Blind thrust rupture of the 2015 M_w 6.4 Pishan earthquake in the Northwest Tibetan Plateau by joint inversion of InSAR and seismic data

Guohong Zhang^{1,*}, Xinjian Shan¹, Yingfeng Zhang¹, Eric Hetland², Chunyan Qu¹, Guangcai

Feng³

¹ State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing,

100029, China. * Email: zhanggh@ies.ac.cn

² Earth and Environmental Sciences, University of Michigan, Ann Arbor, 48103, USA.

³ Laboratory of Radar Remote Sensing, School of Geosciences and Info-Physics, Central South University, Changsha, 410083, China

Abstract: The July 3rd, 2015 Pishan, China M_w 6.4 earthquake occurred within the Hetian fold belt, a frontal thrust region between the Northwestern Tibetan Plateau and the Tarim basin. We investigate the fault geometry and the rupture process of the Pishan earthquake based on joint inversion of teleseismic body waves and InSAR measurements. Our results show that the top of the fault that ruptured in the Pishan earthquake is buried 5 ± 2 km beneath the surface and that the earthquake ruptured only a segment of a deeply-seated detachment lying under the Hetian fold belt. Our inferred coseismic slip model shows two slip asperities, located in the depth range of about 7 to 9 km and 10 to 11 km. Additionally, we resolve a slip deficit region between the slip asperities, which might indicate friction heterogeneity on the fault plane. The earthquake ruptured for ~15 seconds, releasing a total seismic moment of 4.7×10^{18} N·m. We also show that the latest Pishan earthquake caused positive Coulomb stress changes on back thrust faults, potentially decreasing the time to the next earthquake on those faults. Based on our Pishan coseismic slip model, along with both the trend of the anticline

system and the pattern of coseismic deformation, we envision an ongoing east-west extensional growth of the anticlines in the Western Kunlun frontal thrust region in addition to the northern underthrusting of the Northwestern Tibetan Plateau below the Tarim basin.

Keyword: Blind thrust earthquake; the Northwest Tibetan Plateau; the 2015 Mw 6.4 Pishan earthquake; joint inversion of InSAR and seismic data; InSAR coseismic deformation

1 Introduction

On July 3rd, 2015, the Mw 6.4 Pishan earthquake occurred around 20 km northeast of Pishan County, Hetian region, Xinjiang province of China. The focal mechanism from USGS body-wave moment tensor solution indicated that the coseismic slip was oblique thrust, with a hypocentral depth of 20 km. The earthquake caused only modest fatalities and economic loss, probably due to the deeply seated hypocenter, as well as its remote distance relative to populated cities. The Pishan earthquake occurred in the northern edge of the western Kunlun Shan, the collision margin between the Northwestern Tibetan Plateau and the Tarim basin (Fig. 1A), which is delineated mainly by the strike-slip Kangxiwa fault (KF) and the Western Kunlun frontal thrust fault (WKF, also referred to as the Tieklik Thrust fault). The KF is a very seismically active fault and is usually deemed as the western continuation of the Altyn Tagh fault (ATF), which hosted the most recent 2014 Yutian Mw 6.9 earthquake at its eastern end (Fig. 1A). Historical events on the WKT, on the other hand, indicate a low level of seismicity within the frontal thrust region. There are only two other events in the Global Centroid Moment Tensor (gCMT) catalogue prior to the occurrence of the 2015 Pishan quake (Fig. 1B). Additionally, contemporary geodetic measurements show less than 2 mm/yr of convergence across the WKT (Pan et al., 2007).

Neither field surveys nor geodetic measurements detected any fault scarps associated with the

2015 Pishan earthquake, and thus it is important to determine which seismogenic structure ruptured during the event. Based on local tectonic settings and focal mechanisms, the Pishan earthquake most likely occurred either on a gently southwest dipping fault segment that extends north into the Tarim basin, or on a steeply north dipping back thrust fault that lies on the border of the Tarim basin and the Northwestern Tibetan Plateau. Although two recent studies generally agreed that a gently southwest dipping thrust fault should be responsible for the 2015 Pishan earthquake, they disagreed as to the shallowest segment of the fault that ruptured (Li et al., 2016; He et al., 2016). It is important to note that only the static final fault slip was inferred from geodetic data in the studies of Li et al. (2016) or He et al. (2016). Here we conduct a joint inversion of both seismic data and InSAR coseismic measurements, with an aim to, in part, provide better resolution of the source fault geometry. Additionally, seismic data provides information on the rupture processes of the earthquake, and thus we infer the spatiotemporal details of the coseismic slip in the latest Pishan earthquake.

In this study, we first infer the source fault of the 2015 Pishan earthquake, based on a grid search assuming uniform slip on a planar fault plane and using the InSAR measurements alone. Second, we discretize the best fitting fault plane found in the grid search into sub-faults and estimate the spatiotemporal pattern of coseismic slip through joint inversion of teleseismic data and InSAR data, by fitting the seismic waveforms and the geodetic coseismic deformation data simultaneously (Bertrand et al., 2002). We also investigate the ability of each data set to resolve the coseismic slip, as well as illustrate the advantages of joint inversion through a full resolution test using synthetic data. We further discuss the potential changes in earthquake risk in the frontal thrust region due to the latest Pishan earthquake.

2 Data and rupture inversion strategy

We use seismograms recorded at teleseismic distances from the Pishan epicenter ($30^\circ < \Delta < 90^\circ$), obtained from the Incorporated Research Institutions in Seismology (IRIS). We choose 20 P waveforms and 8 SH waveforms, which have good signal-to-noise ratios and are well distributed in azimuth around the epicenter (Fig. 2). We only model the first 35 seconds of the P -wave coda and the first 50 seconds of the SH coda. We first deconvolve the instrument response from the seismograms, and then integrate the resulting seismograms to obtain ground displacement records. Finally we bandpass filter the waveforms from 0.8 to 0.01 Hz for P waves and from 0.4 to 0.01 Hz for SH waves.

We use two InSAR interferograms (Fig. 3A; Fig. 3B), one formed by PalSAR images in ascending mode (L-band, where one wavelength equals 23.6cm) and the other by Sentinel-1A images in descending mode (C-band, where one wavelength equals 5.6cm). Full details of the interferogram processing is in Feng *et al.* (2016). The PalSAR interferogram was formed using SAR data acquired on 22 February and 26 July, 2015. The Sentinel-1A interferogram was generated using SAR data acquired on 24 June and 18 July, 2015. Note that these interferograms may include possible interseismic or postseismic deformation. We assume the interferograms are records of only the coseismic deformation. It is difficult, if not impossible, to separate those signals from the coseismic deformation. However, based on the inferred fault slip rate (Pan et al., 2007), and few historical large earthquakes, the possible interseismic deformation over such short periods of the interferogram time spans is likely negligible compared to the coseismic deformation. The interferograms contain about two (Sentinel-1A) or three (PalSAR) weeks of potential postseismic deformation, and it is impossible to separate the coseismic from postseismic deformation in the interferograms, although we surmise that the postseismic deformation over the short duration of the interferograms is likely smaller than the

coseismic deformation. In order to reduce the number of InSAR data in the inversions, we use the downsampling method of Feng et al., (2015), which considers both the fringe rate and the coherence, to reduce the interferograms to 726 and 766 LOS measurements for the PalSAR and the Sentinel-1A interferograms, respectively.

Note that the two InSAR interferograms are one-dimensional (1D), measuring deformation only along the Line-Of-Sight (LOS) of the satellite, and thus are not able to delineate the full 3-dimensional (3D) coseismic deformation of the Pishan earthquake (Wright et al., 2004). At least three 1D interferograms with differing viewing geometries are needed in order to obtain the complete 3D coseismic deformation. However, we can use the ascending and descending interferograms to approximate the east-west and up-down deformation. Specifically, we assume that the north-south deformation is negligible in the interferograms, since InSAR measurements are insensitive to deformation along north-south direction (Feng et al., 2015). The peak motion of the inferred coseismic uplift and subsidence is ~12 cm and ~6 cm, respectively, which indicates a typical coseismic deformation for a thrust event (Fig. 3C). On the other hand, the estimated east-west component of deformation shows that the eastern side of the Pishan earthquake coseismically moved eastward, while the western side moved to the west, which indicates an east-west extension, with a peak motion of ~5 cm. We discuss implications for such an extensional pattern in a later section.

To invert for the spatiotemporal rupture process of the 2015 Pishan earthquake, we follow the inversion procedure of Delouis *et al.* (2002), which uses a multi-time window inversion scheme. We use the simulated annealing algorithm to achieve the final optimal cost function F_{cost} , which consists of two parts, the weighted normalized root mean square misfit to the data and minimization of the total seismic moment $F_{min M0}$:

$$F_{\text{cost}} = \frac{W_{\text{SAR}} \text{RMS}_{\text{SAR}} + W_{\text{TELE}} \text{RMS}_{\text{TELE}}}{W_{\text{SAR}} + W_{\text{TELE}}} + F_{\text{min } M0}$$

In the minimization process of the cost function, F_{cost} , we carry out several preliminary inversion tests to find the weight for each data set. We find that a 50% higher weight of one of the data types (i.e., seismologic or geodetic) relative to the other results in only minor changes in the inferred rupture process, along with a slightly better fitting solution to the higher weighted data set. The weighting strategy does have an effect on the inversion results; however, as long as we achieve a reasonable good fit for both the teleseismic and InSAR data, variations of weighting do not change the main characteristics of the inferred rupture process. In the optimal joint inversion, teleseismic data and InSAR measurements are assigned equal weights. Since the moment is usually overestimated (Delouis *et al.*, 2002), minimization of the moment, $F_{\text{min } M0}$, is adopted, which can be written as follows:

$$F_{\text{min } M0} = \exp(M_{0-\text{cal}} / M_0 - 1) \cdot C_{\text{min } M0},$$

where $M_{0-\text{cal}}$ and M_0 are the computed seismic moments from our inversion and the moment from gCMT solution, respectively, and $C_{\text{min } M0}$ is a factor weighting the moment minimization. We test several values for $C_{\text{min } M0}$ within the range (0,1) and find that $C_{\text{min } M0} = 0.1$ is sufficient.

In the inversion scheme, the source fault is represented by a discontinuity in an elastic half-space (Olson and Aspel, 1982; Okada, 1985). The fault plane is then discretized along strike and dip into 3×3 km² sub-faults. The local source time function of each sub-fault is simulated by three mutually overlapping isosceles triangular functions with 1.0 sec half-duration. We allow a large range of the rake and the rupture velocities in each sub-fault, from 50° to 90° (where 90° and 0° is pure thrust slip and pure left lateral strike slip, respectively) and from 1.0 to 3.8 km/s, respectively.

3 Fault model, resolution test and rupture process

Due to the fact that no surface breaks have been documented during the Pishan earthquake,

determining an initial fault model is not straightforward. We follow a two-step strategy to converge on the final fault model. First, we estimate the location, strike, length and width of the fault model based on the InSAR coseismic fringes (Fig. 3; Table 1). By doing so, we reduce the trade-offs that commonly exist between the fault geometry and inferred fault slip (e.g., Zhang et al., 2015). However, we cannot estimate the fault dip directly from the InSAR measurements or from the aftershock hypocenters due to the scatter in the aftershocks (Fig. 1C). For the second step, we conduct a grid-search to achieve the optimal dip angle and the upper edge depth of the source fault, which we refer to as the “burial depth” hereafter (Fig. 4). Teleseismic data are not sensitive to the fault geometry so we use only InSAR measurements in this preliminary inversion. We find an optimal fault dip of $15^\circ \pm 5^\circ$ and burial depth of 5 ± 2 km (Fig. 4). The final fault model parameters are listed in Table 1, and based on these, we further invert the spatiotemporal evolution of the rupture process in the 2015 Pishan event using teleseismic data and InSAR simultaneously.

Prior to considering the data, we perform a full resolution test to identify the resolving power of both the InSAR and seismic data. We generate synthetic data using the input source model shown in Fig. 5A, to which a low level of noise is added, varying between ± 5 cm for InSAR data and $\pm 10\%$ of the amplitude of the teleseismic data. We use a constant rupture velocity of 2.7 km/s and a constant rake of -7° to simulate the synthetic waveforms and InSAR measurements. We find InSAR coseismic measurements have very good resolution on sub-faults at shallow depth. However, InSAR data has almost no resolution on sub-faults at the hypocentral depth and lower, with some of the fault slip over-estimated and some of the features mis-located (Fig. 5B). For comparison, the resolution of teleseismic data decreases with increasing depth, yet becomes better again at the hypocentral depth and remains relatively good to the bottom of the fault model (Fig. 5C). Finally, we find that the

resolution of the joint inversion is improved substantially, as it benefits from largely complimentary resolution of the InSAR and teleseismic data. The input slip on sub-faults both at shallow depth and at hypocenter depth is well resolved in the joint inversion, with some slip at greater depth and greater distance from the hypocenter also relatively well resolved (Fig. 5D).

Fig. 6 shows the final fault slip distribution from inversion of either InSAR measurements or teleseismic waveform alone, as well as the result of the joint inversion of both data sets (Fig. 6). We use Normalized Root Mean Squares (NRMS) to evaluate the fit to the data for each model. We obtain rather good data fit during all of the inversions, although the inversion of InSAR or teleseismic data alone results in slightly better fit to the data that was inverted, compared to the fits resulting from the joint inversion. The NRMS is 0.23 for InSAR data or 0.49 for teleseismic data when the InSAR or teleseismic data is inverted alone, respectively. For the joint inversion, the NRMS for InSAR measurements and teleseismic data is 0.27 and 0.54, respectively. The data fitting of teleseismic data (both *P* and *SH* waveforms) and InSAR measurements from joint inversion are shown in Fig. 7, Fig. 8, and Fig. 9. In general, most of the waveforms are well fitted (Fig. 7; Fig. 8) and most of the fringes of the InSAR data are reproduced by the result of the joint inversion (Fig. 9). The residuals of the waveforms are mainly from the simplifying assumption of a one-dimensional crustal velocity structure (e.g., Zhang et al., 2012). The InSAR residuals, on the other hand, may include possible atmospheric vapor effects, topographic error, deformation resulting from aftershocks, over-simplified fault geometry, or un-modeled postseismic processes.

Using only InSAR coseismic measurements, the fault slip is inferred to have occurred northwest of the hypocenter with two resolved slip patches, the dominant one mainly up-dip of the hypocenter and a second slip patch down-dip of the hypocenter (Fig. 6A). The fault slip inferred from the

teleseismic data alone, however, finds a larger, more diffuse region of slip also to the northwest of the hypocenter. Teleseismic data results in a larger slip asperity down-dip of the hypocenter, and a smaller slip patch up-dip (Fig. 6B). The discrepancies between the slip models from InSAR or teleseismic data largely result from the differing resolution for the two data sets, yet the common features between these two models can be established, such as the two main slip asperities located up-dip and down-dip of the hypocenter, and a region with low coseismic slip between the two slip asperities at hypocentral depths (Fig. 6A; Fig. 6B). Inverting the InSAR or teleseismic data separately, the seismic moment is $4.5 \times 10^{18} \text{ N}\cdot\text{m}$, or $5.0 \times 10^{18} \text{ N}\cdot\text{m}$, respectively.

Using both seismic and InSAR data in a joint inversion for slip in the Pishan earthquake, we obtain the rupture process in the 2015 Pishan event (Fig. 6). Similar to separate data inversion, the final fault slip from joint inversion shows two slip patches, the largest of which is located mainly up-dip and to the west of the hypocenter, in the depth range of about 7 to 9 km. The second slip patch is down-dip and also to the west of the hypocenter, in the depth range of about 10 to 11 km (Fig. 6). Maximum slip reaches ~1.0 meter, with almost pure thrust slip. The total moment of our joint Pishan slip model is $4.7 \times 10^{18} \text{ N}\cdot\text{m}$, equivalent to a moment magnitude of M_w 6.4, assuming a shear modulus of 30 GPa. The inferred timing of the rupture shows that the Pishan earthquake starts at the hypocenter, generating moderate slip up to 0.7 meters almost immediately after the earthquake initiation. During the first 1 to 5 seconds, rupture propagates mainly unilaterally to the west along the fault plane, in both the up-dip and down-dip directions. At this stage of the rupture process, the down-dip slip patch includes up to 0.5 meters of peak slip. Slip in the larger, up-dip slip patch is completed 15 seconds after earthquake initiation. The entire rupture lasts ~20 seconds, but 95% of the seismic moment is released during the first 15 seconds.

4 Discussion

Since there were no surface breaks associated with the Pishan earthquake, it was not immediately clear which fault structure ruptured during the earthquake. Without knowing which structure ruptured, it was difficult to assess the impact of the 2015 earthquake on ongoing earthquake risk in this region. Li et al., (2016) conducted an elaborate study based on seismic profiles and relocated aftershocks, and inferred that a detachment dipping to the southwest, buried underneath the Hetian fold belt might be related to the latest Pishan rupture (Li et al., 2016). He et al. (2016) used geodetic measurements of the coseismic deformation, and also determined that a seismogenic structure dipping to the southwest was responsible for the latest Pishan earthquake. In contrast to Li et al. (2016), He et al. (2016) argued that the coseismic slip extended to the surface, at which they inferred non-negligible coseismic offsets.

With regard to whether coseismic slip extended to the surface or not, the conclusions of He et al. (2016) and Li et al. (2016) bear significant discrepancies in terms of future earthquake risk. In models with coseismic shallow slip, there is likely significant stress drop on the shallowest segment of the source fault, and thus the earthquake potential on it should be largely decreased. In addition to the surface slip in the model of He et al. (2016), they infer an unbroken region of the fault between the deep and shallow slip, which represents a location for a potential earthquake, possibly more destructive than the 2015 Pishan event. However, He et al. (2016) suggested that the near-surface slip was probably an artifact of the fault geometry model, or possibly after-slip that occurred in the days following the coseismic slip. It is also worth noting that He et al. (2016) only used one ascending track of InSAR measurements and very limited near-field GPS stations, whereas we use both ascending and descending tracks of InSAR data, in addition to teleseismic data. If the Pishan earthquake was blind (i.e., with no coseismic slip extending to the surface), as argued for by Li et al. (2016) and inferred

here, the deep coseismic slip asperity might further load the shallow segment of the fault or neighboring faults, such as a back thrust fault, resulting in secondary slip on those fault segments, as occurred during the 2013 Lushan blind thrust earthquake (Zhang et al., 2016).

Using these multi-sensor data, we argue that the Pishan earthquake ruptured a segment of a deeply-seated detachment fault with coseismic slip only extending to 5 ± 2 km beneath the surface. Due to the blind nature of the Pishan earthquake, a shallow fault, if one exists, might be under continued seismogenic stressing, and may be a location of a future shallow earthquake. More importantly, coulomb stress changes (CSC) caused by the Pishan earthquake on back thrust faults are positive (Fig. 10) and at levels that have been demonstrated to correlate with heightened seismic activity (Toda et al., 2005; Lin et al., 2004). These positive CSC might indicate heightened earthquake potentials on those faults.

An interesting feature in the rupture process of the Pishan earthquake is a slip deficit region at the hypocentral depth, with coseismic slip patches both up-dip and down-dip of it (Fig. 6). Such heterogeneous slip behavior is likely due to fault friction heterogeneity (Kanamori and Stewart, 1976; Das and Aki, 1977). As shown in previous earthquake studies, such as the 2008 Wenchuan earthquake (e.g., Zhang et al., 2012) and the 2015 Nepal Gorkha earthquake (e.g., Zhang et al., 2015), the slip deficit region may indicate either a strong seismic barrier (Das and Aki, 1977), or an aseismic region of the fault (Kanamori and Stewart, 1976). In the latter case, the stress that is accumulated would be released by after slip, possibly coincident with smaller aftershocks. In the former case where the slip deficit region continues to be locked, the stress increase created by the surrounding coseismic slip may hasten a subsequent moderate, yet destructive, earthquake in the slip deficit region. High resolution geodetic monitoring is required to further identify the possibility of coseismic slip within the slip

deficit region.

Li et al., (2016) identified three anticlines in the Hetian thrust and fold belt, which are all trending in an almost east-west direction. The 2D coseismic deformation of the Pishan earthquake we derived from the InSAR measurements, as well as the predicted deformation in our joint coseismic slip model, show prominent east-west extension (Fig. 3; Fig. 11). Interestingly, we also calculate a positive CSC at 5km depth with a northwest-southeast pattern (Fig. 10). It may be more than coincidence that the geometry of the anticline system is consistent with the pattern of the Pishan coseismic deformation and the positive CSC. The rupture did not extend to the surface, possibly due to the absence of an active fault near the surface. Additionally, rather than propagating further northward, the Pishan earthquake instead propagated to the west. Based on the rupture process from our joint inversion, we envision that the latest Pishan earthquake was a response to the tectonic stress resulting from the Northwestern Tibetan Plateau overthrusting the Tarim craton as a result of the India-Asia collision (Jiang and Li, 2014). However, the pattern of the coseismic deformation, the positive CSC, and the rupture process of the Pishan earthquake may characterize ongoing east-west extensional growth of the anticlines in the Western Kunlun frontal thrust region, in addition to the northward migration process of the Northwestern Tibetan Plateau over the Tarim Basin. We imagine that there have been many such Pishan-like earthquakes in the past that have shaped the anticline systems.

5 Conclusions

Using both teleseismic broadband waveforms and InSAR measurements, we determine a model of the rupture process during the 2015 Mw 6.4 Pishan, China, earthquake. In order to reduce the LOS ambiguity, we resolved the 2D coseismic deformation fields along east-west and north-south directions based on the two 1D interferograms. We find that:

(1) There are two slip asperities with substantial coseismic slip, the larger of the two located in the depth range of 7 to 9 km and the other one in the depth range 10 to 11 km. The Pishan earthquake is almost pure thrust, with maximum slip reaching 1.0 meter. The main rupture process lasts ~15 seconds, during which 95% of the seismic moment is released. The total moment of our coseismic slip model is 4.7×10^{18} N·m, equivalent to a moment magnitude of M_w 6.4.

(2) The Pishan earthquake ruptured a segment of a deeply-seated detachment fault, buried 5 ± 2 km beneath the surface. The earthquake potential on the back thrust faults are heightened due to the coseismic stress perturbations resulting from the Pishan earthquake, similar to as following the 2013 Lushan blind thrust earthquake (Zhang et al., 2016).

(3) The Pishan rupture left a slip deficit region between the two slip asperities, probably indicating heterogeneous friction on the fault plane. Future geodetic monitoring of postseismic deformation will help to resolve whether the region of low coseismic slip is an aseismic region or is a seismogenic barrier that has yet to rupture in an earthquake.

(4) The Pishan earthquake propagated mainly to west, with both the distribution of the anticline system and the pattern of the Pishan coseismic deformation showing a component of east-west extension. Such rupture behavior and the trends of the anticlines may indicate an east-west extensional growth of the anticlines in the Western Kunlun frontal thrust region in addition to the northward convergence between the Northwestern Tibetan Plateau and the Tarim.

Acknowledgements

This work is co-supported by grants from the Chinese National Science Foundation (41474013)、Basic Scientific Funding of Institute of Geology, China Earthquake Administration (IGCEA1613) and State Key Laboratory of Earthquake Dynamics (LED2014A01). The topographic data is downloaded

from <http://srtm.csi.cgiar.org>. Envisat ASAR and ALOS-1 PalSAR data are from European Space Agency and JAXA, respectively. The English of the manuscript have been improved by Sue West and Dr. W. Gong. Aftershocks are from Dr. Fang and focal mechanisms are from USGS and GCMT (last accessed on 30, March, 2016). Coulomb 3.3 is used to calculate the Coulomb stress changes. Figures are generated by Generic Mapping Tools (Wessel and Smith, 1998).

References

- Das, S. and Aki K., 1977. Fault Plane With Barriers: A Versatile Earthquake Model, *Journal of Geophysical Research*, 82(36):5658–5670
- Delouis B., D. Giardini, P. Lundgren, and J. Salichon, 2002. Joint Inversion of InSAR, GPS, Teleseismic, and Strong-Motion Data for the Spatial and Temporal Distribution of Earthquake Slip: Application to the 1999 Izmit Mainshock. *Bull. Seism. Soc. Am.*, 92(1): 278-299
- Feng, G., Li, Z., Shan, X., Zhang L., Zhang G., Zhu J., 2015. Geodetic Model of the April 25, 2015 Mw 7.8 Gorkha Nepal Earthquake and Mw 7.3 Aftershock Estimated from InSAR and GPS Data, *Geophysical Journal International*, 203(2): 896-900
- Feng G., Li Z., Xu B., Shan X., Zhang L., Zhu J., 2016. Coseismic Deformation of the 2015 Mw 6.4 Pishan, China, Earthquake, Estimated from Sentinel1 and ALOS2 Data, *Seismological Research Letters*, accepted.
- Gan W.J., Zhang P.Z., Shen Z.K., Niu Z.J., Wang M., Wan Y.G., Zhou D.M., Cheng J., 2007. Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements. *Journal of Geophysical Research*, 112(B8), 582-596
- He P., Wang Q., Ding K., Wang M., Qiao X., Li J., Wen Y., Xu C., Yang S., Zou R., 2016. Source model of the 2015 Mw 6.4 Pishan earthquake constrained by InSAR and GPS: insight into blind

- rupture in the western Kunlun Shan. *Geophysical Research Letters*, 43(4), 1511-1519.
- Jiang X. and Li Z., 2014. Seismic reflection data support episodic and simultaneous growth of the Tibetan Plateau since 25 Myr. *Nature Communications*, 5:5453-5453.
- Kanamori H. and Stewart G., 1976. Seismological Aspects of the Guatemala Earthquake of February 4, 1976, *Journal of Geophysical Research*, 83:3427–3434.
- Lin, J., R.S. Stein, 2004. Stress triggering in thrust and subduction earthquakes, and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults, *Journal of Geophysical Research*, 109(B2):259-259.
- Li T., Chen J., Fang L., Chen Z., Thompson A. J., Jia C., 2016. The 2015 M w 6.4 Pishan Earthquake: Seismic Hazards of an Active Blind Wedge Thrust System at the Western Kunlun Range Front, Northwest Tibetan Plateau. *Seismological Research Letters*, 87(3), doi: 10.1785/0220150205
- Okada, Y., 1985. Surface deformation due to shear and tensile fault in a half-space, *Bull. Seism. Soc. Am.*, 75, 1135-1154.
- Olson, A. H., and R.J. Aspel., 1982. Finite fault and inverse theory with applications to the 1979 Imperial Valley earthquake, *Bull. Seism. Soc. Am.*, 72, 1969-2001.
- Pan J.W., Li H.B., 2007. Late Cenozoic morphotectonic features of the thrust belt in the front of the West Kunlun Mountains. *Geological Bulletin of China*, 26(10):1368-1379.
- Toda S., Stein R.S., Richards-Dinger K., Bozkurt S., 2005. Forecasting the evolution of seismicity in southern California: Animations built on earthquake stress transfer, *Journal of Geophysical Research*, 110(B5):361-368
- Wessel, P., and W. H. F. Smith, 1998. New, improved version of the Generic Mapping Tools released, *Eos Trans. AGU*, 79(47), 579.

- Wright T.J., Parsons B., Lu Z., 2004. Toward mapping surface deformation in three dimensions using InSAR. *Geophysical Research Letters*, 31(1), 169-178
- Zhang G., Hetland E., Shan X., 2015. Slip in the 2015 Mw 7.9 Gorkha and Mw 7.3 Kodari, Nepal, Earthquakes Revealed by Seismic and Geodetic Data: Delayed Slip in the Gorkha and Slip Deficit between the Two Earthquakes, *Seismological Research Letters*, 86(6):1578-1586
- Zhang G., Hetland E.A., Shan X., Vallée M., Zhang Y., Qu C., 2016. Triggered slip on a back reverse fault in the Mw6.8 2013 Lushan, China earthquake revealed by joint inversion of local strong motion accelerograms and geodetic measurements. *Tectonophysics*, 672-673:24-33
- Zhang G., Vallée M., Shan X., Delouis B., 2012. Evidence of sudden rupture of a large asperity during the 2008 Mw7.9 Wenchuan earthquake based on strong motion analysis. *Geophysical Research Letters*, 39(17):26-33

Figures

Fig. 1. Tectonic settings, InSAR coverage and aftershocks of the 2015 Pishan Earthquake. 1A: significant historical earthquakes and local faults around the study region. Blue arrows are the GPS velocities from Gan et al (2007). Acronyms: WKF, the Western Kunlun frontal thrust fault; KF, the Kangxiwa fault; ATF, the Altyn Tagh fault; KKF, the Karakoram fault. 1B: Red star and red beach ball are the epicenter and focal mechanism of the 2015 Pishan earthquake from the USGS, respectively. Blue beach-balls are historical events from gCMT. White circles are relocated aftershocks. Purple and

black squares show the footprints of the Sentinel-1A and ALOS-2 SAR images, respectively. 1C: A profile of the aftershocks along AA'. Red line is the optimal fault location determined in this study.

Fig. 2. Teleseismic stations used during joint inversion. Blue triangles are stations with both P and SH waveforms. Red or black triangles are stations with only P or only SH waveforms, respectively.

Fig. 3. InSAR coseismic interferograms and 2D coseismic deformation of the Pishan event. 3A: The ascending track of InSAR coseismic measurements obtained by ALOS-2 SAR images. 3B: The descending track of InSAR coseismic measurements obtained by Sentinel-1A SAR images. 3C and 3D: The inferred vertical (3C) and east-west (3D) coseismic displacement. Blue rectangle is the source fault projected to the surface. Red star and beach-ball are the epicenter and focal mechanism of the Pishan earthquake.

Fig. 4. Plot of Normalized Root Mean Squares (NRMS) for forward models with varying fault burial depth and dip angle. Black circle shows the location of the optimal burial depth and dip angle.

Fig. 5. Resolution tests for synthetic data inversion. 5A: The input source model; 5B: The inverted fault slip from InSAR measurements; 5C: The inverted fault slip from teleseismic data; and 5D: The inverted fault slip from joint inversion. Black triangle shows the hypocenter.

Fig. 6. Fault slip distribution and rupture process of the Pishan earthquake. 6A and 6B are the static fault slip distribution and a slip-versus-depth profile at distance 27 km from InSAR data inversion, respectively. 6C and 6D are the static fault slip distribution and a slip-versus-depth profile at distance 27 km from teleseismic data inversion, respectively. 6E and 6F are the static fault slip distribution overlaid by the rupture timing and a slip-versus-depth profile at distance 27 km from joint inversion, respectively.

Fig. 7. Observed (black) and predicted (red) teleseismic P waveforms of the Pishan earthquake by the joint slip model.

Fig. 8. Observed (black) and predicted (red) teleseismic SH waveforms of the Pishan earthquake by the joint slip model.

Fig. 9. InSAR prediction and residuals by the joint slip model. 9A and 9B are the InSAR predictions along the ascending and the descending tracks, respectively. 9C and 9D are the InSAR residuals of the ascending and the descending tracks, respectively. Note that Fig. 9A and Fig. 9B share the same color scale with Fig. 3A.

Fig. 10. Coulomb stress change (CSC) at 5 km depth on back thrust faults with a rake of 85° , resulting from coseismic slip in the Pishan earthquake. Also shown are focal mechanism, aftershocks and epicenter of the Pishan earthquake.

Fig. 11. Source fault and the predicted 3D coseismic deformation from our joint coseismic slip model

of the Pishan earthquake. 11A: Black arrows are the modeled horizontal displacement. Color shows

the vertical component of the predicted deformation. Black dotted points indicate the outline of the Slik anticline. 11B: Topographic height versus predicted vertical displacement. Red curved line shows the variation of the altitude along AA' profile, with its corresponding red scale shown to the left. The dotted and solid blue lines are the predicted vertical displacement, with a corresponding blue scale shown to the right. 11C: Black curved lines and red line are local faults interpreted by Li et al., (2016) and the source fault used in our joint inversion, respectively.

Tables:

Table 1. Source fault parameters

NW point/°	Strike/°	dip angle /°	length/km	width/km	Top depth/km	Bottom depth/km
(37.73, 77.84)	115	15	55	33	5	13.5