) One of the several antecedent streams that cut across the rising thrust block. This stream is flowing along a northwest directed fault at the contact of granitic and volcanic rocks of the Spinatizha Crystalline Complex. (d) A northwest striking synthetic strike-slip fault cutting across an abandoned alluvial fan surface. An active ephemeral stream follows the trend of this secondary fault of the shear system. (e) Looking south along a strand of the main Chaman fault displacing first generation of alluvial fan sediment (Qf1) against the third generation alluvial fan sediment (Qf3). (f) View looking northwards along the pop-up zone, the Roghani ridge, between Chaman and Spinatizha faults, which marks the northern extent of transpression. This isolated ridge is emerging from a mantle of Quaternary alluvium including the displaced Bostankaul alluvial fan to the east of the ridge. The ridge mainly comprises metamorphic rocks of the Spinatizha Crystalline Complex. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Spinatizha fault

The Spinatizha fault is similar to many of the east-southeast dipping second order structures described by Ruleman *et al.* (2007) that are mostly west of the main Chaman fault and are the result of both left-lateral slip and convergence on the main Chaman fault. These faults form a set of thrust faults of semi-arcuate shape at the front of the Spinatizha Crystalline Complex (Figure 4). The north–south trending Spinatizha fault thrusts crystalline rocks over the Quaternary alluvial fans deposits in the northern part of the mapped area [this and Lawrence *et al.*'s (1981) study]. In contrast, the Spinatizha fault cut across alluvial fan deposits in the southern part of the study area. These thrust

faults represent a growing thrust system that is propagating westward and widening the mountain range that comprises the Spinatizha Crystalline Complex. The pop-up zone, which comprises the Spinatizha Crystalline Complex and the alluvial fan deposits between Chaman and Spinatizha faults, is the hanging wall of the Spinatizha fault and may be the results of fault propagation growth folding. The presence of this thrust is marked by an abrupt change in the drainage pattern within the Chaman Basin. The stream pattern is dominantly linear and almost parallel between the Spinatizha thrust and the main Chaman fault, but radiate and become braided after traversing the Spinatizha fault (Figure 5b). Individual local topographic highs developed within the thrust block, which mostly deflect the streams around them.

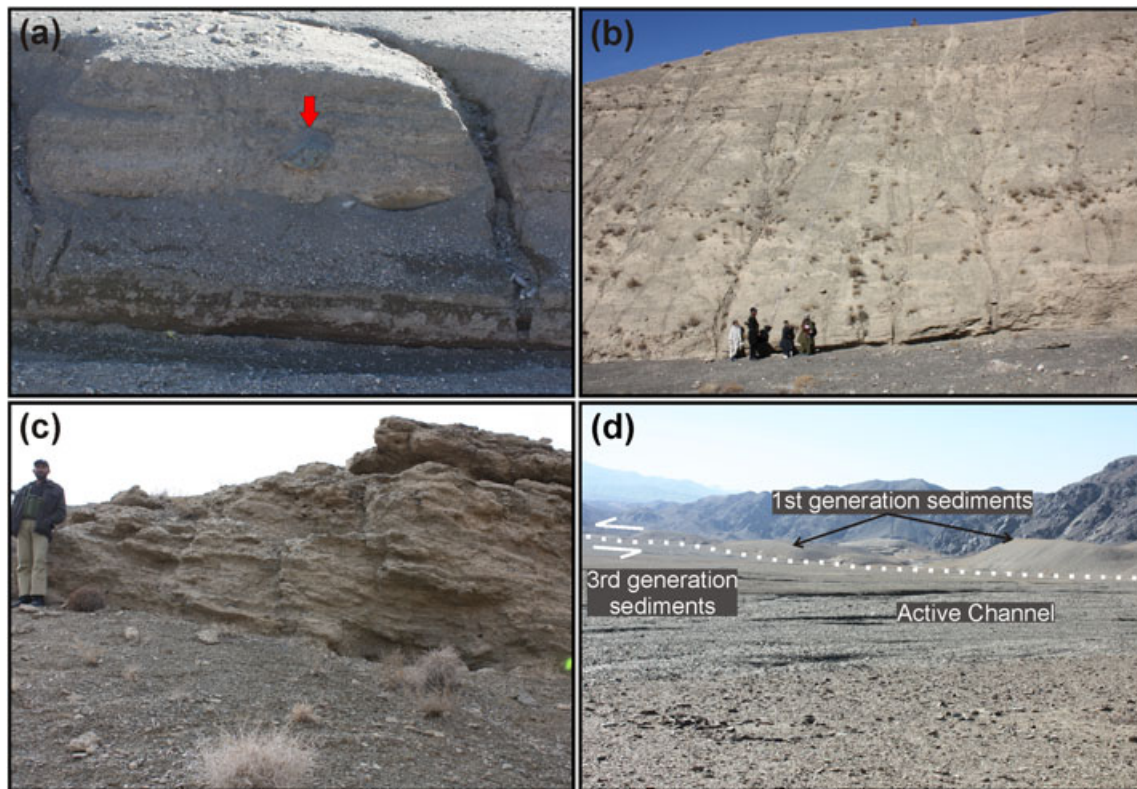


Figure 7. Field photographs showing alluvial fans and their sedimentology within the study areas (see Figure 4 for location). (a) Typical alluvial fan sediments, here incised ~3.5 m by an ephemeral stream within the Chaman Basin. The sediments comprise mainly shale and sandstone with occasional meter-sized silt-sandstone boulders derived from Khojak Pass Mountains (boulder in the center of the photograph is about 60 cm across). (b) Stream cutting exposing about 40 m thick alluvial fan sediments. (c) View of a tilted partially lithified conglomerate within the oldest alluvial fans proximal to the main Chaman fault. (d) View of typical third generation alluvial fans that overlay part of the Chaman fault. The oldest alluvial fans (first generation) are present near the base of the mountain front. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Stream deflection is more common in the southern part of the study area where the Spinatizha fault has uplifted the eastern part of the Quaternary alluvial fan surface south of the Spinatizha Crystalline Complex.

Discussion

The active strand of the Chaman fault system and the Chaman Basin that is examined in this study provides an example of the interaction between growing structures and co-evolving landscapes. Drainage patterns and landform/landscape analysis along such evolving structures have been used to examine fold growth and lateral propagation of thrust faults in other regions of the world (e.g. Keller *et al.*, 1999; Owen *et al.*, 1999; Azor *et al.*, 2002; Keller and Pinter, 2002; Scharer *et al.*, 2004; Oskin and Burbank, 2007). However such studies are rare and our study is the first of its kind along the western margin of the India-Asian collision zone, which will add to the growing knowledge of the tectonic geomorphology of restraining bends.

The Chaman and Spinatizha faults have a strong impact on the geomorphic expression within the Chaman Basin. The streams in the proximity of the Chaman fault are highly incised with well-defined stream banks and parallel stream drainage has developed. Streams that traverse the bajadas along the transpressional front in a medial position within the Chaman Basin are characterized by a radiating stream network (Figure 4). With the westward widening transpression the once radiating draining pattern in the frontal planes has evolved within the uplifting landscape. Streams flowing across the uplifting landscape have incised the existing radiating drainage and thus freeze or 'quench' it within the active

transpression. In the mapped area this radiating pattern is replaced by a strike-slip dominant stream pattern in the central part, while in the northern and southern parts away from the main Chaman fault linear streams have become more braided. Climate does affect ephemeral drainage network; however this kind of ephemeral stream pattern is also well documented along growing thrusts and associated folds (e.g. Pearce *et al.*, 2004; Castelltort and Simpson, 2006).

While the Chaman fault left-laterally displaces the streams (Figure 5a) shaping the downstream drainage pattern into a more regularly spaced linear and parallel streams network, the Spinatizha fault perturbs the drainage by increasing the local base level either for the stream to become braided after crossing the elevated ground or to be deflected locally around the noses of the rising topography (Figure 3). The deflection of drainage around growing landforms is a common characteristic in transpressional settings (Humphrey and Konrad, 2000; Miller and Slingerland, 2006). Thus the longitudinal topographic rise associated with this transpression is the defining factor in shaping the geomorphology within the Chaman Basin.

The northern extreme of the transpression is represented by the ~10 km-long isolated Roghani ridge that rises steeply from 1740 m to ~2000 m above mean sea level (Figures 3 and 6f). The sharp change in relief and the highly incised narrow valleys within the deformed Quaternary landforms and Roghani ridge suggest that there is a rapid and active interaction between the landscaping processes and the active tectonics of the growing folds and faults in this region (Burbank, 1996; Keller and DeVecchio, in press). The interactions of the alluvial and hill-slope processes and the structural uplift and lateral displacement over considerable time spans ultimately shape the drainage

patterns and geomorphology (Owen *et al.*, 1999). In addition to the topographic analysis, geomorphic indices of active tectonics, including S_{mf} , V_f , recent stream entrenchment, and SL-gradient index of the ridge and surrounding area support the view that this topography is actively evolving and influencing the drainage development.

Topography, wind and water gaps of the Roghani ridge

The lenticular shaped Roghani ridge is a southwest-verging thrust block oriented north-northeast-south-southwest (NNE-SSW), and is flanked by Quaternary fanglomerates, with its northern and southern noses actively rising from below the Quaternary to recently deposited sediment (Figure 3b). The meta-volcanic rocks comprising the ridge are of upper greenschist facies of the Spinatizha Crystalline Complex (Lawrence *et al.*, 1981). The ridge lies to the west and just south of the gentle double bend in the Chaman fault. The topography reveals a domal shape of the ridge with the highest point at ~ 1965 m above mean sea level at the center of the ridge and plunges northwards and southwards. Transverse profiling highlights the ridge's asymmetry with an almost vertical eastern cliff face and a gently sloping western limb (Figure 8).

The uplift of the Roghani ridge above the depositional plain has strongly perturbed the local base level. A small aggrading basin between the Roghani ridge and Khojak Pass Mountains has formed in response to this uplifting block, and the Quaternary deposits have partly buried the trace of the Chaman fault (Figure 7d). A highly incised and gently west-sloping bajada surrounds the ridge from all sides except to the east. Most of the drainage flow from the ridge is towards the west.

The ridge is dissected by three prominent water gaps and two corresponding wind gaps with elevations of the streams beds decreasing northwards. The water gaps divide the ridge into southern, central, and northern segments, each with different topographic expressions (Figures 3 and 8). The central and northern water gaps are antecedent streams that have maintained their courses across this propagating thrust block. The central wind gap is situated ~ 115 m below the highest adjacent point at the top of the thrust block and ~ 77 m above the current stream course (water gap), which infers a total uplift of $\sim 77 \pm 15$ m since stream abandonment.

This wind gap is located $\sim 1348 \pm 15$ m south of the water gap, suggesting a southward displacement of the ridge along the Chaman fault. The northern wind gap near the northern nose of the ridge is situated ~ 56 m above the adjacent water gap and ~ 90 m below the adjacent high point at the crest of the thrust block. These two gaps are ~ 450 m apart. Although complex in nature, the presence of wind and water gaps likely indicate an older drainage network that pre-dates uplift (Simpson, 2004; Miller and Slingerland, 2006; Douglass *et al.*, 2009).

With the continued interaction of strike-slip Chaman fault and Spinatizha thrust fault the following is recognized: (1) a decrease in topographic relief and a decrease in the relief of the wind and water gaps along the direction of growth; (2) a diversion of drainage around the tips of the thrust block; (3) the lateral displacement of wind and water gaps in the direction of strike-slip movement; and (4) deep incision and deformation of younger deposits.

Bostankaul alluvial fan

The Bostankaul alluvial fan is one of the first-generation (oldest) alluvial fans mapped during this study. This alluvial fan borders

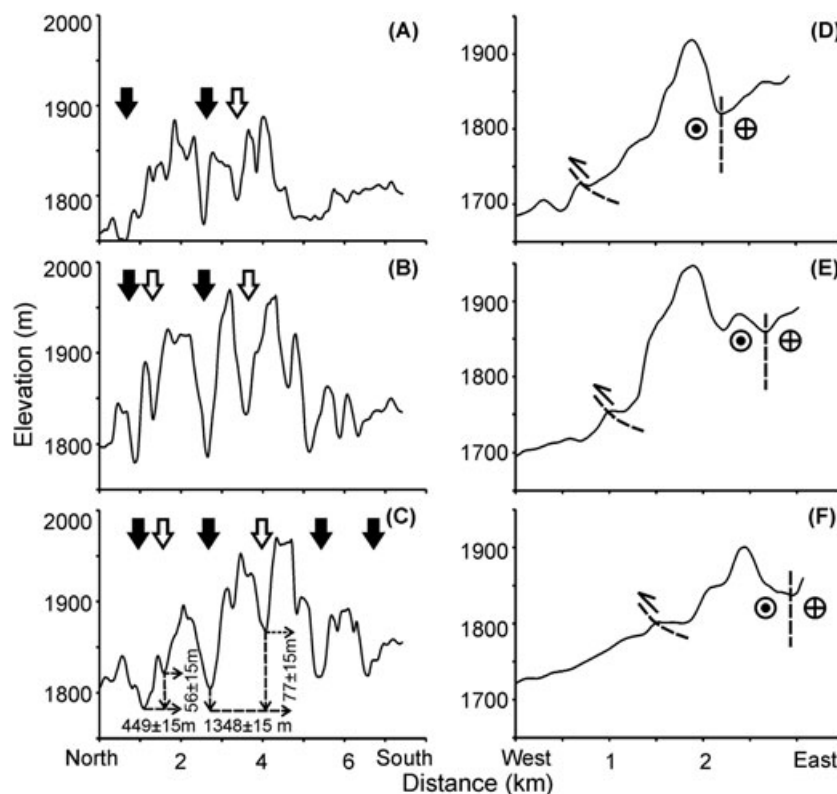


Figure 8. Longitudinal (A)–(C) and transverse (D)–(F) topographic profiles across the Roghani ridge and surrounding areas. Filled arrows point to water gaps while hollow arrows mark the locations of wind gaps. Note the gradual decrease in the elevation of the wind gaps from the center of the ridge towards north. The central water gap and corresponding wind gap are 1348 ± 15 m apart, while the wind gap is 77 ± 15 m above the present level of the water gap. Transverse profiles (on the right) with probable locations of Chaman and Spinatizha faults show a highly asymmetrical ridge with an almost vertical eastern ridge front. See Figure 3b for the location of profiles A–F.

the Roghani ridge on the east and has an erosional contact with the rocks of the Khojak Pass Mountains on the east, and is being eroding by an active stream to the south (Figures 2, 4 and 6f). In the north, the Bostankaul alluvial fan coalesces with another alluvial fan to form a bajada. In the west where the Bostankaul alluvial fan partly borders the rock of the Roghani ridge, a strand of the Chaman fault cuts across the main body of the Bostankaul alluvial fan and displaces it left-laterally by 1150 ± 55 m (measured in the field and from satellite images) (Figures 3b and 7d). The southward displaced part of the Bostankaul alluvial fan, which is west of the strand of the Chaman fault, rises ~40 m above the present depositional surface and is the only east facing fault scarp present in the study area; however it is almost at the same elevation of ~1850 m as the northward displaced portion of the Bostankaul alluvial fan.

Stream length (SL)-gradient index

SL values were calculated for 134 reaches with a 25 m fixed contour interval along 14 trunk streams that traverse the Roghani ridge and the Chaman fault zone; point values were then used to produce an SL index map (Figures 9 and s5, Table s4). Analysis of the index map suggests strong tectonic controls rather than bedrock controls on stream gradients. The higher SL index values on the west of the fault suggest recent and continued uplift of the Roghani ridge. SL values gradually becoming lower

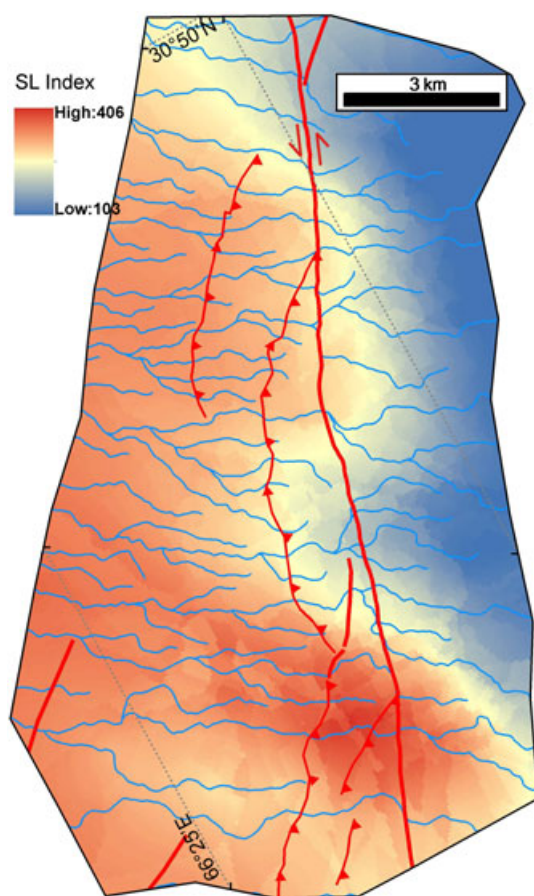


Figure 9. Stream length (SL)-gradient index map of the area based on SL index values from 14 transverse trunk streams that cross the Roghani ridge and fault zone; see Figure 1b for the location of streams and structures. Higher SL index values on the west of the fault suggest recent uplift. The lower values in the fault zone are due to shearing and less resistive fault gouge. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

near the Chaman fault zone, which is likely due to shearing and less resistive fault gouge. In contrast, lower SL values on the eastern side of the fault zone are due to a comparatively flatter surface with lower gradients.

Valley floor width to valley height ratio (V_f)

The V_f values at Roghani ridge were measured at ~800 m from the mountain front for three major transverse stream channels (Figure 10). The V_f values range from 0.61 to 1.30, which suggests continued and comparatively higher uplift rates of the ridge. However, lower V_f values for the central and northern valleys suggest a higher uplift and incision rate for this part of the Roghani ridge than for the southern part.

Mountain-front sinuosity (S_{mf})

The S_{mf} value for the ~9 km-long western front of the Roghani ridge is 1.27 (Figure 3b), which is in Keller and Pinter's (2002) predicted range ($S_{mf} = 1.0$ –1.6) for active range bounding fault zones. The S_{mf} values calculated along the eastern margin of the ridge front encompassing the drainage area of each of the three major water gaps range from 1.23 for the central water gap to 1.32 for the northern water gap. The active fault along the eastern margin of the Roghani ridge explains the straighter mountain front along the east as compared to the western margin that has been dissected by the streams that flowed through the wind and water gaps.

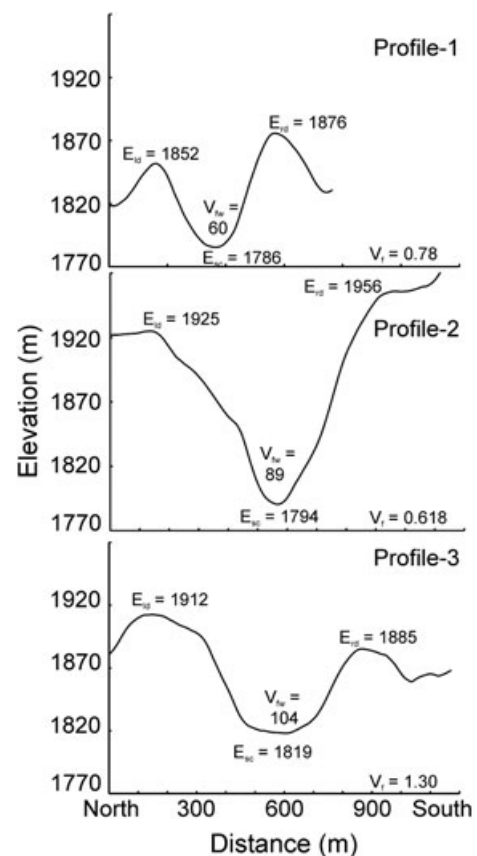


Figure 10. Valley floor width to height ratios (V_f) for the three antecedent streams from north to south (see Figure 3b for locations) recording a general trend of higher uplift in the northern portion of the ridge with maximum uplift at its center. The V_f values range from 1.30 in the south to 0.61 in the north.

Entrenchment (E)

The E values that were calculated from eight different streams at an average distance of 1.5 km from the Roghani ridge front vary from ~1 m of entrenchment to almost 6 m. The central part of the ridge has slightly lower E values than the southern and northern stretches, which suggest that the ends of the ridge are more active (Figure 11). However, the overall E values of 1 to 6 m suggest a relatively active tectonic regime (Azor *et al.*, 2002).

The S_{mr} , V_r , and E values are also consistent with lateral propagation of the ridge. SL and E values are consistent with the progressive and continued deformation of the recent deposits. These values demonstrate higher uplift rates at the center and southern segments of the ridge in contrast to the northern segment that is consistent with the topographic relief of the ridge and the northward decrease in elevation of the water and wind gaps along the ridge.

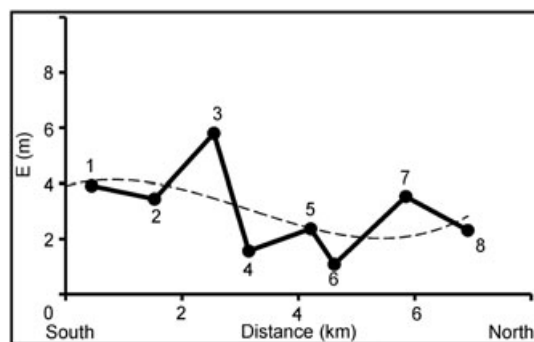


Figure 11. Entrenchment (E) values along the western front of the Roghani ridge, calculated for eight streams with more than 50 m width at an average distance of 1.5 km from the mountain front. The E values of 1 to 6 m resemble a recently uplifted thrust block. Locations of points 1–8 are shown in Figure 3b.

Tectonic implications

The location of wind and water gaps together with the displaced Bostankaul alluvial fan can be used to estimate the Late Quaternary slip rates along this fault system. A lateral displacement of 1150 ± 55 m recorded by the Bostankaul alluvial fan surface is in agreement with the 1348 ± 15 m distance between the central water gap and the corresponding wind gap. This suggests that this segment of the Chaman fault has moved ~1150 m since the abandonment of the Bostankaul alluvial fan surface. In addition, the topographic difference of 77 ± 15 m between the present day water and the wind gaps has recorded the dip slip component of this evolving transpression associated with the Chaman and Spinatizha faults. Figure 12 summarizes the likely present-day structural setting for this transpression and the resulting landscape. We argue that this is due to the presence of a half positive flower structure, a common structure along bends in the continental strike-slip faults (Mann, 2007).

Most of the slip rate (~30 mm/yr) resulting from the relative motion of Indian and Eurasian plates in this region is accommodated along the Chaman fault (Sella *et al.*, 2002). However, the difference in the azimuths of the strike of the Chaman fault (~N34°) and the Indian plate relative moment (N12°E) essentially requires some convergence within the Indian plate boundary zone (Molnar and Dayem, 2011), which is a common phenomenon along intracontinental strike-slip faults within the transform boundary zones (Frankel and Owen, in press). The resultant convergence from this geometric setting along the Indian plate boundary zone has caused the formation of the Suliman-Kirhar (SK) fold-thrust belt (Figure 1a). A slip partitioning rate of ~3 to 13 mm/yr is estimated along several thrust faults present within the SK fold-thrust belt zone using the last 200 years earthquake data of the region (Ambraseys and Bilham, 2003; Szeliga *et al.*, 2009). The Spinatizha thrust fault is one of the several thrusts that may account for this convergence within the boundary. We estimate the strike-slip and

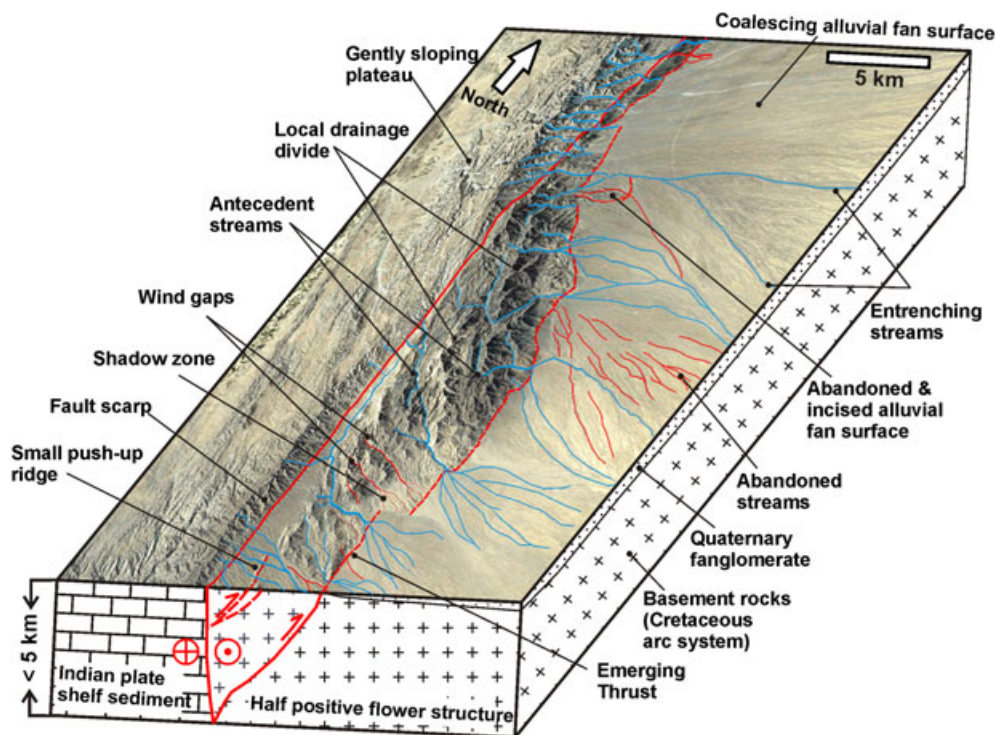


Figure 12. Block diagram showing major typical landforms and topography expected along a restraining bend of gentle curvature along a left-lateral strike-slip fault. Structures traced on Google Earth image covering a part of the Chaman fault are speculated from the surface downward making a half-positive flower structure. The vertical scale is estimated from the gravity and tectonic model of the area after Jadoon and Khurshid (1996). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

dip-slip component for this system based on our topographic analysis and the morphostratigraphy of the alluvial fan deposits around the Roghani ridge. We argue that the alluvial fan surfaces of the first generation of alluvial fan sediment (Qf1) that surrounds the ridge are of the same age. Since the abandonment of these alluvial fan surfaces is contemporary with the stream deflection of the central water gap and consequent development of the associated water gap (Figure 8) we assume that the total lateral displacement of the Bostankaul alluvial fan and the vertical uplift of the central water gap was time equivalent. Consequently the 1150 ± 55 m left-lateral displacement along the Chaman fault is time equivalent to the 77 ± 15 m uplift of the wind gap. This suggests that since the abandonment of the Bostankaul alluvial fan surface the Chaman fault has moved 1150 ± 55 m left-laterally while uplift along the Spinatizha thrust accounts for 77 ± 15 m in the same time period giving an estimate of ~ 14 m to 1 m of strike-slip to the thrust movement. Although this thrust is a subsidiary structure of the Chaman fault system it provides the opportunity to understand the strain partitioning along the plate boundary and to estimate the convergence rate of the Indian plate.

Conclusions

The Roghani ridge and Bostankaul alluvial fan are part of an evolving landscaping system representing the interaction of active tectonics and erosional processes. The abandoned oldest alluvial fan surface is deeply incised by narrow V-shaped valleys and is left-laterally displaced along an active segment of the Chaman fault. The asymmetrical Roghani ridge, with a steep eastern cliff face and a gently sloping western limb, has formed on the hanging wall of the southeast dipping Spinatizha thrust fault. Topographic and geomorphic characteristics of the ridge indicate a northward lateral growth of the Spinatizha fault as a subsidiary of the Chaman fault. The location of the wind and water gaps in the ridge supports the view that there has been northward uplift of the ridge and lengthening of the Spinatizha thrust fault. Geomorphic indices also suggest a progressive and continued activity of the Spinatizha thrust fault. The Spinatizha thrust fault represents one of the several transpressions present along the Chaman fault that help compensate for the convergence required by the difference in azimuths of the strike of the Chaman fault and the relative motion of Indian and Eurasian plates.

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