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A Slip Gap of the 2016 M_w 6.6 Muji, Xinjiang, China, Earthquake Inferred from Sentinel-1 TOPS Interferometry

by Wanpeng Feng, Yunfeng Tian, Yong Zhang, Sergey Samsonov, Rafael Almeida, and Peng Liu

ABSTRACT

We use Sentinel-1A/1B Terrain Observation with Progressive Scans (TOPS) data to map coseismic and postseismic displacements for the 25 November 2016 M_w 6.6 Muji earthquake in southwestern Xinjiang, China. Two tracks (T27 and T107) of the TOPS data captured the coseismic deformation area with a maximum line-of-sight deformation of ~ 0.25 m in the descending track (T107). The inverted best-fitting coseismic slip model in this study shows that the mainshock was a right-lateral strike-slip rupture on the western segment of the Muji fault, with an optimal dip angle of $80^\circ \pm 4^\circ$. Two separated slip zones exist in the coseismic slip model, with the maximum slip of 1.6 m located in the western slip zone. The total geodetic moment is 9.87×10^{18} N·m, equivalent to an earthquake of M_w 6.6. Our model shows that a patch between the two slip zones remained unruptured during the mainshock, indicating a potential future seismic risk. Aftershocks recorded in the first 45 days after the mainshock delineate the modeled rupture patches well. The components of the regional Global Positioning System velocities parallel to the Muji fault have been inverted to obtain an interseismic slip rate of ~ 10 mm/yr on this structure. The recent large strike-slip earthquakes in this area, that is, the 2015 M_w 7.2 Tajikistan earthquake (left-lateral) and 2016 M_w 6.6 Muji earthquake (right-lateral), may be an indicator of conjugate fault systems at the west boundary between the Indian and Eurasian plates in response to north–south convergence produced by the collision of the two plates.

INTRODUCTION

A moderate-size shallow earthquake with a moment magnitude of 6.6 hit the Xinjiang Uygur Autonomous region of China on 25 November 2016 at 14:24:30 (UTC). The earthquake epicenter from the U.S. Geological Survey (USGS) was 39.23° N, 74.02° E. Local media reported that some infrastructure was damaged to different extents, and about 40 people were injured during the event. Because of the sparse population in the region, no further severe damages were reported. Geographically,

the earthquake occurred near the border of China and Tajikistan. The USGS named the event as the Karakul, Tajikistan, earthquake after Karakul Lake located 47 km west-southwest of the event. The European-Mediterranean Seismological Center named it the southern Xinjiang, China, earthquake. The Chinese Earthquake Administration (CEA) officially reported the event as the Akto earthquake because the epicenter was located within Akto County, Xinjiang. Geologically, the earthquake was located along the western segment of the Muji fault (hereafter, Muji fault) on the northern margin of Muji graben that is the western margin of the Chinese Pamir (Fig. 1). To better represent the seismogenic fault of the event, we will rename the event as 2016 Muji earthquake in this study.

The 2016 M_w 6.6 Muji earthquake occurred near the triple border of China, Kyrgyzstan, and Tajikistan (Fig. 1). The epicenter zone is surrounded by the main Pamir thrust to the north, the Karakul graben (Karakul Lake) to the west, the right-lateral strike-slip Rongkul fault to the south, and the right-lateral strike-slip and normal segments of the Muji fault to the east (Chevalier *et al.*, 2011; Mahmood and Gloaguen, 2012) (Fig. 1, inset). Because of the inaccessibility of the region surrounding the 2016 Muji earthquake, there is limited data constraining present regional tectonic motions and local tectonic structures. The most recent large earthquake in the region occurred on 7 December 2015 in Tajikistan with M_w 7.2 (Nanjundiah *et al.*, 2016; Sangha *et al.*, 2017), ~ 110 km southwest of the Muji earthquake (Fig. 1). This left-lateral strike-slip earthquake ruptured a north-northeast–south-southwest-trending fault located south of Karakul Lake (Fig. 1). An M_w 6.6 thrust-slip event on 26 June 2016 was recorded seismically on the northern line extension of the 2015 Tajikistan earthquake fault (Fig. 1), where another M_w 6.6 thrust-slip event on 5 October 2008 was recorded along a nearby segment (Qiao *et al.*, 2014). Between 1976 and 2016, there were 18 $M > 5.5$ events with shallow depths of < 25 km (not counting the Muji and Tajikistan events). These events were obtained from the Global Centroid Moment Tensor catalog (Ekström *et al.*, 2012). They have a diversity of focal mechanisms (Fig. 1), implying a

▲ **Figure 1.** Spatial coverages of Synthetic Aperture Radar (SAR) data used in this study and tectonic setting of the 2016 M_w 6.6 Muji earthquake (inset). The white thick polygons are the spatial coverage of both the descending (T107) and ascending (T27) Sentinel-1 Terrain Observation with Progressive Scans (TOPS) data. The east–west-trending brown thick line indicates the surface trace of the Muji earthquake fault determined by the Interferometric Synthetic Aperture Radar (InSAR) data processed in this study, whereas the north–south-trending one is the fault trace of the 2015 M_w 7.2 Tajikistan earthquake (Nanjundiah *et al.*, 2016; Sangha *et al.*, 2017). Red velocities (in online version) are the fault-parallel component of the Global Positioning System (GPS) velocities (blue in online version) from Ge *et al.* (2015). The focal mechanism plots represent the Global Centroid Moment Tensor (CMT) moment tensor solutions. Red stars (in online version) are the epicenter of the Muji earthquake determined by U.S. Geological Survey. The fault lines (inset) were modified based on Chevalier *et al.* (2015). The color version of this figure is available only in the electronic edition.

complicated tectonic setting with strain accommodated on a variety of tectonic structures. Based on present Global Positioning System (GPS) velocities (Fig. 1) from Ge *et al.* (2015), the region generally moves southward with respect to the Indian plate at an average rate of ~ 25 mm/yr. The Muji fault is an east–west-trending fault segment of the northwest end of the Karakoram fault, with average slip rate of at least 4 mm/yr over the Holocene (Chevalier *et al.*, 2011). However, details of the subsurface structure of the Muji fault were unknown prior to the mainshock of the 2016 event.

In this study, we use the Sentinel-1A/1B Terrain Observation with Progressive Scans (TOPS) imaging mode data to map surface coseismic and postseismic displacements associated with the 2016 M_w 6.6 Muji earthquake and determine the seismogenic fault geometry and coseismic slip distribution of the earthquake. Finally, the loading rate of the Muji fault is discussed in the context of the geologic velocity field.

INSAR OBSERVATIONS OF THE 2016 MUJI EARTHQUAKE

The Sentinel-1A/1B (S1), a C-band Synthetic Aperture Radar (SAR) constellation in the European Copernicus program have become major SAR data sources for regular Earth observations after the instrumental failure of ENVISAT and ALOS. Thanks to the friendly data policy of the European Space Agency (ESA), users can search and download S1 SAR data through the ESA data hub interface, free of charge. Based on the current ESA imaging schedule, SAR data covering Tibet from any single track is acquired every 24 days. There are four S1 tracks flying over the epicentral area of the 2016 Muji earthquake, of which ascending track 27 and descending track 107 cover the whole earthquake deformation area (Figs. 1 and 2). We selected three interferometric pairs from both T27 and T107 to obtain coseismic and postseismic displacements associated with the 2016 Muji earthquake (Table 1).

In this study, all SAR data were processed using an automated Interferometric Synthetic Aperture Radar (InSAR) processing system, *gInSAR*, which is being developed by the first author at the Canada Center for Mapping and Earth Observation for the next generation of RADARSAT-2 (Feng *et al.*, 2016). The GAMMA software (Wegmüller *et al.*, 2015) is used as a kernel processor of interferometry in this system. Single S1 TOPS SAR acquisition is composed of three swaths stored in separate Single-Look Complex files. Individual bursts are organized in order in each swath. A limited overlap between any two adjacent bursts is preserved. Because of the high azimuth Doppler variation of TOPS SAR data, a stringent coregistration strategy is required to reach coregistration accuracy of better than 0.001 pixel, thus avoiding potential phase jumps in azimuth (Yague-Martinez *et al.*, 2016). To meet this requirement, a DEM-assisted alignment method (Nitti *et al.*, 2008) is applied to implement a coarse coregistration. A refinement is then followed using a subpixel tracking method iteratively. Finally, a spectral diversity algorithm (Scheiber and Moreira, 2000) is applied to the overlapping area of two consecutive bursts. The Shuttle Radar Topography Mission (SRTM) v.4.1 30-m elevation data were used in this study for coregistration and topographic phase removal in the interferograms (Farr *et al.*, 2007).

Figure 2 shows coseismic and postseismic interferograms generated in this study. Two independent deformation patterns can be observed in both the descending (Inf1) and ascending (Inf2) tracks. Because of the imaging characteristics of spaceborne SAR sensors, InSAR results are a synthetic measurement of the 3D displacements of the ground object along the satellite

Table 1 Details of the Sentinel-1 Terrain Observation with Progressive Scans (TOPS) Interferograms Generated in This Study							
Interferogram	Track	Direction	Acquisitions (yyyy/mm/dd)		pBase (m)	Points*	Phase
			Master	Slave			
Inf1	T107	Descending	2016/11/25	2016/12/19	78.2	2254	Coseismic
Inf2	T27	Ascending	2016/10/20	2016/12/07	98.6	2238	Coseismic
Inf3	T27	Ascending	2016/12/07	2016/12/31	51.7	-	Postseismic

pBase, the perpendicular component of spatial baseline.
 *The number of downsampled points used in the inversion.

line-of-sight (LoS) direction. Based on the incidence and azimuth angles of SAR acquisitions, the projection vectors at the center of the SAR data from surface east–north–up (ENU) coordinate system to LoS direction are $[-0.5403, -0.1278, 0.8317]$ for the ascending track (T27) and $[0.6141, -0.1474, 0.7754]$ for the descending track (T107). Variation of incidence angle from near to far range in a SAR swath can reach $\sim 10^\circ$ for TOPS data used in this study, which should be taken into account in the slip modeling. The projection vectors show that the principal difference between ascending and

descending LoS changes comes from the east–west contribution; therefore, the predominant coseismic displacements in the Muji earthquake are most likely east–west, due to opposite signs of LoS changes along profile A–B (Fig. 2). There are no sharp offsets in the LoS profiles, which suggest that the rupture was blind. The maximum LoS displacement along the profiles is ~ 129 mm at 39.2° N from Inf1 (Fig. 3), and the maximum observed surface LoS change in the entire epicentral area reaches up to ~ 220 mm in Inf1 (not shown on the profiles). There is another acquisition available in T27 on 13 November

▲ **Figure 2.** (a) Coseismic interferogram of T107 (Inf1), (b) coseismic interferogram of T27 (Inf2), and (c) postseismic interferogram of T27 (Inf3). The thick vectors show the flight direction of the satellites, whereas the thin and shorter ones indicate the looking direction of the SAR sensors. The color version of this figure is available only in the electronic edition.

▲ **Figure 3.** Line-of-sight (LoS) displacements along the three profiles shown in Figure 2. Dots are InSAR LoS changes extracted from the interferograms along the profiles with a buffer of 4 pixels for each point. (a), (b), and (c) correspond to profiles A–B, C–D, and E–F, respectively. All plots share the same legend in (a). The color version of this figure is available only in the electronic edition.

2016 that can be used to form a coseismic interferogram with the postseismic acquisition on 7 December 2016 (Table 1), but that interferogram has significant atmospheric effects of 10–30 mm in the vicinity of the deformation center, which are almost 20%–40% of the LoS deformation. To reduce effects of these artifacts in the inversion, we discarded this interferogram and used Inf1 and Inf2 (Table 1) in the slip inversion. We note here that the slave images of Inf1 and Inf2 were taken on 7 and 19, respectively, and therefore cover potential postseismic processes in the first few days after the mainshock. The first postseismic interferogram (Inf3, Table 1) was available 35 days after the mainshock. As shown in Figure 3, no observable postseismic deformation can be detected in the earthquake area during this period. At 39.3° N, all interferograms show a relatively large LoS change variation that makes it very difficult to identify the potential small postseismic deformation with Inf3 only. Effects of topographic errors, atmospheric signals, or changes of snow cover can all likely result in uncertainties in the InSAR measurements (Fig. 3).

GEODETTIC MODELING AND COSEISMIC SLIP

During the past two decades, particularly since the pioneering studies with InSAR (Wright *et al.*, 1999; Simons *et al.*, 2002), several geodetic modeling packages have been developed and were widely used, including Oksar from Centre for Observation and Modelling of Earthquakes, Volcanoes and Tectonic (Wright *et al.*, 1999; Funning *et al.*, 2005), MudPy from the University of California, San Diego (Melgar and Bock, 2015; Melgar *et al.*, 2016), and PSOKINV (Feng *et al.*, 2009; Feng, 2015). In this study, we use PSOKINV for our geodetic slip inversion. A resolution-based downsampling method (Lohman and Simons, 2005) was applied to downsample Inf1 and Inf2 (Table 1).

Both nonlinear and linear inversions are usually considered to determine the geometric parameters and slip distribution of a blind earthquake. Fault locations and focal mechanisms can be directly determined through geodetic modeling under the constraints of InSAR measurements, and prior information is not necessary, theoretically. However, applying reasonable conditions during the inversion can significantly reduce the computing time. In practice, seismic solutions are always a good starting point. Based on the moment tensor solution from the USGS, the fault that ruptured is either a right-lateral strike-slip fault striking west–east or a left-lateral strike-slip fault striking north–south. To test which fault ruptured during the Muji earthquake, we carried out a forward simulation with a simple single-fault model with a uniform slip of 1 for each nodal plane from the above focal mechanism. The fault dimension was fixed at 10 km width and 40 km length. To directly compare the

▲ **Figure 4.** (a) The LoS change simulation based on the right-lateral nodal plane from the Global CMT focal mechanism with the satellite viewing geometry of T107. (b) same as (a), but with the satellite viewing geometry of T27. (c) and (d) are similar to (a) and (b) but use a left-lateral nodal plane from the Global CMT focal mechanism as input in the simulation. The color version of this figure is available only in the electronic edition.

similarity between the simulation and InSAR observations, we synthesized the LoS changes of the forward simulation with satellite viewing geometry parameters identical to those of T27 and T107. This test is qualitative, and we do not expect a perfect data fitting but rather to compare overall deformation patterns generated from a single nodal plane with the InSAR observations. The simulation (Fig. 4) shows that the right-lateral nodal plane produces LoS deformation patterns similar to both T27 and T107, but the simulation from the left-lateral slip solution shows completely different patterns. Therefore, the right-lateral nodal plane from the USGS focal mechanism can be considered responsible for the Muji earthquake, and we will adopt the right-lateral strike-slip nodal-plane parameters as *a priori* information in the modeling.

Thanks to excellent interferometric coherence of Inf1 and Inf2, the location of the fault trace of the Muji earthquake can be directly marked, based on the coseismic fringes of the InSAR results (Fig. 2). The derived east-southeast–west-north-west-trending fault agrees well with the location of the previously mapped Muji fault (Fig. 1). The top center of the fault was fixed at N39.226°, E74.219° (Table 2). The fault dimension is further fixed at 60 km length by 20 km depth in the modeling, which sufficiently covers the entire slip zone. Only dip angle is unknown, which can be estimated with a simple 1D grid search at the linear inversion stage. The fault discretization was done using a depth-dependent strategy (Fialko, 2004) which allows us to have fine patch size for the shallow part and coarse ones at depth. A damping factor of 1.25 was used, and the smallest patch size at the surface is 0.5 km for both length and width. A total of

Table 2
Fault Parameters of the 2016 M_w 6.6 Muji Earthquake

Source	Hypocenter			Dimension					M_w
	Longitude (°)	Latitude (°)	Depth (km)	Strike (°)	Dip (°)	Rake (°)	Length (km)	Width (km)	
USGS	74.021	39.230	17	107	76	174	-	-	6.6
				199	84	14	-	-	
IGP	74.0	39.3	9	303	74	-162	-	-	6.7
InSAR*	74.219*	39.226*	<15*	105.5	80 ± 4	-161 ± 12	55	20	6.6

A rigidity modulus of 30 GPa was used in the moment magnitude calculation. USGS, U.S. Geological Survey; IGP, Institute of Geophysics; InSAR, Interferometric Synthetic Aperture Radar.

*The location of the InSAR-derived fault model is the upper center of the rectangle fault plane used in this study, based on which the geometric fault model can be built. The depth of < 15 km from the InSAR model indicates that the major slip appears above 15 km. Length and width indicate length and width fixed during the inversion. The strike was calculated based on the fault trace that was fixed based on the InSAR fringes.

250 patches were used in each iteration. The Green's matrix on the theoretical LoS deformation for each patch is calculated using an elastic dislocation model (Okada, 1985) with 1 mm of slip. A nonnegative bounded strategy with a conjugate least-squares algorithm was applied to determine the best-fit slip distribution (Ward and Barrientos, 1986; Funning *et al.*, 2007; Zhang *et al.*, 2009). An initial rake range of $[-120, 150]$ was used in the linear inversion. All geometry parameters used in the modeling are listed in Table 2.

Mathematically, the relationship between the InSAR observations and the fault slip can simply be described as $AS = d$, in which A is the Green's matrix, S is the slip vectors, and d is the InSAR LoS displacements. To balance the trade-off between the model roughness and data misfits, a second-order Laplacian operator L was also applied in A . More details on the mathematic background of inversion can be found in previous works of the first author (Feng, 2015; Feng *et al.*, 2017).

To obtain an optimal dip angle, an iterative method was applied to determine a best-fitting solution in the least-squares sense with varied fault dip angles. A series of smoothing strengths were also used at each given dip angle. In total, 110 slip models were tested, and their misfits and model roughness were used to determine the minimum data-fitting solution (Fig. 5a). The slip model with dip 80° S reaches the minimum misfit at all given smoothing strengths, suggesting that the smoothing strength does not significantly affect the estimate of optimal dip angle in our case. This is also in good agreement with the USGS moment tensor solution, 76° S. However, the misfit variances of the models with dips ranging from 76° to 84° are less than 4 mm, far smaller than the atmospheric artifacts in each interferogram. This indicates that the uncertainty of the dip angle estimate is at most $\pm 4^\circ$ (Fig. 5a). The best-fit slip model (Fig. 6a) was finally determined using a dip of 80°, and the optimal smoothing parameter was selected with a trade-off curve plot (Fig. 5b).

The total geodetic moment in the Muji earthquake is 9.87×10^{18} N·m, based on the slip model determined from InSAR coseismic displacements (Fig. 5a), which is equal to an M_w 6.6 earthquake. Interferograms modeled with the viewing geometry parameters of Inf1 and Inf2 (Fig. 7) recover their LoS deformation patterns well. Only small residuals were observed along the mountain range (Fig. 7c,f), and they could result from local topography errors, topography-correlated atmospheric signals, or even changes of snow coverage. No significant residual patterns were observed, suggesting that the determined slip model in this study is most likely to be real.

DISCUSSION

Complexity and Stress drop of the Coseismic Rupture

As shown in Figure 6, the maximum coseismic slip did not reach the surface. The shallow zone of the Muji fault without significant slip could be explained with a shallow-slip deficit mechanism (Fialko *et al.*, 2005). This could result from the highly cracked or damaged rocks around the seismic fault through previous earthquakes (Barbot *et al.*, 2008; Cochran *et al.*, 2009). Significant historical accumulative offsets of 40–200 m were

▲ Figure 5. (a) Optimal estimation of fault dip angle with an iterative method. (b) The optimal smoothing strength selection using a trade-off plot between observation misfits and slip-model roughness. The color version of this figure is available only in the electronic edition.

▲ **Figure 6.** (a) Coseismic slip of the 2016 M_w 6.6 Muji earthquake determined in this study and (b) its triggered Coulomb stress changes. The colored circles are relocated aftershocks during the first 45 days after the mainshock. The color version of this figure is available only in the electronic edition.

revealed across the Muji fault (Chevalier *et al.*, 2015), implying that the Muji fault had experienced a number of destructive events prior to the 2016 Muji earthquake.

The two-slip patches (Fig. 6) derived from the InSAR results are the total slip accumulation during the time period spanned by the data. The first postseismic SAR acquisition

(T27) was acquired 12 days after the mainshock, which means that the coseismic interferogram (Inf1) could include part of postseismic displacements accumulated in the first 12 days. There is no way for the InSAR data itself to distinguish this. However, the early seismic solution of the 2016 Muji earthquake from IGP/CEA presented two similar slip centers, though they are much deeper than the geodetic slip model, due to the limited model resolution provided by far-field seismic data (see Data and Resources). Further, the seismic source time function shows two peaks during the total 20 s rupture duration, and seismic energy released in two subevents is comparable (Fig. 8a). The coseismic accumulative geodetic moment along strike from the coseismic slip model determined in this study also presents a two-peak pattern, similar to the source-time function (Fig. 8b). The InSAR coseismic measurements (Inf1 and Inf2) also cover the potential effects of the few early aftershocks. However, the largest aftershock before the first T27 SAR data were acquired is only with a magnitude of 3.8, and the total seismic moment released from all recorded aftershocks until one month after the mainshock is still much lower than that released in each of the slip patches (Fig. 8b). Therefore, the two separate slip patches observed in this study that can be confirmed both coseismically ruptured during the mainshock. Concentrated single slip zone is common in previous earthquakes (e.g., Fielding *et al.*, 2013; Wang and Fialko, 2015; Feng *et al.*, 2017), but there are also several previous events in a similar fashion to the 2016 Muji earthquake, for example, the 1999 M_w 7.6 İzmit (Reilinger *et al.*, 2000), the 2004 M_w 6.0

▲ **Figure 7.** Data fitting derived from the InSAR-determined slip model of the 2016 Muji earthquake. (a) Rewrapped Inf1 in a LoS range of -3 to 3 cm, (b) the predicted surface deformation from the slip model using the same SAR viewing geometry as Inf1, and (c) residuals of (a) and (b). Similar to (a)–(c), (d)–(f) are for Inf2. The color version of this figure is available only in the electronic edition.

▲ **Figure 8.** Comparison of (a) source-time function and (b) accumulated geodetic moment (this study) along the strike of the Muji fault. The color version of this figure is available only in the electronic edition.

Parkfield (Kim and Dreger, 2008), and the 2010 M_w 6.9 Yushu earthquakes (Li *et al.*, 2011).

With a 3D elastic dislocation model (Okada, 1992), we calculated the Coulomb stress changes at the center of each rectangular fault patch along the Muji fault, based on the InSAR-derived coseismic slip model. More details on calculations can be found in the previous studies (e.g., King *et al.*, 1994; Lin and Stein, 2004). General physical parameters, including a shear modulus of 40 GPa and an effective frictional coefficient of 0.4 for which fluid pore pressure is ignored, were used. Figure 6b shows that the significant Coulomb stress drop can be observed in areas corresponding to the principal slip zones, whereas the stress was increased around the slip center. The maximum Coulomb stress change (> 50 bar) appears right above the western slip center, ~ 30 km west of the hypocenter. The slip gap had a Coulomb stress increase of ~ 20 bar. Under the framework of the rate-and-state-dependent friction law in earthquake physics (Barbot *et al.*, 2008, 2009), coseismic rupture initiates within the velocity-weakening zone and terminates in the velocity-strengthening zone in which the fault behaves aseismically. If the slip gap area corresponds to a patch with velocity-strengthening properties, the coseismic-triggered stress could be released by afterslip. For instance, a rapid afterslip took place right after the 2014 M_w 6.0 Napa earthquake (Li *et al.*, 2015; Wei *et al.*, 2015), and afterslip following the 2010 M 7.2 El Mayor–Cucapah earthquake had even lasted over 6 yrs following the mainshock (Samsonov *et al.*, 2017). Early aftershocks during the period of 45 days since the mainshock were recorded by the China Seismograph Network (Zheng *et al.*, 2010); most events were located in the surround-

ing regions of the coseismic rupture zones, and only a few events were within the slip gap (Figs. 6b and 8b). During the preparation of this study, only a few postseismic interferograms were available, in which no observable postseismic deformation across the Muji fault was identified, due to local significant atmospheric artifacts. The physical properties of the observed coseismic slip gap cannot be solved in this study, due to missing immediate near-field observations. Subsequent aftershocks and potential postseismic displacements in the vicinity of the epicentral area of the mainshock should be still valuable to identify the fault physical properties.

Tectonic Loading and Its Implications for the Local Earthquake Cycle

Using the regional GPS velocity data (Ge *et al.*, 2015), we calculated the interseismic tectonic loading across the Muji fault by rotating the velocity coordinate system to be parallel to the Muji fault. The resulting velocity field clearly illustrates the relative movements across the Muji fault (in Fig. 1). To estimate the tectonic loading rate on the Muji fault quantitatively, we selected 55 GPS stations at a distance no greater than 200 km from the Muji fault, at which the GPS velocities were calculated relative to the stable Indian plate (the predominant movements in the study area are mostly north–south; in Fig. 1). We removed a mean rate of -15.5 mm/yr (negative corresponds to southward movements) from the north–south component of the GPS velocities, and no operation was applied for the east–west component.

According to the classic elastic rebound theory (Reid, 1910; Scholz, 1998), the elastic energy should be accumulated during the interseismic period at depth. A secular deep-slip rate can be estimated using a half-space elastic-screw dislocation model

$$v(x) = \frac{V}{\pi} \arctan\left(\frac{x}{D}\right) \quad (1)$$

(Savage and Burford, 1973), in which x is the distance (km) to the fault, and V is the secular slip rate below the locking depth of D (km). To determine the optimal locking depth and slip rate that can best fit the observations, we set up a grid search for both the parameters (Fig. 9a). A weighted least-squares method was used to estimate misfits (σ), which are defined as $\sigma^2 = \frac{\sum w_i (x_i - \tilde{x}_i)^2}{n}$, in which n is 55, x_i are the measured slip rates parallel to the Muji fault, $\tilde{x}_i$ are the velocities simulated with the screw model, and w_i is the normalized data weight based on the GPS errors. The computation steps were 0.5 km for locking depth and 0.5 mm/yr for slip rate.

The grid search yields a global minimum at a depth and a slip rate of 12.2 ± 10 km, 9.4 ± 2.5 mm/yr. The uncertainties of the two parameters were calculated based on the contour of the best-fit misfit plus 1 observed GPS error. The GPS data

▲ **Figure 9.** (a) Misfit map showing the optimal estimates of locking depth and secular slip rate along the Muji fault. (b) GPS velocities parallel to the Muji fault and best-fit secular interseismic slip rate at the depth. The color version of this figure is available only in the electronic edition.

provide weak constraints on the locking depth, which results in large uncertainties. As shown in Figure 9a, the slip rates at locking depths from 2.5 to > 30 km can explain the observations equally well (Fig. 9a).

In contrast to the local geological estimate of the slip rate (> 5 mm/yr) along the Muji fault (Chevalier *et al.*, 2011, 2015), the optimal geodetic slip rate is 9.4 mm/yr. The discrepancy between the geological and geodetic slip rates has also been observed along other faults such as the San Andreas fault system (SAFS; e.g., Tong *et al.*, 2014; Zeng and Shen, 2014). Differing from this study, the geodetic slip rates along SAFS were lower than those inferred from geological offsets. Tong *et al.* (2014) proposed that using a viscoelastic half-space below an elastic plate in the geodetic modeling could significantly reduce the differences between the geological and geodetic slip rates. This implies that the geodetic slip rate of 9.4 mm/yr on the Muji fault may be still underestimated, due to only the elastic crust being considered in this study. Based on the classic elastic rebound theory (Reid, 1910), the elastic strain in both sides of the fault accumulated during the interseismic phase should be released during the mainshock. In the sense of the slip, the coseismic displacements in the near field should be equal to that accumulated in the far field through the whole earthquake cycle. As shown in Figure 9b, the maximum coseismic deformation is < 150 mm near the fault, and the deformation rate at a distance of 150 km is ~0.45 mm/yr. Then the earthquake repeat interval might be only 34 yrs. However, there is no other M 6–7 earthquake recorded in this region in the last century. This could indicate that either the 2016 M_w 6.6 Muji earthquake was not a characteristic event in the

region, or that the tectonic loading rate of 9.4 mm/yr must be accommodated with a complex fault system other than the Muji fault only. The latter could be true because the 2015 M_w 7.2 Tajikistan earthquake just took place a year ago.

Because of the inaccessibility of the region surrounding the 2016 Muji earthquake, there is limited data constraining present regional tectonic motions and local tectonic structures. A set of normal faults (Chevalier *et al.*, 2015) were mapped around the Karakul graben (Karakul Lake; Fig. 1) and interpreted as responsible for the early formation of the lake, but they are not likely responsible for the 2015 M_w 7.2 left-lateral strike-slip Tajikistan earthquake (Nanjundiah *et al.*, 2016; Sangha *et al.*, 2017). The left-lateral strike slip 2015 M_w 7.2 Tajikistan earthquake fault and the right-lateral Muji fault present a conjugate set of faults, which accommodate the present northward convergence of the Indo-Eurasia collision at the west end of the Tibetan plateau.

CONCLUSIONS AND FUTURE WORK

With Sentinel-1 TOPS interferometry, we investigate the fault geometry and slip distribution of the 2016 M_w 6.6 Muji earthquake. By incorporating the regional GPS velocity data, we also estimate the optimal locking depth and secular slip rate on the Muji fault prior to the earthquake. With these preliminary results, we conclude the following:

1. Sentinel-1 TOPS SAR data provided excellent InSAR results which allow us to investigate surface deformation following a seismic event. Within 30 days after the Muji earthquake, four tracks of TOPS interferometric pairs

were ready for localized deformation mapping. With the T27 and T107 tracks, we obtained clear coseismic deformation measurements, in which the maximum LoS displacements reach ~ 0.25 m. A postseismic interferogram covering the period from 7 to 35 days after the mainshock does not show convincing postseismic signals. More data will be required to reveal potential small deformation in the coming 1 or 2 yrs.

2. The best-fitting InSAR-derived slip model shows that two separated slip zones (Fig. 6a) ruptured during the mainshock, with nearly pure right-lateral strike slip and a maximum slip of ~ 1.6 m at 5 km depth. The total geodetic moment of the earthquake is 9.87×10^{18} N·m, equivalent to an earthquake of M_w 6.6, which is consistent with seismic solutions from both USGS and IGP/CEA. A maximum Coulomb stress increase of 50 bars was imposed at shallow depths just above the eastern rupture zone. A slip gap can be observed at around 20 km along the strike, where no coseismic slip was revealed and few aftershocks were recorded in the first 45 days after the mainshock.
3. Interseismic GPS velocity map reveals a clear right-lateral motion across the Muji fault (Fig. 9b), which suggests a loading rate of 9.4 ± 2.5 mm/yr below 12.2 ± 10 km depth. This estimate is almost double the geological slip rate, 5 mm/yr, implying that the nearby fault structures of the Muji fault should also significantly accommodate part of the regional tectonic loading. The Muji earthquake combined with the Tajikistan earthquake may be evidence that conjugate strike-slip faulting is an important mechanism for accommodating the northward motion of the Indian plate in the Pamirs.

DATA AND RESOURCES

Interseismic Global Positioning System (GPS) velocities were released by [Ge et al. \(2015\)](#). Original Sentinel-1 Terrain Observation with Progressive Scans (TOPS) Single-Look Complex (SLCs) were released by the European Space Agency (ESA) data hub (<https://scihub.copernicus.eu/dhus/>, last accessed May 2017). The TOPS interferograms and coseismic distributed slip model have been shared in a personal dropbox account (https://www.dropbox.com/sh/h4ia3a0vfib2uxj/AAD270GWtZA20IGiRU-P_1Zsa?dl=0, last accessed May 2017). The geodetic inversion package PSOKINV is available upon request. The other data for IGP (Institute of Geophysics)/Chinese Earthquake Administration (CEA) are available at <http://www.cea-igp.ac.cn/tpxw/275080.html> (last accessed May 2017).

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