Fault geometry of 2015, Mw7.2 Murghab, Tajikistan earthquake controls rupture propagation: Insights from InSAR and seismological data

Simran Sangha^a, Gilles Peltzer^{a,b}, Ailin Zhang^a, Lingsen Meng^a, Cunren Liang^b, Paul Lundgren^b, Eric Fielding^b

^a*Earth, Planetary, and Space Science Department, University of California, Los Angeles, California, USA*

^b*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA*

Abstract

Combining space-based geodetic and array seismology observations can provide detailed information about earthquake ruptures in remote regions. Here we use Landsat-8 imagery and ALOS-2 and Sentinel-1 radar interferometry data combined with data from the European seismology network to describe the source of the December 7, 2015, Mw7.2 Murghab (Tajikistan) earthquake. The earthquake reactivated a ~ 79 km-long section of the Sarez-Karakul Fault, a NE oriented sinistral, trans-tensional fault in northern Pamir. Pixel offset data delineate the geometry of the surface break and line of sight ground shifts from two descending and three ascending interferograms constrain the fault dip and slip solution. Two right-stepping, NE-striking segments connected by a more easterly oriented segment, sub-vertical or steeply dipping to the west were involved. The solution shows two main patches of slip with up to 3.5 m of left lateral slip on the southern and central fault segments. The northern segment has a left-lateral and normal oblique slip of up to a meter. Back-projection of high-frequency seismic waves

Preprint submitted to Earth and Planetary Science Letters

January 11, 2017

recorded by the European network, processed using the Multitaper-MUSIC approach, focuses sharply along the surface break. The time progression of the high-frequency radiators shows that, after a 10 second initiation phase at slow speed, the rupture progresses in 2 phases at super-shear velocity ($\sim 4.3\text{-}5$ km/s) separated by a 3 second interval of slower propagation corresponding to the passage through the restraining bend. The intensity of the high-frequency radiation reaches maxima during the initial and middle phases of slow propagation and is reduced by $\sim 50\%$ during the super-shear phases of the propagation. These findings are consistent with studies of other strike-slip earthquakes in continental domain, showing the importance of fault geometric complexities in controlling the speed of fault propagation and related spatiotemporal pattern of the high-frequency radiation.

Keywords: Earthquake, Tajikistan, InSAR, Geodesy, Seismology, Back-projection

1. Introduction

The earthquake occurred on December 7, 2015 on the Sarez-Karakul Fault (SKF), in the Gorno-Badakshan Autonomous Region of Eastern Tajikistan. Its moment magnitude (M_w) is 7.2 and its centroid moment tensor and distribution of aftershocks indicate left-lateral, strike-slip movement on a NE oriented, nearly vertical fault (USGS, 2015). The earthquake has a similar magnitude and mechanism as the Sarez-Pamir earthquake, which stroke the region on 18 February 1911 (Kulikova et al., 2016). The 1911 earthquake triggered a massive landslide, building a 600 m high dam known as the Usoi Dam on the Murghab River, which resulted in the formation of Sarez Lake

11 (Schuster and Alford, 2004; Ambraseys and Bilham, 2012). No damage to
12 Usoi Dam was reported following the 2015 event but the seismic hazard in
13 the region makes it a sensible target of study. Important questions to be
14 addressed touch on the significance of the 2015 event within the current tec-
15 tonic regime of the Pamir Mountains, the characterization of its rupture and
16 direction of propagation and the possible implications for the dam stability
17 (ISDR, 2000).

18 In this paper we use satellite optical and radar interferometry (InSAR)
19 data jointly with seismological data to describe the source of the 2015 earth-
20 quake. In the following sections we summarize the tectonic setting of the
21 region, describe the geometry of the fault rupture, and present the static slip
22 solution obtained by inversion of InSAR data. The second part of the paper
23 presents the seismological data used in a back-projection method to describe
24 the rupture propagation with time. The last section discusses the correspon-
25 dence between the migration of the source location of high-frequency waves
26 with geometric complexities of the rupture and the implications of these ob-
27 servations.

28

29 **2. Tectonic setting**

30 The Pamir Mountains developed at the western syntaxis of the Himalaya
31 collision front, north of the Indus-Tsang-Po Tertiary suture zone. They are
32 composed of an assemblage of East-West trending belts squeezed between
33 Paleozoic, Mesozoic, and Tertiary suture zones (Burtman and Molnar, 1993).
34 Since the onset of the collision, north-south shortening is accommodated by

35 a series of thrust systems raising the elevation of the mountains to ~ 4500 m,
 36 between the Tajik depression to the west and the Tarim Basin to the East
 37 (Fig. 1). Seismological (Burtman and Molnar, 1993; Pegler and Das, 1998;
 38 Sippl et al., 2013; Schurr et al., 2014) and geological observations (Tapponnier
 39 et al., 1981; Coutand et al., 2002) have shown that a large fraction of the
 40 India-Asia convergence has been absorbed by southward subduction of the
 41 Asian crust along the Main Pamir Thrust to the north and the northward
 42 subduction of the Indian plate to the south. The northward migration of the
 43 Pamir is accommodated along its eastern front by right-lateral movement on
 44 the Kashgar-Yecheng fault system and more internally by the Kongur Shan
 45 fault system, a well-developed right-lateral, transtensional fault system that
 46 connects to the Tashgorgan Fault and eventually the Karakorum Fault to the
 47 south (Robinson et al., 2004; Chevalier et al., 2011, 2015; Robinson et al.,
 48 2015; Chevalier et al., 2016). Along its western side, the northward movement
 49 of the Pamir is accommodated by left-lateral movement on a north-south
 50 shear zone including the Darvaz and the Badakhshan faults connecting to the
 51 Chaman and Herat faults to the south (Cowgill, 2010; Mohadjer et al., 2010;
 52 Schurr et al., 2014) (Fig. 1). Shallow seismicity of central and northern Pamir
 53 indicates that present-day deformation within the range is concentrated in
 54 the center and west side of the northern half of the range (Strecker et al.,
 55 1995; Sippl et al., 2013; Schurr et al., 2014; Kulikova et al., 2016). Campaign
 56 GPS velocities indicate a rather consistent NNW movement of the interior of
 57 the Pamir at a rate of ~ 13 -20 mm/yr with respect to stable Eurasia (Reigber
 58 et al., 2001; Mohadjer et al., 2010; Zubovich et al., 2010; Ischuk et al., 2013;
 59 Zubovich et al., 2016) suggesting that the rate of the internal deformation of

60 the range is low compared to the rate of convergence along the Main Pamir
61 Thrust.

62 The SKF is a $\sim$ NE striking fault that extends from Sarez Lake to Karakul
63 Lake in central northern Pamir and seems to extend towards the SW in
64 a more distributed shear zone south of the Sarez-Murghab Thrust System
65 (Fig. 1), (Sippl et al., 2013). A cluster of shallow seismicity occurs at the
66 intersection of the two fault systems. A NE-SW trend of seismicity high-
67 lights the shear zone with focal solutions consistent with sinistral slip on
68 NE oriented planes (Schurr et al., 2014). In the NE part of the Karakul
69 Lake Valley, Strecker et al. (1995) describe the SKF surface morphology as
70 a set of en echelon segments bearing evidence of down-dip and left-lateral
71 movements. However, the source mechanisms of the few small earthquakes
72 along the fault trace, the 2015 Mw7.2 event, and its aftershocks, all indicate
73 sinistral strike slip as opposed to oblique or normal slip (Schurr et al., 2014).
74 Although the main fault of this asymmetric graben runs along the western
75 side of the valley (Komatsu, 2016), south of Karakul Lake the recent faulting
76 activity is observed along the eastern side of the valley with vertical and
77 left-lateral offsets of glacial deposits, small stream channels, and fluvial ter-
78 races (Strecker et al., 1995; Schurr et al., 2014; Komatsu, 2016). South of the
79 valley, the fault enters a region of high relief in the direction of Sarez Lake.
80 Observation of the surface morphology in high resolution SPOT and Digital
81 Globe satellite images available on the Google Earth server shows a region of
82 rugged terrain with snow covered peaks, deeply incised valleys, steep and fast
83 eroding slopes and many occurrences of landslides, which obscure potentially
84 active fault scarps in the morphology. As a result, the SKF morphological

85 trace cannot be followed in the area of the 2015 epicenter, which is located
86 in the vicinity of Sarez Lake (USGS, 2015).

87

88 **3. The 2015 Murghab surface rupture and model fault geometry**

89 The SKF system is the only active fault system in the Pamir's interior
90 that strikes NE and exhibits sinistral motion according to geomorphological
91 and seismic observations (Strecker et al., 1995; Schurr et al., 2014; Kulikova
92 et al., 2016). It is best exposed along the eastern side of the Karakul Valley
93 between the Sarez and Karakul lakes. To determine the extent of the 2015
94 rupture along the fault system, we combined observations of the mainshock
95 surface displacement obtained by pixel correlation of Landsat-8 panchromatic
96 images and ALOS-2 radar amplitude images, along with observations of in-
97 terferograms formed with Sentinel-1A and ALOS-2 radar data (Fig. 2, 3, S1,
98 S2, S3).

99 The correlation of Landsat-8 images acquired before and after the event
100 was calculated using the COSI-Corr software (Leprince et al., 2007). Despite
101 the severe relief of the Pamir, which resulted in a low SNR in some areas of
102 the map, both the E and N components of surface displacement show a clear
103 discontinuity along a ~ 35 km-long segment aligned with the exposed fault
104 extending from the high relief area north of Sarez Lake to the south part of
105 the Karakul Valley (Fig. 2 and S1). We combine the East (E) and North
106 (N) components of the surface displacement into the fault-parallel component
107 $D = N \times \cos(\alpha) + E \times \sin(\alpha)$, assuming a constant fault azimuth ($\alpha = \text{N}54.6^\circ\text{E}$)
108 to construct the fault slip distribution curve for the section where the break

109 reached the surface (Fig. 2c). The distribution shows a trimodal distribution
110 with maxima reaching 2.7, 3.7, and 4.3 m along the 30 km section of the
111 fault north-east of the epicenter. The fault geometry obtained with Landsat
112 data is corroborated by the discontinuity observed in the azimuth offset field
113 obtained with ALOS-2 radar data (Fig. S2). Despite the noise due to the
114 lack of correlation of the amplitude pixels (see Supplementary Information),
115 the combined observations of Landsat-8 and ALOS-2 pixel offsets allowed us
116 to map the rupture up to the point where it enters the Karakul Valley (Fig.
117 S2).

118 The fringe pattern observed in the coseismic interferograms clearly shows
119 that the fault activated during the 2015 event extends into the Karakul Valley
120 (Fig. 3). However, the continuity of interferometric phase across the valley
121 indicates that the rupture did not reach the surface along that section. The
122 density of fringes suggests that slip occurred at shallow depth under the
123 valley floor up to the latitude of $N38^{\circ}32'$ (Fig. 3).

124 We combined these observations to construct a simplified fault model
125 formed of two right-stepping, $\sim$ NE oriented en-echelon segments, connected
126 by a shorter segment more easterly oriented. The southern segment corre-
127 sponds to the Sarez Lake area where the rupture started. The modeled fault
128 is extended both to the north and to the south to account for possible slip
129 at depth beyond the section that could be mapped from surface movement
130 (Fig. 3).

131

132 4. InSAR data

133 We used synthetic aperture radar (SAR) data from two satellite mis-
134 sions: the European Space Agency’s (ESA) C-band Sentinel-1A and the
135 Japan Aerospace Exploration Agency’s (JAXA) L-band Advanced Land Ob-
136 servation Satellite 2 (ALOS-2) missions. Five interferograms spanning the
137 mainshock event were generated using the InSAR Scientific Computing En-
138 vironment (ISCE) software (Rosen et al., 2012). A modified version of ISCE
139 was used for the ALOS-2 wide swath/stripmap data pairs (Liang and Field-
140 ing, 2016).

141 All interferograms were multilooked, filtered by a power-spectrum filter
142 (Goldstein and Werner, 1998), and projected in a geographic coordinate sys-
143 tem for further analysis. The phase unwrapping was performed using the
144 branch-cut method (Goldstein et al., 1988) through a module of the Repeat
145 Orbit Interferometry PACkage (ROIPAC) software (Rosen et al., 2004), al-
146 lowing us to achieve a conservative yet complete unwrapping of the coherent
147 parts of the images in the vicinity of the surface rupture. Unlike other un-
148 wrapping approaches, this module allowed us to limit the extent of the un-
149 wrapped phase field in noisy areas and recover isolated, coherent patches of
150 phase using manual cuts and bridges. This proved to be effective in the areas
151 of rugged topography and in the vicinity of the surface rupture where the
152 combined effects of foreshortening, shadow, ionospheric noise, tropospheric
153 noise, and phase aliasing render automatic unwrapping impossible.

154 The ALOS-2 descending tracks and both Sentinel-1A tracks were acquired
155 in wide swath mode and cover the full extent of the 2015 rupture while the
156 ALOS-2 ascending tracks were acquired in stripmap mode and only partially

157 cover the surface rupture (Table S1, Fig. S3). The variety of viewing direc-
158 tions from ascending and descending passes of the satellites offers an excellent
159 measure of the surface displacement field around the rupture.

160

161 **5. Variable slip solution from InSAR data**

162 The five interferograms in Fig. S3 are used to constrain the fault geom-
163 etry and kinematic parameters of the coseismic model. The data are first
164 subsampled using a quad-tree approach to reduce the number of data points,
165 keeping more points in the zones of higher phase gradient (Jónsson et al.,
166 2002) (Fig. 4). The fault is approximated by three rectangular planes aligned
167 with the surface segments determined in Section 3. The dip angles of the pla-
168 nar faults are not imposed and are adjusted in the inversion, while all other
169 geometric parameters are fixed for each fault segment (Table 1). Each fault
170 plane is divided into 2.7-3.4 km x 2.5 km fault patches and the strike-slip and
171 down-dip components of slip are estimated for each fault patch. In addition,
172 a smoothing coefficient controlling the strength of a Laplacian smoothing
173 operator, which is applied to two components of slip over the entire fault, is
174 also estimated. The solution is tapered down to zero along the north, south,
175 and bottom edges of the fault but the slip is not forced to zero along the
176 vertical edges between contiguous fault planes.

177 The inversion method uses a hybrid approach combining a Bayesian ap-
178 proach based on the Markov chain Monte Carlo (MCMC) sampling of the
179 parameter space defining the fault geometry and the smoothing coefficient
180 with prior probability distributions, and a restricted, least-squares inversion

181 to solve for the slip components (Fukuda and Johnson, 2008; Lundgren et al.,
182 2013). At each sample iteration of the fault segments' dip angles and smooth-
183 ing coefficient, a slip distribution solution is estimated using a singular-value
184 decomposition (SVD) inversion with a Laplacian regularization. The solu-
185 tion is kept in a Markov chain if the weighted RMS of the fit is improved
186 relative to the previous kept solution (Fukuda and Johnson, 2008). When
187 convergence is achieved, the statistics on the solutions kept in the Markov
188 chain give the posterior probability density distribution for the sampled pa-
189 rameters (Fig. 5 and S4), defining the most probable solution and confidence
190 intervals.

191 The slip solution corresponding to the most probable fault geometry and
192 smoothing coefficient is shown in Fig. 6. The three fault segments all have
193 steep dips (Table 1) and the slip mostly horizontal (Fig. 6), consistent with
194 the CMT solution of the event (USGS, 2015). A large patch of slip (up to
195 ~ 3.5 m) covers about two thirds of the southern segment and most of the
196 central segment between the surface and a depth of ~ 15 km. The hypocen-
197 ter of the earthquake (USGS, 2015) is located at the southern end of this
198 patch. Slip on the northern segment reaches about a meter and is rather
199 uniformly distributed over most of the fault plane down to 20 km. On the
200 northern segment, the slip has a significant down-dip component consistent
201 with normal faulting on a west dipping plane.

202 Our final coseismic model leads to a satisfactory fit to the five interfer-
203 ograms (Fig. 4). The largest misfits are observed in the near-field of the
204 surface rupture near the junction along the central and northern segments
205 of the fault. A reason for this misfit is the simplified geometry and slip dis-

206 cretization of the modeled fault, which do not follow the likely complexities
207 of the real breaks. The other reason of the misfit could be due to non-
208 elastic deformation associated with ground settlement and landslides in the
209 Karakul Valley. Ground settlement may be produced by the shaking during
210 the earthquake or be associated with the permafrost active layer condition
211 changes during the time spanned by interferograms. The fault runs along
212 the eastern side of the valley where periglacial geomorphic features can be
213 observed in Landsat-8 images and high resolution images available on Google
214 Earth. Furthermore, two of the ALOS-2 interferograms have pre-earthquake
215 images acquired ~ 5 and ~ 16 months before the event and they may show
216 ground movement in the permafrost active layer in the Karakul Valley.

217 The CMT seismic moment for this event was reported as $\sim 7.8 \times 10^{19}$
218 Nm from the Global Centroid Moment Tensor catalog (GCMT) and as
219 $\sim 10.1 \times 10^{19}$ Nm from the National Earthquake Information Center (NEIC)
220 (USGS, 2015), which respectively correspond to 57% and 74% of the total
221 geodetic moment of $\sim 13.70 \times 10^{19}$ Nm we estimated (Table 1). It is generally
222 observed that the geodetic moment exceeds seismic moment. For instance,
223 a study on sites through Mediterranean Europe and Turkey indicates that
224 seismic moment may vary between 22-71% of the geodetic moment (Ward,
225 1998). All post-earthquake images used in the present study are acquired
226 between 12 December 2015 and 13 January 2016, so the geodetic moment
227 may include a postseismic contribution from aseismic deformation. While
228 preseismic scenes were acquired up to 16 months before the event, the low
229 internal rate of deformation within the interior of the Pamir (Reigber et al.,
230 2001; Mohadjer et al., 2010; Zubovich et al., 2010, 2016) suggests there is

231 unlikely a significant contribution from preseismic deformation.

232

233 **6. Seismological observations**

234 The kinematic rupture process of the 2015 Mw7.2 Murghab earthquake is
235 effectively captured by the back-projection (BP) approach. We adopted the
236 Multitaper-MUSIC array processing technique (Meng et al., 2011), which
237 resolves closely spaced sources and is less sensitive to aliasing, yielding a
238 sharper image of the rupture process than the standard beamforming ap-
239 proach (Ishii et al., 2005). We also applied a 'reference window' strategy,
240 which eliminates the 'swimming' artifacts, a systematic apparent drift of the
241 high-frequency energy towards the station arrays. We performed the BP
242 analysis on coherent seismograms recorded by the European seismic network
243 (EU), composed of 57 broadband stations evenly distributed across conti-
244 nental Europe with epicentral distances between 40° and 60° (Fig. 7b). The
245 data of the EU network are available from the IRIS website (IRIS, 2016).
246 The seismograms are filtered between 2s and 0.5s, the highest band with
247 adequate waveform coherency. The first 5s of the P-wave arrivals are aligned
248 with a multichannel cross-correlation technique.

249 In standard BP, the travel times from sub-source locations to receiver sta-
250 tions are calculated based on 1D reference velocity models (e.g. IASP91). To
251 account for the travel time variations due to 3D Earth structures, BP applies
252 a timing correction inferred from the hypocenter alignment. This procedure
253 assumes that initial P wave arrivals originate from the International Seis-
254 mological Center (ISC) hypocenter location (73.20° E, 40.38° N). A set of

255 travel time errors due to 3D structures is obtained by cross-correlating the
 256 initial 5s of the P waves. The subsequent ruptures are tracked based on
 257 their differential travel times relative to the hypocenter. This strategy works
 258 when the source is close to the hypocenter but become less effective when
 259 the source moves away from the hypocenter. To account for the travel time
 260 error at distant source location, we apply an additional correction of slow-
 261 ness (ray parameter) that controls the trade-off between source location and
 262 travel time. In our previous work of the 2015 Mw7.8 Gorkha earthquake,
 263 we demonstrate that the slowness calibration effectively mitigates the spa-
 264 tial biases of BP source locations (Meng et al., 2016). In that paper, we also
 265 confirm that the slowness-calibrated BP resolves synthetic kinematic rupture
 266 scenarios constructed with empirical Green’s functions. The correction term
 267 of slowness can be effectively calibrated using the location errors of the after-
 268 shocks. In the case of the Murghab earthquake, we derived the slowness error
 269 based on a Mw5.4 aftershock that occurred on 12/07/15 with a hypocenter of
 270 38.64° N, 73.20° E at a depth of 19.9 km, located at the northeast end of the
 271 Murghab mainshock rupture. Its catalog epicenter and the source location
 272 inferred from back-projection is shown in Fig. 7a. We compared the relative
 273 separations between the mainshock and aftershock epicenter locations—with
 274 respective uncertainties of 5.5 km and 5.7 km—in both the NEIC (~ 60.97
 275 km) and ISC (~ 65.17 km) catalogues (USGS, 2015; ISC, 2016). The relative
 276 separation of ~ 4.2 km is reasonably small, which is essential for a reliable
 277 slowness calibration.

278 Figure 7 compares the locations of BP-inferred high-frequency radiators
 279 before and after the calibrations. Before the calibrations (Fig. 7a), the BP

280 source locations are biased to the northwest of the fault surface trace. After
281 the calibrations (Fig. 7c), the distribution of the high-frequency radiators
282 relative to the mainshock's epicenter follows remarkably well the fault geom-
283 etry derived from the satellite images. Source radiation is reliably imaged for
284 a duration of 50 s indicating unilateral rupture with speed around 3 km/s on
285 average. Coherent energy initially emits near the hypocenter and reaches its
286 maximum at 10s after the origin time. The high-frequency radiation contin-
287 ues as the rupture propagated northeastwards. At around 20s, the rupture
288 experiences a sudden fluctuation in speed and the high-frequency energy
289 amplifies and reaches a second maximum. This stage of rupture spatially
290 coincides with the kink of the surface fault trace. Such geometrical barrier
291 in non-planar faults is efficient in generating the high-frequency radiation by
292 abruptly changing the rupture velocity and slip-rate.

293 At a more detailed level the time propagation of the high-frequency radia-
294 tors may indicate that the rupture initiated in the vicinity of the hypocenter
295 without a clear propagation for ~ 10 seconds, then propagated to the NE
296 over a distance of ~ 32 km for 6.5 seconds where it came to a halt for ~ 3
297 seconds before resuming its north-eastward propagation up to the end of the
298 break. In this scenario, it is worth noting that the high-frequency power is
299 released during the initiation phases of separate rupture segments and radi-
300 ation power reduces when the fault propagates at faster speed (Fig. 7 d and
301 e).

302 Such a rupture time history is similar to time profiles observed for strike-
303 slip events of $M > 7.5$ (Wang et al., 2016). In the case of the 2015 Murghab
304 earthquake, speeds observed over the 10-16 km and 20-28 km sections of the

305 fault exceed the shear waves velocities of 3.55-3.6 km/s that are reported for
306 the upper crust in this part of Pamir(Mechie et al., 2012).

307

308 7. Discussion

309 The December 2015 Murghab event reactivated a ~ 79 km-long section
310 of the SKF in northern Pamir. The 3-segment fault model obtained from
311 Landsat-8 pixels offsets and inversion of InSAR data have steep dip angles
312 toward the west in agreement with the narrow zone of seismicity observed
313 across Karakul Lake down to a depth of 20 km (Schurr et al., 2014). The slip
314 solution indicates sinistral slip of up to 3.5 m and a small normal component
315 of up to 1 m along the northern segment, south of Karakul Lake. This
316 solution is consistent with the regional seismicity of northern Pamir interior,
317 which shows predominantly strike-slip mechanisms on NE-oriented planes
318 (Schurr et al., 2014) and the fault trace morphology typical of trans-tensional
319 fault systems in the Karakul Valley (Strecker et al., 1995).

320 The Murghab earthquake fault is formed of two right-stepping segments
321 connected by a more easterly oriented segment in the restraining bend. This
322 geometry seems to have controlled the rupture propagation velocity and the
323 generation of high-frequency energy. From the epicenter near the southern
324 end of the fault the rupture propagated at a slow rate for about 10 s before
325 speeding up to super shear velocity (~ 5 km/s) for 6.5 s until it reached the
326 restraining bend between the two main segments. Between 16.5 and 19.5
327 seconds the rupture pursued its propagation at a slower rate and sped up
328 again at a rate of ~ 4.4 km/s for 8.5 s to break the third segment of the fault.

329 Super-shear rupture propagation seems to be common for large strike-slip
 330 events in the continental domain (e.g., Bouchon and Vallée, 2003; Avouac
 331 et al., 2014; Wang et al., 2016). For example, in the case of the 2001 Kunlun
 332 event, a 3-phase rupture propagation scenario was proposed in which the
 333 middle (Kusai) segment appears to have ruptured at a speed of 6 km/s over
 334 a distance of 175 km (Vallée et al., 2008). The abrupt end of the super-shear
 335 segment corresponds to a fault geometric complexity where the main Kunlun
 336 fault splits into the Xidatai segment to the North and the Kunlun Pass seg-
 337 ment to the South (Lasserre et al., 2005; Klinger et al., 2006). In addition,
 338 the decrease of the rupture speed appears to correspond to an increase in ra-
 339 diation of high-frequency amplitude (Vallée et al., 2008). Such characteristics
 340 corresponds to our observations of the 2015 Murghab event rupture propa-
 341 gation where a restraining bend in the central part of the rupture appears
 342 to have slowed down its propagation for about 3 seconds between two linear
 343 sections rupturing at super-shear velocities. Moreover, the high-frequency
 344 radiation history we observe shows two maxima corresponding to the slow
 345 phases of the rupture, first near the hypocenter at break initiation and second
 346 through the restraining bend of the fault.

347 Super-shear ruptures generate strong shaking of the ground, preferentially
 348 in the direction they propagate. The NE propagation of the 2015 rupture
 349 may have focused most of its shaking energy away from Sarez Lake, thus
 350 preserving the dam formed by the landslide that was triggered by the Sarez-
 351 Pamir earthquake in 1911. A close look at the pixel offset map around
 352 the western termination of Sarez Lake reveals that the lake banks along its
 353 northern and southern shores settled down into the lake by several meters

(Fig. 8). While most of the land that was mobilized during the 1911 landslide appears stable in the coseismic displacement map, a section of its eastern edge moved ~ 3 m toward the lake and its southern edge moved up to 5 m toward the south into Shadau Lake. A more severe landslide, mobilizing an area of ~ 1.6 km² with 17 m of horizontal shift toward the NE is visible along the SW shore of the Sarez Lake (Fig. 8). The landslide corresponds to the collapse of a steep slope reactivating a large open fracture at the crest line.

The significance of the Sarez-Karakul fault in north central Pamir is difficult to determine because of its slow rate compared to the rates of faults occurring along the edges of the range (Schurr et al., 2014). Possible extension of the fault southwest of the Sarez Lake is unclear in the morphology because of the high and rapidly eroding relief of the Western Pamir. However, a NE-SW alignment of seismicity extends south of the Sarez-Murghab Thrust system with focal mechanisms consistent with sinistral slip on NE-oriented planes (Schurr et al., 2014). The shear zone highlighted by this alignment of seismicity and the SKF together may define an incipient, NE-trending trans-tensional, sinistral system that isolates the NW corner of the Pamir, allowing its westward extrusion towards the Tajik Basin. The movement of the crustal corner is accommodated to the north along the Main Pamir Thrust (MPT), as evidenced in GPS measurements across the Ali Valley (Zubovich et al., 2016), and is gradually absorbed in the fold belt developed in the sedimentary cover of the Tajik basin and the subduction of the Afghan lithospheric mantle under the western Pamir (Schurr et al., 2014).

The localized extension developing in northern Pamir along the sinistral, NE-trending and dextral, NW-trending conjugate systems can be com-

pared with the fault systems developing in southern Tibet where north-south graben valleys develop at the termination of stepping strike-slip faults (e.g., Armijo et al., 1989). Copley et al. (2011) argue that the coupling between the subducting Indian mantle and the crust in southern Tibet is required to allow normal faulting to develop in a north-south convergence setting. The same argument may apply to northern Pamir, which is overlaying the Asian mantle lithosphere along the north Pamir thrust (e.g., Pegler and Das, 1998; Mechie et al., 2012). The normal component of movement observed along the SKF and other graben systems in northern Pamir may indicate a high level of coupling between the Pamir lower crust and the Asian mantle.

8. Conclusion

We have shown that the Mw7.2, 2015 Murghab earthquake ruptured three segments of the Sarez-Karakul Fault that are steeply dipping to the northwest and organized in a right-stepping configuration. The fault slip-solution obtained by inversion of InSAR data shows two main patches of up to 3.5 m of left slip on the south and central segments and oblique, normal and left slip of up to 1 m on the northern segment. Back-projection of the 0.5-2 seconds band period of the seismic waves onto the fault plane reveals the complexity of the rupture propagation through time. After an initiation phase characterized by high energy radiation and slow propagation velocity, the rupture accelerated to ~ 5 km/s over a distance of 30 km, slowed down for about 3 seconds along the restraining bend segment of the fault and sped up again at super-shear velocity along its last segment. The coincidence of

403 the high-frequency radiators' location and rupture history observed in the
404 seismological record, and the fault geometry and static solution derived from
405 space-based geodesy is remarkable. These findings show the capability of the
406 back-projection method, enhanced by aftershock calibrations, to describe de-
407 tails of the rupture kinematics of a moderate size event in a remote part of
408 the world.

409

410 **Acknowledgments**

411 We thank M.-H. Huang and C. Yin for discussions on inversion ap-
412 proaches. Two anonymous reviewers gave detailed and constructive com-
413 ments that improved the original manuscript. European Space Agency,
414 Copernicus Sentinel data 2015, retrieved from ASF DAAC 7 January 2016.
415 ALOS-2 data were provided by the Japan Aerospace Exploration Agency
416 (JAXA) under PI Project P1372. Panchromatic Remote-sensing instrument
417 for Stereo Mapping (PRISM) data was obtained from JAXA
418 (<http://www.eorc.jaxa.jp/ALOS/en/aw3d30/>). The Incorporated Research
419 Institutions for Seismology (IRIS) (www.iris.edu) and the European OR-
420 FEUS (www.orfeus-eu.org) data centers provided access to broadband seis-
421 mograms. The earthquake catalogs were obtained from the International
422 Seismological Center (ISC) bulletin (<http://www.isc.ac.uk/>), National Earth-
423 quake Information Center (NEIC) (<http://earthquake.usgs.gov/>), and IRIS
424 (<http://ds.iris.edu/>). A. Zhang was supported by NSF EarthScope proposal
425 EAR-1614609. Some figures were prepared using the Generic Mapping Tools
426 (GMT; Wessel and Smith (1998)). The work was done in part at the Jet

427 Propulsion Laboratory, California Institute of Technology under contract
428 with NASA.

429

430 Ambraseys, N., Bilham, R., 2012. The Sarez-Pamir Earthquake and Land-
431 slide of 18 February 1911. *Seismol. Res. Lett.* 83, 294–314. [http:](http://dx.doi.org/10.1785/gssrl.83.2.294)
432 [//dx.doi.org/10.1785/gssrl.83.2.294](http://dx.doi.org/10.1785/gssrl.83.2.294).

433 Armijo, R., Tapponnier, P., Han, T., 1989. Late Cenozoic right-lateral strike-
434 slip faulting in southern Tibet. *Journal of Geophysical Research: Solid*
435 *Earth* 94, 2787–2838. <http://dx.doi.org/10.1029/JB094iB03p02787>.

436 Avouac, J.P., Ayoub, F., Wei, S., Ampuero, J.P., Meng, L., Leprince, S., Jo-
437 livet, R., Duputel, Z., Helmberger, D., 2014. The 2013, Mw 7.7 Balochistan
438 earthquake, energetic strike-slip reactivation of a thrust fault. *Earth and*
439 *Planetary Science Letters* 391, 128–134. [http://dx.doi.org/10.1016/](http://dx.doi.org/10.1016/j.epsl.2014.01.036)
440 [j.epsl.2014.01.036](http://dx.doi.org/10.1016/j.epsl.2014.01.036).

441 Bouchon, M., Vallée, M., 2003. Observation of long supershear rupture during
442 the magnitude 8.1 Kunlunshan earthquake. *Science* 301, 824–826. [http:](http://dx.doi.org/10.1126/science.1086832)
443 [//dx.doi.org/10.1126/science.1086832](http://dx.doi.org/10.1126/science.1086832).

444 Burtman, V.S., Molnar, P., 1993. Geological and geophysical evidence for
445 deep subduction of continental crust beneath the Pamir. *Special Paper*
446 281, 1–76. <http://dx.doi.org/10.1130/SPE281-p1>.

447 Chevalier, M.L., Leloup, P.H., Li, H., 2016. Comment on No late Quaternary
448 strike-slip motion along the northern Karakoram fault published by robin-
449 son et al. in *epsl*, 2015. *Earth and Planetary Science Letters* 443, 216–219.
450 <http://dx.doi.org/10.1016/j.epsl.2016.03.031>.

451 Chevalier, M.L., Li, H., Pan, J., Pei, J., Wu, F., Xu, W., Sun, Z., Liu, D.,
452 2011. Fast slip-rate along the northern end of the Karakorum fault system,

453 western Tibet. *Geophysical Research Letters* 38. [http://dx.doi.org/10.](http://dx.doi.org/10.1029/2011GL049921)
454 1029/2011GL049921.

455 Chevalier, M.L., Pan, J., Li, H., Liu, D., Wang, M., 2015. Quantification of
456 both normal and right-lateral late Quaternary activity along the Kongur
457 Shan extensional system, Chinese Pamir. *Terra Nova* 27, 379–391. [http:](http://dx.doi.org/10.1111/ter.12170)
458 [//dx.doi.org/10.1111/ter.12170](http://dx.doi.org/10.1111/ter.12170).

459 Copley, A., Avouac, J.P., Wernicke, B.P., 2011. Evidence for mechanical
460 coupling and strong Indian lower crust beneath southern Tibet. *Nature*
461 472, 79–81. <http://dx.doi.org/10.1038/nature09926>.

462 Coutand, I., Strecker, M.R., Arrowsmith, J.R., Hilley, G., Thiede, R.C., Ko-
463 rjenkov, A., Omuraliev, M., 2002. Late Cenozoic tectonic development of
464 the intramontane Alai Valley, (Pamir-Tien Shan region, central Asia): An
465 example of intracontinental deformation due to the Indo-Eurasia collision.
466 *Tectonics*. 21, 1053–1071. <http://dx.doi.org/10.1029/2002TC001358>.

467 Cowgill, E., 2010. Cenozoic right-slip faulting along the eastern margin of the
468 Pamir salient, northwestern China. *Geological Society of America Bulletin*
469 122, 145–161. <http://dx.doi.org/10.1130/B26520.1>.

470 Fukuda, J., Johnson, K.M., 2008. A fully Bayesian inversion for spatial
471 distribution of fault slip with objective smoothing. *Bulletin of the Seismo-*
472 *logical Society of America* 98, 1128–1146. [http://dx.doi.org/10.1785/](http://dx.doi.org/10.1785/0120070194)
473 0120070194.

474 Goldstein, R.M., Werner, C.L., 1998. Radar interferogram filtering for

475 geophysical applications. *Geophysical Research Letters* 25, 4035–4038.
 476 <http://dx.doi.org/10.1029/1998GL900033>.

477 Goldstein, R.M., Zebker, H.A., Werner, C.L., 1988. Satellite radar interfer-
 478 ometry: Two-dimensional phase unwrapping. *Radio science* 23, 713–720.
 479 <http://dx.doi.org/10.1029/RS023i004p00713>.

480 IRIS, 2016. Moment Tensor for MW 7.2 (GCMT) TAJIKISTAN (Inactive).
 481 <http://ds.iris.edu/spud/momenttensor/11031297>. [Online; accessed
 482 September-2016]. <http://dx.doi.org/doi:10.17611/DP/11031297>.

483 ISC, 2016. ISC Bulletin: event catalogue search. [http://www.isc.ac.uk/](http://www.isc.ac.uk/iscbulletin/search/catalogue/)
 484 [iscbulletin/search/catalogue/](http://www.isc.ac.uk/iscbulletin/search/catalogue/). [Online; accessed September-2016].

485 Ischuk, A., Bendick, R., Rybin, A., Molnar, P., Khan, S.F., Kuzikov, S.,
 486 Mohadjer, S., Saydullaev, U., Ilyasova, Z., Schelochkov, G., Zubovich,
 487 A.V., 2013. Kinematics of the Pamir and Hindu Kush regions from GPS
 488 geodesy. *Journal of geophysical research: solid earth* 118, 2408–2416. [http:](http://dx.doi.org/10.1002/jgrb.50185)
 489 [//dx.doi.org/10.1002/jgrb.50185](http://dx.doi.org/10.1002/jgrb.50185).

490 ISDR, 2000. Usoi Landslide Dam and Lake Sarez - An Assessment of Hazard
 491 and Risk in the Pamir Mountains, Tajikistan. 1, United Nations Publica-
 492 tion.

493 Ishii, M., Shearer, P.M., Houston, H., Vidale, J.E., 2005. Extent, dura-
 494 tion and speed of the 2004 Sumatra–Andaman earthquake imaged by
 495 the Hi-Net array. *Nature* 435, 933–936. [http://dx.doi.org/10.1038/](http://dx.doi.org/10.1038/nature03675)
 496 [nature03675](http://dx.doi.org/10.1038/nature03675).

- 497 Jónsson, S., Zebker, H., Segall, P., Amelung, F., 2002. Fault slip distribu-
 498 tion of the 1999 Mw 7.1 Hector Mine, California, earthquake, estimated
 499 from satellite radar and GPS measurements. *Bulletin of the Seismolog-*
 500 *ical Society of America* 92, 1377–1389. [http://dx.doi.org/10.1785/](http://dx.doi.org/10.1785/0120000922)
 501 [0120000922](http://dx.doi.org/10.1785/0120000922).
- 502 Klinger, Y., Michel, R., King, G., 2006. Evidence for an earthquake barrier
 503 model from Mw~7.8 Kokoxili (Tibet) earthquake slip-distribution. *Earth*
 504 *and Planetary Science Letters* 242, 354–364. [http://dx.doi.org/10.](http://dx.doi.org/10.1016/j.epsl.2005.12.003)
 505 [1016/j.epsl.2005.12.003](http://dx.doi.org/10.1016/j.epsl.2005.12.003).
- 506 Komatsu, T., 2016. Geomorphic Features of the Eastern Pamirs, with a
 507 Focus on the Occurrence of Intermontane Basins, in: *Mapping Transi-*
 508 *tion in the Pamirs*. Springer, pp. 55–68. [http://dx.doi.org/10.1007/](http://dx.doi.org/10.1007/978-3-319-23198-3_4)
 509 [978-3-319-23198-3_4](http://dx.doi.org/10.1007/978-3-319-23198-3_4).
- 510 Kulikova, G., Schurr, B., Krüger, F., Brzoska, E., Heimann, S., 2016. Source
 511 parameters of the Sarez-Pamir earthquake of 1911 February 18. *Geo-*
 512 *phys. J. Int.* 205, 1086–1098. <http://dx.doi.org/10.1093/gji/ggw069>.
- 513 Lasserre, C., Peltzer, G., Crampé, F., Klinger, Y., Van Der Woerd, J.,
 514 Tapponnier, P., 2005. Coseismic deformation of the 2001 Mw= 7.8
 515 Kokoxili earthquake in Tibet, measured by synthetic aperture radar in-
 516 terferometry. *Journal of Geophysical Research: Solid Earth* 110. [http:](http://dx.doi.org/10.1029/2004JB003500)
 517 [//dx.doi.org/10.1029/2004JB003500](http://dx.doi.org/10.1029/2004JB003500).
- 518 Leprince, S., Barbot, S., Ayoub, F., Avouac, J.P., 2007. Automatic and pre-
 519 cise orthorectification, coregistration, and subpixel correlation of satellite

520 images, application to ground deformation measurements. *Geoscience and*
 521 *Remote Sensing, IEEE Transactions on* 45, 1529–1558. [http://dx.doi.](http://dx.doi.org/10.1109/TGRS.2006.888937)
 522 [org/10.1109/TGRS.2006.888937](http://dx.doi.org/10.1109/TGRS.2006.888937).

523 Liang, C., Fielding, E.J., 2016. Interferometric Processing of ScanSAR Data
 524 Using Stripmap Processor: New Insights From Coregistration. *IEEE*
 525 *Transactions on Geoscience and Remote Sensing* 54, 4343–4354. [http:](http://dx.doi.org/10.1109/TGRS.2016.2539962)
 526 [//dx.doi.org/10.1109/TGRS.2016.2539962](http://dx.doi.org/10.1109/TGRS.2016.2539962).

527 Lundgren, P., Poland, M., Miklius, A., Orr, T., Yun, S.H., Fielding, E.,
 528 Liu, Z., Tanaka, A., Szeliga, W., Hensley, S., et al., 2013. Evolution of
 529 dike opening during the March 2011 Kamoamo fissure eruption, Kīlauea
 530 Volcano, Hawaii. *Journal of Geophysical Research: Solid Earth* 118, 897–
 531 914. <http://dx.doi.org/10.1002/jgrb.50108>.

532 Mechie, J., Yuan, X., Schurr, B., Schneider, F., Sippl, C., Ratschbacher,
 533 L., Minaev, V., Gadoev, M., Oimahmadov, I., Abdybachaev, U., et al.,
 534 2012. Crustal and uppermost mantle velocity structure along a profile
 535 across the Pamir and southern Tien Shan as derived from project TIPAGE
 536 wide-angle seismic data. *Geophysical Journal International* 188, 385–407.
 537 <http://dx.doi.org/10.1111/j.1365-246X.2011.05278.x>.

538 Meng, L., Inbal, A., Ampuero, J.P., 2011. A window into the complexity of
 539 the dynamic rupture of the 2011 Mw 9 Tohoku-Oki earthquake. *Geophys-*
 540 *ical Research Letters* 38. <http://dx.doi.org/10.1029/2011GL048118>.

541 Meng, L., Zhang, A., Yagi, Y., 2016. Improving back projection imaging
 542 with a novel physics-based aftershock calibration approach: A case study

543 of the 2015 Gorkha earthquake. *Geophysical Research Letters* 43, 628–636.
544 <http://dx.doi.org/10.1002/2015GL067034>.

545 Mohadjer, S., Bendick, R., Ischuk, A., Kuzikov, S., Kostuk, A., Saydul-
546 laev, U., Lodi, S., Kakar, D., Wasy, A., Khan, M., et al., 2010. Parti-
547 tioning of India-Eurasia convergence in the Pamir-Hindu Kush from GPS
548 measurements. *Geophys. Res. Lett.* 37. [http://dx.doi.org/10.1029/](http://dx.doi.org/10.1029/2009GL041737)
549 [2009GL041737](http://dx.doi.org/10.1029/2009GL041737).

550 Pegler, G., Das, S., 1998. An enhanced image of the Pamir-Hindu Kush
551 seismic zone from relocated earthquake hypocentres. *Geophys. J. Int.* 134,
552 573–595. <http://dx.doi.org/10.1046/j.1365-246x.1998.00582.x>.

553 Reigber, C., Michel, G., Galas, R., Angermann, D., Klotz, J., Chen, J.,
554 Papschev, A., Arslanov, R., Tzurkov, V., Ishanov, M., 2001. New space
555 geodetic constraints on the distribution of deformation in Central Asia.
556 *Earth and Planetary Science Letters* 191, 157–165. [http://dx.doi.org/](http://dx.doi.org/10.1016/S0012-821X(01)00414-9)
557 [10.1016/S0012-821X\(01\)00414-9](http://dx.doi.org/10.1016/S0012-821X(01)00414-9).

558 Robinson, A., Yin, A., Manning, C., Harrison, T., Zhang, S.H., Wang, X.,
559 2004. Tectonic evolution of the northeastern Pamir: Constraints from the
560 northern portion of the Cenozoic Kongur Shan extensional system, western
561 China. *Geol. Soc. Am. Bull.* 116, 953–973. [http://dx.doi.org/10.1130/](http://dx.doi.org/10.1130/B25375.1)
562 [B25375.1](http://dx.doi.org/10.1130/B25375.1).

563 Robinson, A.C., Owen, L.A., Chen, J., Schoenbohm, L.M., Hedrick, K.A.,
564 Blisniuk, K., Sharp, W.D., Imrecke, D.B., Li, W., Yuan, Z., et al., 2015.
565 No late Quaternary strike-slip motion along the northern Karakoram fault.

566 Earth and Planetary Science Letters 409, 290–298. [http://dx.doi.org/](http://dx.doi.org/10.1016/j.epsl.2014.11.011)
567 10.1016/j.epsl.2014.11.011.

568 Rosen, P.A., Gurrola, E., Sacco, G.F., Zebker, H., 2012. The InSAR scientific
569 computing environment, in: Synthetic Aperture Radar, 2012. EUSAR. 9th
570 European Conference on, VDE. pp. 730–733.

571 Rosen, P.A., Hensley, S., Peltzer, G., Simons, M., 2004. Updated repeat orbit
572 interferometry package released. Eos, Transactions American Geophysical
573 Union 85, 47–47. <http://dx.doi.org/10.1029/2004E0050004>.

574 Schurr, B., Ratschbacher, L., Sippl, C., Gloaguen, R., Yuan, X., Mechie,
575 J., 2014. Seismotectonics of the Pamir. Tectonics. 33, 1501–1518. [http:](http://dx.doi.org/10.1002/2014TC003576)
576 [//dx.doi.org/10.1002/2014TC003576](http://dx.doi.org/10.1002/2014TC003576).

577 Schuster, R.L., Alford, D., 2004. Usoi Landslide Dam and Lake Sarez, Pamir
578 Mountains, Tajikistan. Environmental & Engineering Geoscience 10, 151–
579 168. <http://dx.doi.org/10.2113/10.2.151>.

580 Sippl, C., Schurr, B., Yuan, X., Mechie, J., Schneider, F.M., Gadoev, M.,
581 Orunbaev, S., Oimahmadov, I., Haberland, C., Abdybachaev, U., Minaev,
582 V., Negmatullaev, S., Radjabov, N., 2013. Geometry of the Pamir-Hindu
583 Kush intermediate-depth earthquake zone from local seismic data. J. Geo-
584 phys. Res. 118, 1438–1457. <http://dx.doi.org/10.1002/jgrb.50128>.

585 Strecker, M.R., Frish, W., Hamburger, M.W., Ratschbacher, L., Semiletkin,
586 S., Zamoryyev, A., Sturchio, N., 1995. Quaternary deformation in the
587 Eastern Pamirs, Tadzhikistan and Kyrgyzstan. Tectonophysics. 14, 1061–
588 1079. <http://dx.doi.org/10.1029/95TC00927>.

589 Tapponnier, P., Mattauer, M., Proust, F., Cassaigneau, C., 1981. Mesozoic
 590 Ophiolites, Sutures, and Large-Scale Tectonic Movements in Afghanistan.
 591 Earth Planet. Sci. Lett. 52, 355–371. [http://dx.doi.org/10.1016/](http://dx.doi.org/10.1016/0012-821X(81)90189-8)
 592 0012-821X(81)90189-8.

593 USGS, 2015. M7.2 - 104km W of Murghob, Tajikistan. [http://earthquake.](http://earthquake.usgs.gov/earthquakes/eventpage/us100044k6#general)
 594 [usgs.gov/earthquakes/eventpage/us100044k6#general](http://earthquake.usgs.gov/earthquakes/eventpage/us100044k6#general). [Online; ac-
 595 cessed December-2015].

596 Vallée, M., Landès, M., Shapiro, N.M., Klinger, Y., 2008. The 14 Novem-
 597 ber 2001 Kokoxili (Tibet) earthquake: High-frequency seismic radiation
 598 originating from the transitions between sub-Rayleigh and supershear rup-
 599 ture velocity regimes. Journal of Geophysical Research: Solid Earth 113.
 600 <http://dx.doi.org/10.1029/2007JB005520>.

601 Wang, D., Mori, J., Koketsu, K., 2016. Fast rupture propagation for large
 602 strike-slip earthquakes. Earth and Planetary Science Letters 440, 115–126.
 603 <http://dx.doi.org/10.1016/j.epsl.2016.02.022>.

604 Ward, S.N., 1998. On the consistency of earthquake moment release
 605 and space geodetic strain rates: Europe. Geophysical Journal Inter-
 606 national 135, 1011–1018. [http://dx.doi.org/10.1046/j.1365-246X.](http://dx.doi.org/10.1046/j.1365-246X.1998.t01-2-00658.x)
 607 1998.t01-2-00658.x.

608 Wessel, P., Smith, W.H., 1998. New, improved version of Generic Mapping
 609 Tools released. Eos, Transactions American Geophysical Union 79, 579–
 610 579. <http://dx.doi.org/10.1029/98E000426>.

- 611 Zubovich, A.V., Schne, T., Metzger, S., Mosienko, O., Mukhamediev, S.,
612 Sharshebaev, A., Zech, C., 2016. Tectonic interaction between the Pamir
613 and Tien Shan observed by GPS. *Tectonics*. 35. [http://dx.doi.org/10.](http://dx.doi.org/10.1002/2015TC004055)
614 [1002/2015TC004055](http://dx.doi.org/10.1002/2015TC004055).
- 615 Zubovich, A.V., Wang, X., Sherba, Y.G., Schelochkov, G.G., Reilinger, R.,
616 Reigber, C., Mosienko, O.I., Molnar, P., et al., 2010. GPS velocity field for
617 the Tien Shan and surrounding regions. *Tectonics*. 29. [http://dx.doi.](http://dx.doi.org/10.1029/2010TC002772)
618 [org/10.1029/2010TC002772](http://dx.doi.org/10.1029/2010TC002772).

Fault seg.	Center Lat. (°N)	Center Lon. (°E)	Strike (°)	Width (km)	Length (km)	Dip solution (°)	Geo. moment (10 ¹⁹ Nm)
1	38.261	72.834	215.4	30	41.22	91E + 2.3/ − 6.8	8.271
2	38.442	73.023	234.6	30	12.56	80W + 9.3/ − 7.2	2.059
3	38.578	73.159	210.1	30	26.55	83W + 8.2/ − 3.5	3.396

Table 1: All geometric parameters other than dip are fixed for each fault segment. Top of each fault segment is fixed at surface. Geodetic moments are calculated assuming upper crustal shear modulus of 30 GPa. Total geodetic moment for modeled fault is $\sim 13.70 \times 10^{19}$ Nm.

Figure 1: Simplified tectonics map of Central Pamir. 2015 Sarez Lake Mw7.2 mainshock (yellow star), two Mw5.4 aftershocks (magenta stars) plotted with accompanying focal mechanisms from the Incorporated Research Institutions for Seismology (IRIS) (IRIS, 2016), and background seismicity (open dots) data from the International Seismological Centre (ISC) (ISC, 2016). Quaternary faults from (Mohadjer et al., 2016) shown in black. Coseismic fault trace in thick black (this study). Inset map provides location of study area (red box), with major faults (black). Fault abbreviations are Altyn Tagh Fault= ATF, CF= Chaman fault, DF= Darvaz-Karakul fault, HF = Herat fault, HKP= Hindu Kush-Pamir faults, KF = Karakorum fault, LGF= Longmu-Gozha fault, MFT= Main frontal thrust, MPT= Main Pamir thrust, MF= Muji Fault, PF= Paghman fault, SKF= Sarez-Karakul fault system, SMT = Sarez-Murghab thrust system, TF= Talas Ferghana fault, and TTS =Tanyamas thrust system. Green frames are locations of five InSAR images from Sentinel-1A and ALOS-2 satellites used in this study.

Figure 2: (a) Post-earthquake Landsat-8 panchromatic band image (15 m spatial resolution). (b) North and East components of surface displacement generated from pre-and post-earthquake Landsat-8 images acquired on 10/13/2015 and 10/15/2016, respectively. Low signal-to-noise areas are masked for clarity, and no-data values are colored blue. (c) Left-lateral slip distribution along fault, taken from horizontal ground displacement projected on fault average direction (N54.6°E). Gray shade indicates $\pm 1\sigma$ uncertainty. Star is projected epicenter location. Red circles correspond to along-strike location of fault-perpendicular profiles shown in Fig. S1.

Figure 3: Example of two interferograms used in this study, all unwrapped interferograms are plotted in Fig. S3). Unwrapped phase is re-wrapped so that each color cycle (red-green-blue-red) represents 10 cm of displacement towards the satellite. Arrows indicate direction of LOS with indication of mean incidence angle. Modeled coseismic fault trace is shown in black. Gray areas are zones of low signal coherence where the phase could not be unwrapped.

Figure 4: Comparison of observed and modeled LOS displacement fields for 5 interferograms used in this study. *Top row*: Subsampled interferograms centered on fault. *Middle row*: Synthetic displacement corresponding to most probable model. *Bottom row*: Residual displacements.

Figure 5: Posterior probability density distributions for dip angle of each fault segment estimated from InSAR data inversion. Solid red lines delineate most probable solutions and dashed lines represent 2σ confidence interval.

Figure 6: Variable slip solution from InSAR data inversion. Arrows represent direction of motion of fault-wall from the reader's POV. Note that movement is almost purely strike-slip in the region of large moment release, consistent with the NEIC CMT solution (USGS, 2015).

Figure 7: (a) High-frequency radiators locations estimated using back-projection method with data from European seismic network (b). (c) Same as (a) after location calibration. (d) Beam power time function. (e) Time propagation of high-frequency radiators along mean fault direction. In (a), (c), (d), (e), size of diamond symbols scales with relative power and color indicates time since mainshock.

Figure 8: *Left*: Westward looking view of NW end of Sarez Lake rendered with a shaded, 30 m-posting DEM obtained from Panchromatic Remote-sensing instrument for Stereo Mapping (PRISM, ©JAXA). Terrane that collapsed in 1911 landslide is shown in yellow shade (ISDR, 2000). Flat areas correspond to lake surface: Sarez Lake (foreground), Irkht Bay (left), and Shadau Lake (background). *Right*: Detail of North component of coseismic displacement field shown in Fig. 2. Gray shade indicating magnitude of displacement is saturated in range between -3 m (South) and 3 m (North) for clarity. Contour lines of Usoi Dam and recognized landslide zone (ISDR, 2000) are indicated. Arrows indicate direction and magnitude of horizontal movement of various sections of lake shore.

High-frequency
seismic radiators

Fault-slip solution