Strain partitioning at the eastern Pamir-Alai revealed through SAR data analysis of the 2008 Nura earthquake

Kanayim Teshebaeva, Henriette Sudhaus, Helmut Echtler, Bernd Schurr and Sigrid Roessner

Helmholtz Centre Potsdam, Telegrafenberg, D-14476 Potsdam, Germany. E-mail: kanayim@gfz-potsdam.de

1 INTRODUCTION

In 2008 October, the $M_w$ 6.6 Nura earthquake struck the eastern termination of the intermontane Alai valley between the southern Tien Shan and the northern Pamir of Kyrgyzstan. The shallow thrust earthquake occurred in the footwall of the Main Pamir thrust, where the Pamir orogen is colliding with the southern Tien Shan mountains. We measure the coseismic surface displacements using SAR (Synthetic Aperture RADAR) data; the results show clear gradients in the vertical and horizontal directions along a complex pattern of surface ruptures and active faults. To integrate and to interpret these observations in the context of the regional tectonics, we complement the SAR data analysis with seismological data and geological field observations. While the main moment release of the Nura earthquake appears to be on the Pamir Frontal thrust, the main surface displacements and surface rupture occurred in the footwall along the NE-SW striking Irkeshtam fault. With InSAR data from ascending and descending tracks along with pixel offset measurements, we model the Nura earthquake source as a segmented rupture. One fault segment corresponds to high-angle brittle faulting at the Pamir Frontal thrust and two more fault segments show moderate-angle and low-friction thrusting at the Irkeshtam fault. Our integrated analysis of the coseismic deformation argues for rupture segmentation and strain partitioning associated to the earthquake. It possibly activated an orogenic wedge in the easternmost segment of the Pamir-Alai collision zone. Further, the style of the segmentation may be associated with the presence of Palaeogene evaporites.

Key words: Radar interferometry; Earthquake source observations; Asia.

SUMMARY

On 2008 October 5, a magnitude 6.6 earthquake struck the eastern termination of the intermontane Alai valley between the southern Tien Shan and the northern Pamir of Kyrgyzstan. The shallow thrust earthquake occurred in the footwall of the Main Pamir thrust, where the Pamir orogen is colliding with the southern Tien Shan mountains. We measure the coseismic surface displacements using SAR (Synthetic Aperture RADAR) data; the results show clear gradients in the vertical and horizontal directions along a complex pattern of surface ruptures and active faults. To integrate and to interpret these observations in the context of the regional tectonics, we complement the SAR data analysis with seismological data and geological field observations. While the main moment release of the Nura earthquake appears to be on the Pamir Frontal thrust, the main surface displacements and surface rupture occurred in the footwall along the NE-SW striking Irkeshtam fault. With InSAR data from ascending and descending tracks along with pixel offset measurements, we model the Nura earthquake source as a segmented rupture. One fault segment corresponds to high-angle brittle faulting at the Pamir Frontal thrust and two more fault segments show moderate-angle and low-friction thrusting at the Irkeshtam fault. Our integrated analysis of the coseismic deformation argues for rupture segmentation and strain partitioning associated to the earthquake. It possibly activated an orogenic wedge in the easternmost segment of the Pamir-Alai collision zone. Further, the style of the segmentation may be associated with the presence of Palaeogene evaporites.

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1 INTRODUCTION

In 2008 October, the $M_w$ 6.6 Nura earthquake struck the eastern termination of the intermontane Alai valley in the Pamir-Tien Shan continental collision zone. This earthquake caused 74 deaths and the destruction of property and infrastructure (Kalmetieva et al. 2009). The epicentre was located in southeastern Kyrgyzstan at 39.51°N and 73.72°E, near the border with China and Tajikistan (Fig. 1). This region corresponds to the northernmost sectors of the Pamir orogen and the structurally complex collision zone between the Trans Alai and the Tien Shan mountains to the north (Fig. 1). Because of the rugged topography and the past political conditions in this remote area between China, Kyrgyzstan and Tajikistan, the regional geological setting is not well known.

The epicentral area of the Nura earthquake is located at the southern flank of the Trans Alai range and within the footwall block of the easternmost thrust system delineating the Pamir. The Trans Alai range of the Pamir and the associated contractional features of this region result from the ongoing convergence between the Indian indenter and the Eurasian plate (Burtman & Molnar 1993). Recent geodetic analysis from continuous GNSS networks (Yang et al. 2008; Zubovich et al. 2010) across the Pamir orogen revealed that the central sector of the convex-northward Trans Alai accommodates more than 50 per cent of the 25 mm a$^{-1}$ convergence between the Pamir and Eurasia (Reigber et al. 2001; Yang et al. 2008; Zubovich et al. 2010). Whereas most of the intracratonic ranges of the Central Asian orogens record largely distributed shortening and uplift, most of the deformation in the Pamir-Alai zone is accommodated within a narrow zone (Molnar et al. 1973; Arrowsmith & Strecker 1999; Coutand et al. 2002; Strecker et al. 2003, Fig. 1).

The segment of the Trans Alai mountain front affected by the Nura earthquake is situated in the footwall of the Pamir Frontal thrust zone and the eastern termination of the intermontane Alai Valley. This basin represents the vestige of a formerly contiguous sedimentary basin that linked the Chinese Tarim Basin in the east and the Tadjik Depression in the west (Burtman & Molnar 1993; Burtman 2000, Fig. 1). This tectonic segment marks the transition between the generally E-W striking tectonic structures in the central sector of the Trans Alai mountain front and the multiform eastern

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The 2008 Nura earthquake

The 2008 Nura earthquake was recorded by a temporary seismic network deployed by the Tien Shan-Pamir Geodynamic Program (TIPAGE; Krumbiegel et al. 2011; Mechic et al. 2012; Schneider et al. 2013; Sippl et al. 2013) and the Earthquake Task Force group of GFZ Potsdam (German Research Centre for Geoscience). Using these data, Kalmetieva et al. (2009) located the main shock and some aftershocks along the NE-SW striking Irkeshtam fault (IrkF), which was thought to have ruptured during this earthquake. The fault is exposed close to Nura village (Fig. 1). In contrast to Kalmetieva et al. (2009), Krumbiegel et al. (2011) and Sippl et al. (2013) located the Nura main shock at a shallow centroid depth of 4 km along the east–west striking Pamir Frontal thrust (PFT; Fig. 2).

Their main shock location suggests that the Nura earthquake ruptured part of the PFT, instead of the IrkF. This assessment is further supported by their moment tensor solution pointing to a clear east–west oriented fault plane related to a thrust earthquake. Because of the discrepancies in locating the Nura earthquake and the complex structural setting of this region, our remote sensing and field-based study investigates the locus of the faulting and the corresponding surface expression of this earthquake.

We combined SAR remote sensing techniques with seismicity data, tectonic and geological interpretations, and geophysical modelling. We apply the InSAR technique using SAR images from ALOS and ENVISAT satellites, and pixel offset techniques in the ALOS amplitude images to measure surface displacements. Using this approach, we provide surface displacement maps with different line-of-sight (LOS) projections of the 3-D surface displacement (e.g. Wright et al. 2004; Fialko et al. 2005). We also present recently acquired field data of the Nura earthquake surface rupture.

Our new data set provides an excellent opportunity for understanding the active structures of the leading deformation front of the eastern part of the northernmost part of the Pamir, a hitherto poorly studied region. With the seismological results and our measured surface displacement and field data, we characterize the faults that were active during the Nura earthquake, using elastic fault modelling (Okada 1985). With this combined information, we provide additional information on earthquake source parameters to that gained in previous seismological studies. It allows us to define the geometry of the ruptured faults at depth and to determine the contractional nature of the strain partitioning in the eastern Trans Alai.

2 SEISMOTECTONIC SETTING OF THE REGION

2.1 Tectonic setting

The Pamir-Alai region constitutes the collision zone between two mountain systems, the southwestern Tien Shan and the northern Pamir (Fig. 1). The Tien Shan mountains form several ranges that extend approximately 2500 km from east to west (Fig. 1). They are transected into the northeastern and southwestern Tien Shan...
Tectonic and geological map of the eastern Pamir-Tien Shan region from the geological map of 1958 (1:200,000), modified according to our field observations and marked with the surface rupture trace (white line, see also Fig. 6). The regional seismicity is taken from the NEIC catalogue for the years 1973–2011 and the moment tensor of the large 1974 earthquake from Fan et al. (1994). The blue arrows show flow direction of the rivers.

Figure 2. Tectonic and geological map of the eastern Pamir-Tien Shan region from the geological map of 1958 (1:200,000), modified according to our field observations and marked with the surface rupture trace (white line, see also Fig. 6). The regional seismicity is taken from the NEIC catalogue for the years 1973–2011 and the moment tensor of the large 1974 earthquake from Fan et al. (1994). The blue arrows show flow direction of the rivers.

by the almost 800-km-long NW-SE striking Talas-Fergana fault, a major right-lateral strike-slip fault (Molnar et al. 1973; Burtman & Molnar 1993; Burtman 2000; Korjenkov et al. 2012). The contact zone between Tien Shan and Pamir is characterized by generally east–west trending mountain ranges: the Alai range in the southern Tien Shan to the south the Alai valley and the Trans Alai range (Zaalai) in the northern Pamir (Fig. 1).

Shortening and uplift of the Trans Alai began during the Neogene (Molnar et al. 1973; Burtman & Molnar 1993; Arrowsmith & Streecker 1999; Burtman 2000; Coutand et al. 2002) and has continued until the present-day. Fault scarp at the Trans Alai mountain front attest to protracted shortening during the Quaternary (Strecker et al. 1995; Arrowsmith & Streecker 1999). The main N–S shortening between the Pamir and Tien Shan is concentrated in the Trans Alai with estimated rates from GPS data of 10–15 mm yr\(^{-1}\) (Reigber et al. 2001; Yang et al. 2008; Mohajer et al. 2010; Zubovich et al. 2010). Offsets of Holocene terrace deposits along the Trans Alai mountain front suggest that a large part of this regional shortening is accommodated through slip along the south-dipping Main Pamir and the PFTs (Fig. 1; Strecker et al. 1995; Arrowsmith & Streecker 1999). Both faults are surface manifestations of the south-directed intracontinental Alai subduction zone (Burtman & Molnar 1993; Sobel et al. 2011, 2013). The active structures in the Trans Alai thus account for half of the shortening between the Pamir and Eurasia (Li Tao et al. 2012).

Our study area is located at the far eastern end of the Alai valley and corresponds to the footwall of the Main Pamir thrust (MPT) at the eastern bend of the orogen, where the PFT transitions toward a number of SW–NE striking structures that are an integral part of the orogenic wedge of the collision zone between the Trans Alai and the Tien Shan (Figs 1 and 2). The rock units exposed in the Nura region, integrating the Kyzyl-Suu river basin, include folded and thrust Neogene to Quaternary strata (Nikonov et al. 1983, Fig. 2). The faults and folds in the hanging wall of the PFT and 20 km east of the Nura village are associated with an evaporitic detachment and integrate shallow-marine and non-marine Palaeogene sediments (Dan & Terry 1985). A Palaeocene gypsum layer is exposed at the junction of the Kok-Suu and the Kyzyl-Suu rivers with an average thickness of approximately 200 m. Here it thrusts over Eocene silt and sandstones (Nikonov et al. 1983). We observed gypsum exposures also north of and along the IrkF, which emphasizes the importance of evaporites in this tectonic setting. The tectonic province at the eastern closure of the Alai valley also forms a tectonically controlled drainage divide between the Tajik basin in the west of the Pamir and the Tarim basin in the east (Fig. 1), highlighting the role of active tectonism in the landscape evolution of this region.

2.2 Regional seismicity and the Nura 2008 earthquake

The MPT and the PFT are characterized by frequent seismicity associated with the southward subduction of the Eurasian continental crust. In the National Earthquake Information Center (NEIC, United States Geological Survey) catalogue, approximately 267 earthquakes have been recorded with magnitudes of four and larger,
between 1973 and 2011 along the eastern edge of the Alai valley (between 73° E, 39.67° N and 74° E, 39.17° N). Eighty per cent of these events are at depths of less than 40 km.

During the last five decades apart from the 2008 Nura earthquake only two other large earthquakes have occurred in the region: in 1974 the Markansu earthquake and an aftershock of $M_w 6.1$ occurring on the same day (Fig. 2). The 1974 earthquakes are characterized by shallow focal depth of less than 7 km and by an oblique thrust mechanism with a component of strike-slip motion (Fig. 2; Fan et al. 1994). In contrast to the large earthquakes in 1974, the Nura event was well recorded by the TIPAGE network, which also had one seismic station in the Nura village (Mechie et al. 2012; Schneider et al. 2013; Sippl et al. 2013). Furthermore, short-period seismic stations close to the epicentre have been deployed 18 d after the earthquake (Krummbiegel et al. 2011; Mechie et al. 2012; Schneider et al. 2013; Sippl et al. 2013) as well as two additional instruments on the Chinese side of the border (Earthquake Administration of Xinjiang Uygur Autonomous Region), which resulted in valuable information about the aftershocks (Fig. 3).

The Nura main shock earthquake was located at a shallow centroid depth of 4 km along the east–west striking PFT, with the main shock moment tensor solution showing a dominant thrust mechanism and only a minor strike-slip component (Krummbiegel et al. 2011, Fig. 3). This suggests that the earthquake ruptured a segment of the PFT (Krummbiegel et al. 2011; Mechie et al. 2012; Schneider et al. 2013; Sippl et al. 2013) (Fig. 3). In addition, two aftershocks with $M_w > 5$ occurred on the PFT, whereas other moderate-sized aftershocks occurred further northeast, aligning closely with topographic features (Fig. 3). Based on network criteria Krummbiegel et al. (2011) estimated the absolute location precision to be better than 3 km, while relative location errors are significantly smaller.

### 3 SURFACE DISPLACEMENT MEASUREMENTS

SAR data for the Nura epicentral region are available from the ALOS (PALSAR L-band sensor with $\lambda = 23.6$ cm) and ENVISAT (ASAR C-band sensor with $\lambda = 5.6$ cm) satellites. We processed 16 ascending ALOS and seven descending ENVISAT images spanning from 2008 May 8 until 2009 August 20, and we formed differential interferograms and pixel offset maps. Ideally, by combining ascending and descending sets of observations and pixel offsets, 3-D displacements can be measured in the affected area (Wright et al. 2004; Fialko et al. 2005). To provide ground truthing to the SAR-based surface displacement maps, we complement our remote sensing investigations by structural field observations guided by our SAR results.

#### 3.1 InSAR and pixel offset processing

We processed 16 ascending ALOS images and 7 ENVISAT images, with perpendicular baselines of less than 300 m and temporal baselines of less than 14 months using the SARscape and the ROIPAC (Rosen et al. 2004) software packages (see Tables S1 and S2). We then selected one interferogram from each look direction for further analysis (Table 1). The chosen interferogram pairs provided optimal

![Figure 3. Main and aftershock location map of the Nura region with the activated (red colour) Pamir Frontal thrust (PFT) and the Irkeshtam fault (IrkF). The main shock (red star) moment tensor and aftershock locations are after Krummbiegel et al. (2011). The marked profile line (solid green line) is the cross-section of the postulated fault geometry at depth for the PFT and the IrkF shown in Fig. 10.](https://academic.oup.com/gji/article-abstract/198/2/760/597667)
coherence and had short perpendicular baselines, which are 91 m for the ALOS and 131 m for the ENVISAT image pairs (Table 1).

For the ALOS interferogram, we used multilook factors of 1 in the range direction and 5 in the azimuth direction, which resulted in a ground resolution of approximately 20 m × 20 m. To increase the low signal-to-noise ratio in the ENVISAT interferograms, we applied multi-looking factors of 16 in the range direction and 80 in the azimuth direction, which resulted in approximately 320 m of range ground resolution. We removed the topographic phase contribution in the interferograms by using the SRTM DEM data at 90 m resolution (Fan et al. 1994). The resulting differential interferograms were then filtered using an adaptive filter (Goldstein & Werner 1998). For the phase unwrapping, to resolve the 2π-phase ambiguity of the interferograms, we used the Snapphu software package (Chen & Zebker 2001). Noisy and uncorrelated areas, layovers, and unwrapping errors were masked out. Finally, we transform the unwrapped data from the satellite azimuth-range coordinates to ground coordinates, specifically, Universal Transverse Mercator (UTM) coordinates, and we retrieved the surface displacement maps in a cartographic reference frame (Fig. 4).

In addition to SAR interferometry, we used pixel offset estimates between amplitude images of the coseismic data pairs (Table 1) in the range and azimuth directions to measure ground displacements (Fig. 5). These pixel offsets were determined through a cross correlation of small subsets in the image, which provided measures of pixel shifts between the two images at a subpixel resolution. Pixel offset measurements in the image range direction complement the interferometric displacement measurements because they give the component of displacement in slant range direction (Michel & Rignot 1999), the same projection as the ALOS interferogram, but they do not suffer from phase ambiguity (Fig. 5). Pixel offset measurements in the azimuth direction, however, add a new displacement component that is purely horizontal in the satellite’s flight direction. We estimated the offsets with window sizes of 64 and 128 pixels in the range direction and the azimuth direction, respectively.

The range pixel offsets show sharp changes of the surface displacement at the IrkF (Fig. 5). Here we measure up to 1.5 m of displacement south of the IrkF. In the azimuth-pixel offsets, the observed displacement pattern shows a clear left-lateral component of movement along the IrkF (Fig. 5). The difference in the horizontal motion across this oblique thrust fault reaches 2 m.

3.2 Results of the surface displacement measurements

Measuring the coseismic surface displacement using InSAR is challenging in this region of high topographic relief because of abundant areas of layover and all-season snow coverage. In this case, the ALOS data perform better than the ENVISAT data (Fig. 4). The larger average radar-beam incidence angle of 39° emitted by the ALOS SAR sensor reduces layover in the interferograms compared to the 23° incidence angle of the ENVISAT SAR radar beam.

Furthermore, the L-band data are less sensitive to small changes on Earth’s surface relative to the C-band SAR data. Therefore, the L-band data preserve the coherence of the interferometric phase and backscatter characteristics over longer time spans. Although the ENVISAT data seem to be less suitable for measuring surface displacements in this environment, information gained from the different look angle in descending orbit is important and complements the ascending orbit data from ALOS (Wright et al. 2004).

In the ascending ALOS interferograms, we observe clear coseismic surface displacements mainly north of the PFT and at the IrkF (Fig. 4, top panel). We measure widespread motion away from the sensor of about −24 cm and a strong, more localized signal of movement towards the sensor in the northeastern part of the IrkF of about 48 cm. In the epicentral region more south large positive LOS displacements can be observed, but the phase coherence is not well enough preserved to reliably unwrap the interferometric phase for quantitative measures. In the descending ENVISAT interferogram the phase coherence is generally low and again only in the area north of the IrkF measurements of the surface displacements are possible. We here observe widespread motion towards the sensor with up to 6 cm of LOS displacement (Fig. 4, bottom panel). The large differences in the measured LOS displacements between the ascending and descending images are to be expected only for a considerable amount of E–W horizontal surface displacement.

In both interferograms the phase gradients increase from the north towards the IrkF. At the fault gradual phase changes become disrupted and/or the phase coherence is lost abruptly. These observations point to surface rupture. South of the PFT far-field surface displacements can be observed in both interferograms. They show slight positive to negative phase shift.

The pixel offsets add new information to our displacements measured by using InSAR. First, range and azimuth pixel offsets give coherent displacement measurements for the area south of the IrkF, where no InSAR data are available (Fig. 5). Secondly, azimuth pixel offsets provide another and purely horizontal component of the displacement field in an approximately N–S direction. The range pixel offsets show positive LOS displacements south of the IrkF of up to 2 m, pointing to an upward and/or westward motion. Directly at the IrkF and towards north the values drop to zero and less (Fig. 5, left-hand panel). The azimuth pixel offsets also give positive displacements south of the IrkF, reaching values of up to 2 m and showing a northward displacement (Fig. 5, right-hand panel). The values again drop rapidly across the IrkF and become negative. The observed step in the pixel offsets is a feature that extends continuously for approximately 25 km in a northeast–southwest direction, which aligns with the IrkF as mapped in the regional geological maps (Fig. 2). The azimuth pixel offset measurements are affected by strong and wavelike artifacts, that are known to occur for azimuth offset measurements using L-band SAR data (e.g. Gray et al. 2004).
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Figure 4. ALOS (top panel) and ENVISAT (bottom panel) interferograms in wrapped phase and over a shaded relief show the line-of-sight (LOS, black arrows) surface displacement close to the Nura earthquake epicentre (white star). White dashed lines outline the Pamir Frontal thrust (PFT) and the Irkeshtam fault (IrkF). The inset in the top panel shows an enlarged image of the in white outlined area, where steps in the interferometric phase values point to surface rupture.

These errors are caused by heterogeneities in the ionosphere, which behaves dispersive for radar waves. We describe the treatment of data errors in more detail in Section 4.1 and in the Supporting Information (Fig. S1).

3.3 Field observations

Our field work in the fall of 2012 aimed at ground truthing the SAR displacement measurements through mapping of the detected surface rupture of the Nura earthquake. The metre-scale displacements and the sharp discontinuities for a distance of approximately 25 km as defined in our SAR data analysis (Section 3.2) suggest that surface ruptures should be observable in the field.

Information given by locals in combination with our remote sensing data helped to identify prominent, 7-km-long ground ruptures southwest of the Nura settlement on the northwest side of the Nura river, which here flows parallel to the IrkF (Fig. 6). These ruptures constitute steep scarps and fractures in the soil-mantled surface,
with offsets of up to 80 cm (Fig. 6b). Furthermore, in these areas we found a number of fractured erratic glacial boulders that had formed transgranular extension fractures parallel to the surface trace of the rupture (Fig. 6c). Importantly, in addition to the clear vertical offsets associated with the fractures, we were able to observe left lateral displacements along the fractures. These kinematic markers are in excellent agreement with the SAR-measured displacements. Further details of these structural geologic and geomorphologic field investigations are beyond the framework of this study and will be presented in a separate study.

Another important and relevant observation during the field investigations was the observation of exposed evaporite sequences along the IrkF. Along the south side of a road between Nura village and the Chinese border, gypsum is observed within the Palaeo-Eocene stratigraphic sequence. This setting is similar to the better-documented stratigraphic sections farther east, on the Chinese side of the border, in the westernmost Tarim basin (Sobel et al. 2011, 2013). A stratigraphic correlation between these sequences is supported by the presence of Eocene fossils.

The presence of gypsum in the deformation zone may affect the overall rheology and therefore influence the tectonic pattern, the mode of thrust stacking and the nature of the strain partitioning along the strike. The extensive presence of evaporites may also have a major impact on the mechanics of coseismic deformation.

Based on these findings, we posit that the PFT and the IrkF are rooted in a common detachment at depth (Fig. 10). This explains why they were apparently activated during the same earthquake. We use these observations and considerations to infer a potential geometry of the PFT and the IrkF at depth (Fig. 10) and to further explore the nature of this geometry in non-linear and elastic fault modelling.

4 FAULT MODELLING

Using the InSAR surface displacements and the pixel offset measurements, we can potentially put constraints on the fault orientation at depth, the spatial extent, and the fault through non-linear fault modelling. Here we attempt to test if our hypothesis of the rupture continuation and rupture mechanisms (Fig. 10) are consistent with the observed surface displacement pattern at the PFT and the IrkF. In this area it is difficult to measure the surface displacement with sufficient spatial detail and with observations from different look angles to optimally constrain a fault model. We reach the best possible coverage of displacement measurements through the combination of different data sets: interferometric ascending ALOS L-band data and descending ENVISAT C-band data, as well as ALOS range and azimuth pixel offset measurements. While individual data sets are all affected by noise that differs in spatial structure and strength, we consider the variable data quality in the fault modelling through data weighting based on empirically estimated weighting factors as described below.

4.1 Data subsampling and weighting

Our data combination led to a large amount of data points that we could not implement for further digital data analysis. Therefore, we subsample the frequently smooth displacement signal by using the well-established Quadtree Algorithm (Jönsson et al. 2002). Quadtree subsampling enables a spatially irregular subsampling without loss of information and with further noise reduction. From a multimillion point data set we keep only a total number of 3177 points for all four data sets.

The different data sets to be combined have widely differing quality with respect to their signal-to-noise ratio and the amount of correlated data errors (Hanssen 2001), which depends on the sensor wavelength, the acquisition dates (e.g. with or without snow cover) and the temporal baseline between image pairs. To account for the variability of the error content, we form a data weighting matrix from empirically estimated data error variances and covariances. For this error estimation, we use sample variograms and sample covariograms from which we infer the error variances and covariance functions of the individual data sets as described in Sudhaus & Jönsson (2009). A special case here are the azimuth offsets that show a strong anisotropic error component. Here, we apply a simplified method for the error estimation in the presence of anisotropic noise (Knospe & Jönsson 2010) that considers an azimuthal dependence of the error-correlation length. We then combine all estimated variances and covariance functions to a single variance–covariance matrix used in the fault model optimization (for details see Supporting Information, Fig. S1). In this way, based on the data quality, we balance the individual data points in the fault model optimization, which has been shown to stabilize and improve the modelling results in highly non-linear inverse problems (Sudhaus & Jönsson 2009; Duputel et al. 2012).
Figure 6. Field observations of the surface rupture of the Nura earthquake in September 2012, which could be followed along 7 km (a). Surface trace offsets reached a maximum vertical offset of about 80 cm (b) and clear left-lateral motion (c). Photos from Edward Sobel.

4.2 Fault model set-up and optimization approach

For the fault modelling we use the widely applied rectangular dislocation model (Okada, 1985). This model represents the Earth’s crust with a homogeneous, purely elastic half-space and represents the embedded faults through planar, rectangular dislocations with a uniform fault slip. Given this model set-up, the formulations in Okada (1985) allow for analytical calculations of displacements at the surface. Although this model simplifies the faulting processes at depth, it is widely used in studies on earthquake sources, for example, Nissen et al. (2007), Jónsson et al. (2002) and Fialko et al. (2005). The rectangular dislocation model is useful because we often lack information about the actual material heterogeneities and structural complexities of the faults at depth, which is the case in our study, and the forward computation of the fault models is fast.

However, even for such a simplified model set-up, the estimation of fault properties, for example, fault location, orientation and slip on the fault, is a highly non-linear inverse problem. We approach it by using a direct search method (Sambridge 1999). Direct search entails searching a set of physically possible and geologically meaningful models that best reproduce the observed surface displacement data. Specifically, we use an evolutionary algorithm (Sambridge 1999), which mimics a natural selection process (‘survival of the fittest’).

To represent the coseismically activated faults as identified by seismological studies and in the surface displacement data (Fig. 10) with rectangular dislocations, we chose to use three dislocation planes. One of these segments represents the rupture at the PFT and two segments represent the faulting at the IrkF. For the segment at the PFT, we fix the location and fault strike based on
the seismological moment tensor characteristics of the Nura earthquake (Section 2.2 and Table 2). The free model parameters in the optimization for this segment are the dimensions of the fault segment, length and width, the depth of the fault, the fault dip and fault slip along strike and down dip. The relatively tight parameters ranges for fault length and width are chosen based on moment scaling relations (Mai & Beroza 2000). For the fault-model segments along the IrkF, we place constraints from the pixel offset analysis and our field observations, and we fix the fault location, the fault strike, and the segment length in the optimization. Also, we require the same rake for both IrkF segments. Furthermore, we place tight constraints on the poorly resolved fault width based on scaling relations (Mai & Beroza 2000). The remaining model parameters, the depth, the fault dip, the strike-slip, and the dip-slip components, are part of the model parameter space in the optimization (Table 2). With these constraints on the three fault segments we arrive at 14 fault model parameters to be optimized within the given parameter ranges (Table 2). While the common rake constrain on the IrkF segments reduced the model parameter independence to some extent. For the elastic half-space we chose a Poisson’s ratio of 0.29, since we consider relatively fast movements and therefore undrained conditions in the material (Peltzer 1992). In addition to the fault-model and medium parameters, we include data ambiguity parameters that account for common offsets, range, and azimuth linear ramps in the surface displacement measurements; we use three ambiguity parameters per data set, which amounts to 12 additional model parameters.

For the optimization, in our implementation of an evolutionary algorithm, we first randomly pick a set of 200 candidate fault models from the described parameter space. From these candidate models we then chose the best performing half of the models. The criterion for the selection is the misfit between the predicted and the observed data, with misfit function being the $l_2$-norm of the weighted data residuals. These selected models are commonly called the parent generation. The parent models are then used to seed a next model generation, the offspring, by recombining the model parameters to form new models and by altering the parameters of these new models to some extend, which is called mutation. In this way we from 200 offspring models and again do a selection as before to find the next parent generation. We tested different numbers for the size of the parent and offspring populations as well as for the number of generations. We found that we obtain stable solutions for the given population sizes and 500 generations.

### 4.3 Fault model for the Nura earthquake

Our optimization results in a fault model in which the PFT has a steep southward dip of 80° involving 0.9 m of fault dip-slip and negligible strike-slip (Fig. 7). The eastern part of the IrkF dips south with an angle of 37° and becomes steeper to approximately 44° towards the west. The slip estimates at the IrkF’s first and second segment give an oblique thrust mechanism with 1.6 and 2 m of fault dip-slip, and 1 and 1.3 m of left-lateral fault strike-slip, respectively (Table 2). The slip rake, calculated based on the obtained dip-slip and strike-slip components, is 90° for the PFT and 57° for the IrkF segments (Table 2). In combination, the optimum faults form a complex structure with reverse and strike-slip faulting.

The fit of the predicted surface displacements to the observed ones is not entirely satisfying. Obvious is the underestimation of the surface displacements in the hanging wall of the IrkF (Fig. 8). The footwall displacements at the PFT, including the rupture at the IrkF, are generally well modelled as is the far-field in more than 20 km distance from the epicentre (Figs 7 and 8).

### 5 DISCUSSION

The SAR surface displacement measurements of the Nura earthquake and their analysis reveal three important results. First, the Nura earthquake nucleated at the PFT, where a major part of coseismic deformation took place in the footwall. Secondly, we observe surface ruptures along the IrkF to the north of the PFT, where no aftershock activity is observed. Thirdly, we find generally larger surface displacements in the hanging wall of the IrkF than in its footwall (Figs 4 and 5). There is a complex interplay of active faults in the Nura region, which we discuss in the following sections.

#### 5.1 Fault kinematics in the Nura region

The Nura earthquake activated the E–W striking PFT and the SW–NE striking IrkF. Along the active part of the PFT we found evidence for thrust faulting, which is consistent with the seismological analysis of the main shock and the aftershock sequence (Krummigiel et al. 2011). For the IrkF, we found evidence for oblique thrusting, with a significant left-lateral strike-slip component. These observations clearly document that strain partitioning must have taken place between the two faults. From the fault geometry and differential uplift at the surface, we conclude that the PFT and the IrkF likely
Figure 7. InSAR data model results. ALOS (top panels) and ENVISAT (bottom panels) observed data (left-hand panels), predicted data (middle panels) and residuals (right-hand panels) for the three-segments optimum model representing the Pamir Frontal thrust and the Irkeshtam fault. The map-projected segments are marked in solid black lines, thick lines mark the upper edge. Aftershock locations are shown with blue dots.

Figure 8. Pixel offset model results. ALOS range (top panels) and azimuth (bottom panels) observed pixel offsets (left-hand panels), predicted pixel offsets (middle panels) and residuals (right-hand panels) for the three-segments optimum model representing the Pamir Frontal thrust and the Irkeshtam fault. The map-projected segments are marked in solid black lines, thick lines mark the upper edge. Aftershock locations are shown with blue dots.
share a common root at depth. This hypothesis was strengthened by the fault modelling, which requires a steeper fault geometry for the PFT than for the IrKF. The faults therefore seem to form part of an imbricate thrust system (Fig. 10). This is important because it supports the view that the current mountain front of the Trans Alai is part of a northward-advancing thrust wedge that successively involves sectors of the Trans Alai piedmont (e.g. Coutand et al. 2002; Strecker et al. 2003; Sobel et al. 2013).

We observe that the hanging wall of the IrKF accommodates a large part of the N–S contraction relative to the N–S contraction at the PFT. The IrKF is the focus of the highest surface displacement evident from InSAR and pixel-offset measurements (Figs 4 and 5) as well as mapped surface ruptures in the field (Fig. 6). While there is no direct evidence from the seismological data that the IrKF was coseismically active, the transgranular fractures in the boulders found at the fault surface trace (Fig. 6) point to a sudden rupture with high-frequency seismic waves. Because no aftershocks have been observed near the IrKF (Krumbiegel et al. 2011), we conclude that the rupture of the IrKF was coseismic and concurrent with the Nura main shock.

Moreover, the NE–SW strike of the IrKF, which deviates from the E–W dominated structural pattern west of the Nura region, combined with a significant left-lateral strike-slip component on the fault seems to indicate a general pattern of deformation in this sector of the orogenic front (Fig. 3; Krumbiegel et al. 2011; Mechie et al. 2012; Schneider et al. 2013; Sippl et al. 2013). The observed strain partitioning of the N–S contraction into northward thrusting on the E–W striking thrusts and frontal, NE–SW striking sinistrally-oblique thrusting appears to be the predominant tectonic mode.

5.2 Fault mechanics and moment estimates

We estimated the orientation and the fault mechanisms of the active fault segments at depth through analytical dislocation modelling. In this model approach, we assume uniform slip on the faults and a homogeneous elastic medium. We further constrained the location and orientation of the fault at the surface based on our combined data set. We find a qualitatively good agreement between the pattern of the observed and the predicted surface displacements. As described in Section 4.3, however, at the hanging wall of the IrKF the predicted pixel offsets from our best model do not reach the large surface displacement values as measured, with discrepancies amounting to 1 m. Therefore, the model results on the fault dip and slip need to be taken with care, since the estimated model parameters could be biased to an unknown extent. To increase the displacement predictions for the hanging wall of the IrKF, a larger fault slip and/or a more shallow fault dip would be needed. We find that this leads to significant changes in the predicted footwall surface displacements, which are well explained with our optimal model.

The reason for this data-model-mismatch resulting from the purely kinematic rectangular dislocation models might be that this model forces symmetric fault slips on both sides of the dislocation, each accounting for half of the total slip. Additionally, other simplifications of the chosen dislocation model could contribute to the apparent data-model-mismatch, including the oversimplified fault geometry through forced planar dislocations with a uniform slip. We think, however, that the influences of the oversimplified dislocations are second-order to an oversimplified material, as the parameters of the dislocations are part of the optimization, which provides estimates of average values. In contrast, the material properties are assumed before any modelling.

![Figure 9. Test of asymmetric slip hypothesis. (a) Bars show the variance reduction through modelling per data set and distinguishing footwall and hanging wall areas of the Irkeshtam fault. The InSAR data sets provide footwall data only, the range and azimuth pixel offset measurements have been spatially divided (see b and c, respectively) into footwall and hanging wall areas. Shaded horizontal lines at each of the bars give the corresponding variance reduction for increased slip on the fault model (geometry kept fixed) for factors of 1.3–1.8.](https://academic.oup.com/gji/article-summary/198/2/760/597667)
The 2008 Nura earthquake

Figure 10. Interpreted cross section (for location see Fig. 3) across active Pamir Frontal thrust (PFT) and Irkeshtam fault (IrkF) with aftershock locations (green circles). For visualization the gypsum layer possibly exaggerated in thickness.

rocks (Robertson et al. 1958; Bell 1981). If these weak materials were associated with a fault zone, they could be subject to inelastic deformation and effectively decrease the friction of the fault.

Moment magnitude estimates based on our model provide slightly larger values than the seismically inferred. The moment magnitude, $M_w$, is calculated via the geodetic moment through the equation:

$$M_w = \frac{2}{3}M_0 - 0.03 \quad (\text{Kanamori 1977}),$$

where $M_0 = \mu A \bar{D}$, and where $\mu$ is the assumed average crustal rigidity of 30 GPa, $A$ is the fault area and $\bar{D}$ is the average slip on the fault. With our optimum model we derive geodetic moments of $4.99 \times 10^{18}$Nm for the PFT, corresponding to $M_w6.43$, and a larger geodetic moment of $5.43 \times 10^{18}$Nm for the IrkF, which corresponds to $M_w6.46$. Taken together, the moments for both faults add up to $M_w6.65$ for the Nura earthquake, which is similar to the seismically estimated $M_w6.6$ (e.g. Krummbiegel et al. 2011).

More indications for a coseismic rupture with little fault friction at the IrkF could be obtained from a comparison of $M_w$ and the energy magnitude, $M_e$ (Choy & Boatwright 1995). While for many earthquakes, $M_w$ and $M_e$ are similar, low-friction earthquakes with high stress drops generate high-frequency seismic waves, which add to $M_e$ more strongly than to $M_w$ (e.g. Bormann & Di Giacomo 2011). For the Nura earthquake, the USGS reports $M_e7.5$, which is significantly larger than the seismic estimate of $M_w6.6$ (Krummbiegel et al. 2011). Convers & Newman (2011), however, provide a second estimation of $M_w6.6$, which is as large as $M_e$.

Concerning the coseismic fault slip at the IrkF, we interpret the fractured boulders along the surface ruptures as important indicators of coseismic behavior of both faults (see Sections 3.3 and 5.1).

However, to infer the fault slip in our modelling, we use the measured surface displacement from the interferograms that span several months of post-seismic time (10 months for the ALOS data and close to 8 months for the ENVISAT data). Therefore, a significant part of the fault slip could have been generated post-seismically, for example, through afterslip (Scholz 1998). Afterslip is commonly observed in the shallow parts of coseismically activated faults, in which the material properties favour stable sliding (Marone et al. 1991). Unfortunately, the available post-seismic pairs that we processed do not show any significant post-seismic displacements or have a decorrelated interferometric phase in the area of interest, likely because of snow.

5.3 Implications for regional tectonics

From the fault kinematics and the fault mechanics that we have discussed, we form a synthesis of the gathered information and integrate it with the given geology and tectonics of the eastern Pamir-Tien Shan collision zone. Evidently, the Nura earthquake activated a contractional frontal wedge in the footwall of the MPT. The interpretation of the fault geometry and activity as well of the PFT as of the IrkF and the interplay of rock units at depth, are accommodated with the main N–S shortening direction (Fig. 10). The profile shows a distinct change in the lithology across the back-range fault, the PFT, and the front-range fault, the IrkF. At the back-range fault consolidated, folded Cenozoic sediments are upthrust over Paleozoic basement units. At the front-range fault, Quaternary alluvial and Palaeogene pre-orogenic continental sediments have been thrust...
over and left-laterally displaced to the north east along the IrkF zone, that presents a gypsum dominated tectonic mélangé and thick detachment horizon (Fig. 10). The PFT divides two competent rock units and, therefore, appears to facilitate the nucleation of earthquakes, as evident from the Nura epicentre and main shock location and the aftershock concentration observed there. The IrkF forms a boundary between the more competent rock units of the Palaeozoic sediments in the south and the weak rock units of the poorly lithified, gypsum-bearing Palaeogene strata in the north (Fig. 10). The northern structures are dominated by intensely folded and up to 2-km-thick Palaeogene sediments with a high content of mechanically weak gypsum. Gypsum is inferred to lubricate the fault and to facilitate material transport. Such a scenario would explain the relatively high displacements as measured for the hanging wall structure and the lack of seismicity relating to the IrkF zone. We therefore interpret the IrkF as a rather aseismic décollement.

The presence of thick and mechanically weak layers pose questions concerning earthquake characteristics also elsewhere, such as in the Zagros Simply Folded Belt, Iran (e.g. Nissen et al. 2010; Barnhart & Lohman 2013) and in the Cordillera de la Sal, Chile (Kuhn & Reuther 1999). In the Zagros mountains, seismically and geodetically inferred ruptures of moderate to large earthquakes seem to be systematically displaced to more shallow depths with respect to the volumes outlined by aftershock activity. The situation resembles the presented Irkeshtam rupture and the off-set aftershock sequence of the Nura earthquake. Possibly, the proposed significant role of aseismic slip in the Zagros (Barnhart & Lohman 2013) finds a parallel in the faulting style in the north-eastern foothall of the Pamir.

In the Nura region, the northward motion of the Pamir and its collision with the Tien Shan constitutes a fold-and-thrust belt, in which the thrust wedge has been accreted over detachments (Nikonov et al. 1983). One of these detachments might be responsible for the basement structures of the frontal thrust system and associated structures investigated here, similar to other areas along the Indo-Asian collision, such as the Trans-Indus ranges of Pakistan (e.g. Blisniuk et al. 1996, 1998; Ahmad et al. 2005).

### 6 CONCLUSIONS

In our study, we demonstrate the usefulness of InSAR and pixel offset techniques for measuring surface displacements in combination with geological observations and seismological data to enhance our understanding of active tectonics in a structurally complex continental collision zone. We found that the 2008 Nura earthquake (Mw 6.6) ruptured an imbricated thrust system. This thrust system is part of the PFT and constitutes a fold-and-thrust belt in the eastern convex transition of the Trans Alai range, where it collides with the Tien Shan to the north. The IrkF at the deformation front is a moderate-angle décollement fault that seems to be controlled by mechanically weak evaporites lubricating the fault. This fault was coseismically activated by the Nura earthquake, as documented by prominent surface ruptures and fractured boulders along the trace of the rupture; meanwhile, the earthquake nucleated at the back- range PFT. The Nura earthquake thus caused dip-slip thrusting and sinistrally oblique thrusting on the kinematically connected PFT and the IrkF. This event presents an example of coseismic strain partitioning in a tectonically active collision zone, which is characterized by northward orogenic wedge migration toward the Tien Shan mountains.

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### REFERENCES


Table S1. Processed interferograms, bold letters denote the interferograms used in the analyses and model estimation.

Table S2. Processed interferograms continued.

Figure S1. Error estimation results for ALOS and ENVISAT InSAR data as well a the pixel offset measurements. (a) InSAR covariogram samples (points) and the fitted variance-covariance functions (dashed lines), (b) covariogram samples (points) and fitted variance-covariance function (dashed line) for the ALOS range pixel offsets, (c) ALOS azimuth pixel offset measurements of the entire ALOS frame with masked out deformation area for error estimation, (d) Azimuth dependent covariance estimation for the ALOS azimuth pixel offset measurements. The left hemisphere of the polar plot gives the covariogram values per distance and the right hemisphere the fitted covariance function. The estimated variance is plotted at zero distance was done.

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