The 3-D surface deformation, coseismic fault slip and after-slip of the 2010

M_w 6.9 Yushu earthquake, Tibet, China

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Abstract: Using SAR interferometry on C band Envisat descending track and L band ALOS ascending track SAR images, respectively, we firstly obtain two coseismic deformation fields and one postseismic deformation of the 2010 Yushu earthquake, Tibet, China. In the mean while, we also obtain the azimuthal coseismic deformation of the Yushu event by Multi Aperture Interferometry (MAI) technique. With the 3 components of one-dimensional coseismic InSAR measurements, we resolve the complete 3-dimensional deformation of the 2010 Yushu event, which show conformity and complexity to left lateral slip mechanism. The horizontal deformation is basically consistent with a sinistral slip event; whereas the vertical displacement does show certain level of complexity, which we argue is indicative of local fault geometry variation. Based on the InSAR data and elastic dislocation assumption, we invert for coseismic fault slip and early after-slip of the Yushu event. Our inversion results show major coseismic left lateral strike slip with only minor thrust component. And the after-slip model fills most of the slip gaps left by the coseismic fault slip and finds a complementary slip distribution to the coseismic fault slip, which is a good indicator that future earthquake potential on the

Yushu segment has been significantly reduced.

Keyword: The 2010 Yushu earthquake; MAI displacement; 3D coseismic deformation; after-slip inversion; coseismic fault slip inversion

1 Introduction

The Ms7.1 Yushu earthquake, Tibet, China, happened on 13 April 2010 and has caused around 2000 casualties and tens of thousands homeless. In 2008, China mainland has suffered the great Wenchuan earthquake, which has claimed tens of thousands of lives. These two significant earthquakes have both happened along major faults that bound the Bayan Har Block (BHB), a block within Tibet plateau, which deforms severely under the tectonic stress loading from neighboring parts of Tibet in present day (Figure 1). The 2008 Great Wenchuan earthquake occurred on the Longmenshan fault, the eastern boundary of the BHB, exhibiting the collision between the BHB and the Sichuan basin (Burchfiel et al., 2009). The 2010 Yushu event occurred on the southern boundary fault of the BHB, the Xianshuihe-Yushu-Manyi fault zone (XYMF), and thus mainly showed sinistral strike slip (Deng et al., 2003). And the northern boundary of the BHB, namely the Eastern Kunlun fault (EKLF), also hosted several major earthquakes, such as the 1997 Manyi Mw7.6 earthquake and the 2001 Kokoxili Mw7.9 earthquake (Funning et al., 2007; Lasserre et al., 2005). After 5 years, along the same causative fault as the 2008 Wenchuan earthquake, there occurred another devastating earthquake, the 2013 Ms7.1 Lushan earthquake, at 90 km to the southwest of the 2008 Wenchuan epicenter, which was considered to have most probably been triggered by the 2008 Wenchuan event (Wang et al., 2013). After 4 years or so another significant earthquake, the 2014 Ms6.3

Kangding event, happened at the southeastern segment of XYMF. These significant earthquakes and their relation to each other raise questions in common. Studies on complete 3-Dimensional (3D) surface deformation, coseismic fault slip and early postseismic deformation seem to be fundamental to understand the dynamics mechanism of the Yushu event, the faulting characteristics of the XYMF, and the deformation state of the BHB as well.

Previous studies have provided important insights for one dimensional deformation both along Line-Of-Sight (LOS) and along Azimuthal direction (e.g., Li et al., 2011; Hu et al., 2012). From the coseismic deformation and local geologic mapping, we can identify the Ganzi-Yushu fault is the seismogenic structure of the 2010 Yushu event (e.g., Li et al., 2011; Chen et al., 2010). In 1896 and 1854, two strong historical earthquakes ruptured the southeastern segment of the Ganzi-Yushu fault (Chen et al., 2010). During the latest Yushu quake, field investigation found 31 km continuous surface ruptures at around 20 km southeast to the epicenter and around 2 km long of rupture at near Longbao county (Figure 1; Chen et al., 2010). With the help of InSAR images, the surface rupture and the coseismic deformation as well have been revealed in a larger extent and with much more details (e.g., Guo et al., 2010; Zhang et al., 2011; Li et al., 2011; Zhang et al., 2013; Wang et al., 2014). The surface ruptures found by InSAR and offset tracking are consistent with the field investigation at the eastern segments, but the total length of the Yushu rupture reaches around 75 km (Zhang et al., 2011; Zhang et al., 2013; Li et al., 2013). Despite the comprehensiveness of previous studies, it is still open questions on what the main features of the Yushu event's complete 3D deformation is, how the early postseismic

deformation evolves and how the coseismic slip and early after-slip interacts. With the complete 3D deformation, a thorough view of the faulting feature can be directly determined. Furthermore, the postseismic deformation and the after-slip inversion could shed light on how the stress develops and how it might affect future earthquake hazards (Bie et al., 2014).

In this study, we firstly obtain coseismic deformation of the 2010 Yushu event measured through interferometry of SAR images acquired by both descending and ascending tracks. These two deformation fields are one dimensional along LOS, which are not able to delineate the full coseismic deformation of the earthquake due to the LOS ambiguity (Wright et al., 2004). In addition, we also obtain the azimuthal coseismic deformation by Multi Aperture Interferometry (MAI). We then resolve the complete 3D coseismic deformation of the Yushu event by using the 3 components of InSAR LOS measurements. We invert the InSAR data for fault source slip of the Yushu event using linear inversion method under elastic half-space model assumption. Finally we obtain the early postseismic deformation using InSAR and invert for after-slip under the same inversion procedure as the coseismic source slip inversion.

2 SAR data, InSAR and MAI processing

There are two kinds of SAR satellite images available for InSAR and MAI processing. One is the Advanced Land Observing Satellite (ALOS) PalSAR L band data with a wavelength of 23.6 cm in ascending observing geometry. And the other is the Envisat ASAR C band images with a 5.6 cm wavelength in descending observing mode. In order to obtain the coseismic deformation along LOS, we apply conventional InSAR

processing on these two kinds of SAR data. Details of the data description can be found in Table 1. Two-pass differential InSAR method and Gamma software are used to do the processing. We firstly generate the interferograms through interferometry of the SLC images. We simulate the topographic phases by using the SRTM 3-arc second Digital Elevation Model (DEM) under radar slant coordinate and then conduct the interferometry again to remove the topographic phases from the original interferograms, which is usually referred to as differential interferometry (DInSAR). We use precise orbital geometric data to estimate orbital phases and erased them afterwards. The interferograms are unwrapped using the Minimum Cost Flow algorithm (MCF, Werner et al., 2002). Areas with low coherence (coherence under 0.35) will not be unwrapped. Finally, two coseismic deformation fields along ascending and descending LOS are geocoded and generated (Figure 2A and Figure 2B). Note that, there are some parameters used differently during InSAR processing concerning C band ASAR data and L band PalSAR data, for instance, multi-looking is set to be different according to InSAR processing strategy. We follow the exact InSAR processing steps to obtain the postseismic deformation of the Yushu event using L band PalSAR data (Table 1; Figure 3A). We also use Gamma software for the MAI processing. MAI technique can be used to extract azimuthal displacements, which are sub-parallel to north-south direction and a good complementary for InSAR LOS measurements (Bechor et al., 2006). During MAI processing, a split-beam method is often used to separate the full radar signals into forward and backward apertures to yield sub-band SLC images (Barbot et al., 2008). And we process both C band and L band data, however C band data fails to achieve useful

signal due to severe loss of coherence. Here we only describe the MAI processing of L band SAR data. Firstly, two original SLC L band images are divided into two forward sub-band SLC images and two backward sub-band SLC images based on the azimuth common band filtering method (Jung et al., 2009). We conduct the conventional InSAR processing on each pair of the forward and backward SLC data and obtain two interferograms, one forward interferogram and one backward interferogram. Differential processing is then conducted on the two interferograms and we get MAI displacements (Figure 2C). Note that, since we use split-beam method, the radar signals is significantly weakened and thus the resolution of the sub-band SLC images is reduced to about half of the original SLC data, which in return leads to low precision of the MAI displacement measurements.

Figure 2 shows the coseismic deformation fields of the Yushu event under different observing modes. Figure 2A and figure 2B is the coseismic deformation of the Yushu event under descending and ascending mode, respectively. We unwrap the original interferograms and rewrap it with 5.6 cm and 23.6 cm, i.e., one wavelength of C band and L band SAR data, respectively. As shown by both of the two InSAR LOS measurements (Figure 2A and Figure 2B), we detect condense fringes at southeastern segment of the rupture, which indicate severe surface deformation. And we also see continuous fringes at northwestern segment of the rupture. As for the MAI measurements (Figure 2C), the displacements are rather uniform, which shows northward movement on northern side of the rupture and southward displacement on southern side. On the other hand, the postseismic deformation detected by InSAR shows a complementary distribution to the

coseismic deformation (Figure 3A). Regions close to the southeastern segment of the surface rupture, where evidenced large coseismic deformation, has only detected slight postseismic deformation. Whereas at the northwestern segment where insignificant coseismic deformation occurred has evidenced the largest cumulative postseismic deformation of ~6 cm along LOS after ~5 months of the Yushu mainshock.

3 3D coseismic deformation of the Yushu event

We describe firstly about deriving equations of the complete 3D coseismic deformation using 3 components of one-dimensional InSAR measurements. We will then discuss in detail about the fault mechanism of the Yushu event based on the InSAR data and the resolved 3D deformation. According to SAR satellite observing geometry (Figure 4), the relation between InSAR measurements and displacements on surface can be written in Matrix form as:

$$\Delta\rho_{LOS} = -\vec{s} \bullet \vec{U} \quad (1)$$

where $\Delta\rho$ is the InSAR measurements along LOS, minus means objects moving away the satellite. $\vec{U}$ is a 3×1 vector, $\vec{U} = (d_E, d_N, d_V)^T$. And $\vec{s}$ is a unit vector for a certain SAR satellite observing system, which is determined by the so-called incidence angle θ (0, 90) and azimuthal angle α (Figure 4). α is the angle between heading direction of the satellite projected to the surface and due north, positive in clockwise. According to the observing geometry of InSAR and MAI, $\vec{s}$ can be written:

$$\vec{s} = (-\sin\theta \cos\alpha, \sin\theta \sin\alpha, \cos\theta) \text{ for InSAR}$$

And

$$\vec{s} = (-\sin\theta, \cos\theta, 0) \text{ for MAI}$$

So equation (1) can then be modified as:

$$\Delta\rho_{LOS} = -(-\sin\theta\cos\alpha, \sin\theta\sin\alpha, \cos\theta) \begin{pmatrix} d_E \\ d_N \\ d_V \end{pmatrix} \text{ for InSAR}$$

and,

$$\Delta\rho_{MAI} = (-\sin\alpha, \cos\theta) \begin{pmatrix} d_E \\ d_N \end{pmatrix} \text{ for MAI measurements}$$

Or,

$$\begin{pmatrix} \Delta\rho_{LOS-ASC} \\ \Delta\rho_{LOS-DSC} \\ \Delta\rho_{MAI} \end{pmatrix} = - \begin{pmatrix} -\sin\theta_1\cos\alpha_1 & \sin\theta_1\sin\alpha_1 & \cos\theta_1 \\ -\sin\theta_2\cos\alpha_2 & \sin\theta_2\sin\alpha_2 & \cos\theta_2 \\ \sin\alpha_3 & \cos\alpha_3 & 0 \end{pmatrix} \begin{pmatrix} d_E \\ d_N \\ d_V \end{pmatrix} \quad (2)$$

Using equation (2) and the specific observing geometry, we can derive 3D surface deformation $\vec{U}$.

$\vec{U} = -\vec{s}^{-1} \bullet \vec{\rho}$, where $\vec{s}^{-1}$ is the inverse of $\vec{s}$. As for the Yushu case, the unit vector $\vec{s}$ can be calculated using the parameters listed in Table 1:

$$\vec{s}_{YS} = \begin{pmatrix} 0.6132 & 0.1416 & -0.7771 \\ -0.3822 & 0.0812 & -0.9205 \\ 0.9744 & 0.2250 & -0.0000 \end{pmatrix} \text{ and } \vec{s}_{YS}^{-1} = \begin{pmatrix} 1.6136 & -1.3623 & -0.5235 \\ -6.9891 & 5.9006 & 6.7129 \\ -1.2868 & 0 & 0.8098 \end{pmatrix}$$

And the complete 3D coseismic deformation of the Yushu event can be finally written as:

$$\vec{U}_{YS} = \begin{pmatrix} d_E \\ d_N \\ d_V \end{pmatrix} = \begin{pmatrix} 1.6136 & -1.3623 & -0.5235 \\ -6.9891 & 5.9006 & 6.7129 \\ -1.2868 & 0 & 0.8098 \end{pmatrix} \begin{pmatrix} \Delta\rho_{LOS-ASC} \\ \Delta\rho_{LOS-DSC} \\ \Delta\rho_{MAI} \end{pmatrix} \quad (3)$$

Using the equation (3), we obtain the 3D coseismic deformation of the Yushu event based on 3 components of InSAR measurements (Figure 2D, Figure 2E and Figure 2F). Our resolved results show that, the north-south displacements are similar with the MAI component since they have only a slight difference in the observing angle, which shows ~30 cm of maximum northward movement on the northern side of the rupture and ~40

cm of maximum southward displacement on the southern side. Note that InSAR measurements are not sensitive to north-south movement and thus, even with MAI measurements, the north-south component has the least precision in the 3D coseismic deformation derivation. On the contrary, the east-west component of the coseismic deformation is well resolved, which shows both ~50 cm of westward and eastward movement on both the northern side and southern side of the rupture, respectively. We present also the 3D displacements with vectors (Figure 3B). Despite some noise disturbance at far and edge field, we can see that the horizontal displacements are quite consistent with the faulting mechanism of the Yushu event, i.e., left lateral strike slip. However, the vertical displacements of the Yushu earthquake are not quite consistent with sinistral strike slip faulting, which usually show four quadrants of uplift and subsidence (Figure 2D; Figure 3B). We will discuss this unsymmetrical pattern of the resolved vertical displacement in more detail in later section.

4 Coseismic fault slip and after-slip inversion

We use a constrained least-square method to determine the source fault slip and after-slip under elastic half-space assumption and the root mean square (RMS) as a measure of the difference between the observed and the modeled (Wang et al., 2008). The method to describe the relation between the observed and the predicted deformation can be written as:

$$f(\mathbf{s}) = \sum_{i=1}^n W_{i, ratio} \left\| \frac{\mathbf{d}_i - \mathbf{d}_i^0 - \mathbf{M}_i \mathbf{s}}{\delta_i} \right\|^2 + \beta^2 \|\mathbf{H}\mathbf{s}\|^2 \rightarrow \min. \quad (4)$$

where i stands for each InSAR data set, which is re-sampled from the original

interferograms using quad-tree method to get a more manageable data matrix (Johnson et al., 2001). $W_{i, ratio}$ and δ_i are the relative weight between each different InSAR data set and the data uncertainty. $W_{i, ratio}$ is set to be equal for L band and C band InSAR data, but only half of the weight for the MAI data according to their original resolutions. $\mathbf{s}$ and $\mathbf{d}$ are slip vector of each sub-fault and the matrix of observation data, respectively. $\mathbf{d}^0$ is a static offset for InSAR measurements, to account for an unknown unwrapping point during the InSAR processing. $\mathbf{M}$ describes the relation between the model prediction and the observation, the so-called Green's function. Assuming a Poisson ratio of 0.25, we calculate the Green's functions based on the homogeneous elastic half-space model using EDGRN program (Okada, 1992; Wang et al., 2003). β^2 is the smoothing factor, $\mathbf{H}$ and $\|\mathbf{H}\mathbf{s}\|^2$ are the Laplacian operator and the measure of the slip roughness, respectively.

The smoothing term in the misfit function is used to avoid any fluctuation of the slip distribution. We determine the optimal smoothing factor as to be 0.20 by analyzing the trade-off between the squared data misfit and the squared slip roughness, both for the coseismic and postseismic data inversion. In Figure 5, we show only the tradeoff fitting of the coseismic data inversion (Figure 5). From the tradeoff inversion we find that the smoothing factor variations will change the inversion results; however, as long as the smoothing factor is set within a reasonable range (e.g., 0.1-0.3) and we achieve satisfactory fitting to the data, variations of the smoothing factor would not change the main characteristics of the fault slip distribution. One thing to notice, the fault model we use to simulate the earthquake rupture is determined by a series of trial and error

inversion (Table 2). The location, length, width and strike of each segment are estimated directly from the offset data and adjusted by running a few preliminary inversions. In addition, the dip angles of the fault model are set to become steeper from northwestern segment to southeastern segment (Table 2), which is incorporated as possibly suggested by the vertical component of the coseismic deformation (Figure 2D). Our fault model could match well the surface ruptures detected by field investigation (Chen et al., 2010) and offset tracking (Zhang et al., 2013). It is unnecessary to use more complex fault geometry as we did in our previous study (Zhang et al., 2013), which will introduce more tradeoff to inversion process but won't increase the data fitting significantly. The fault model is further discretized into 2 km by 2 km sub-faults along both strike and dip direction.

Note that the azimuthal coseismic data has much larger uncertainty than the LOS data. Thus, in order to evaluate the effect of the azimuthal data, we show two coseismic inversion results, one without the azimuthal data included (Figure 6A) and the other with it (Figure 6B). Parameter settings are set to be the same between the two inversions, except the rake constraint condition. We do not need put any constraint on rake if we use all the data available, including the azimuthal displacement data, since we have obtained the complete coseismic deformation under different observing geometry of InSAR system. If we extrude the azimuthal coseismic displacement data during inversion, we need to put some constraint on the rake, as we usually do in previous resolution test study, e.g., in Wenchuan earthquake slip inversion (Zhang et al., 2011). We can see that the removal of the azimuthal data does not change the inversion result significantly (Figure

6A and Figure 6B). However, with the azimuthal data included, the inverted rake of each sub-fault is better resolved. Below, we only discuss the optimal coseismic inversion results with the azimuthal data included.

Our modeling is quite successful, and the linear correlation between the observation and the prediction is over 90%. Mean residuals are less than 10cm for coseismic data and around 1cm for postseismic data (Table 3). And the 3D coseismic deformation is generally well simulated (Figure 7). After the Yushu earthquake, numerous studies have been conducted about rupture process and coseismic slip distribution inversion (e.g., Zhang et al., 2010; Li et al., 2011). Our results show similar slip pattern as in most of the published studies, which all confirm that the Yushu earthquake is mainly a left lateral strike slip event, with only minor thrusting component at deeper depth (Figure 6B). When considering the location of the epicenter, the coseismic rupture is mainly unilateral propagated to southeast direction. The largest slip of 1.5 m happened at the southeastern segment, where slip breaches to the sub-surface and no shallow slip deficit occurs. Previous studies have shown that large strike slip event usually exhibits shallow slip deficit phenomenon (e.g., Fialko et al., 2005). Yet we do find some shallow slip deficit at the northwestern segment of the coseismic rupture (Figure 6B). Our estimation of the seismic moment reaches 1.8×10^{19} N.m, equivalent to a magnitude of Mw6.8. Figure 6C displays the cumulative after-slip model of the Yushu event, which have two main asperities, one at the northwestern segment in shallower depth, the other at the southeastern segment in deeper depth (Figure 6C). The maximum after-slip is around 0.25 m and the cumulative postseismic moment reaches 7.0×10^{17} N.m, ~5% of the

coseismic moment.

5 Discussion

By its observing nature, InSAR measurements are sensitive to up-down movement (Shan et al., 2011) and thus the vertical component we obtain should be well resolved (Figure 2D). The unsymmetrical pattern of the vertical displacements could be explained by nonlinear elastic rheologies in the vicinity region, by local variation of the fault geometry, by step-over structures, or combinations of such factors. Nonlinear elastic rheologies are proposed by Pelzer et al., (1999), to explain the unsymmetrical InSAR observation during the 1997 Manyi earthquake; however, such nonlinear rheologies are not common in real earthquakes, as shown by other studies (e.g., Funning et al., 2007). The other two factors may both play certain part for the unsymmetrical pattern of the vertical displacements. Step-over can cause local push-up or pull-apart structures that were observed during the 2010 Yushu event (Chen et al., 2010), which will inevitably affect the vertical displacement pattern. In our inversion and modeling, we incorporated local variations in our fault geometry to explain such unsymmetrical pattern of the vertical displacements. The variations in the fault geometry include variable fault strike angles and dip angles among different segments (Table 2) and we obtain good match between the observed displacement and the predicted (Figure 7). We thus argue that the incorporated fault geometry, along together with local step-over structures that occurred during the 2010 Yushu event, could be reasons for the unsymmetrical pattern of the vertical displacements.

After-slip is the stress adjustment of the coseismic stress perturbation and is usually

deemed to occur in a complementary way with the coseismic fault slip. In the Yushu case, we do found such complementary pattern between coseismic fault slip and after-slip (Figure 6B and Figure 6C). At the southeastern segment, there is large coseismic fault slip, which means most of the seismic energy accumulated has been released, and thus has little after-slip. On the contrary, at the northwestern segment, there occurs smaller coseismic slip, which means seismic energy has not been released completely, and thus has larger after-slip to release that energy (Figure 6C).

Future earthquake potential could roughly be estimated based on the coseismic fault slip and after-slip pattern. Regions with larger coseismic slip should have larger coseismic stress drop and thus less earthquake potential in near future. Regions with larger postseismic slip should also have less earthquake potential. When combining both coseismic and postseismic slip, we find that the Yushu earthquake has almost left no slip gap in the upper 20km elastic crust, indicating that the energy accumulated before and during the event has been released and future earthquake potential on the coseismic and poseismic fault region is low. However, for a typical strike slip event, the Yushu earthquake should increase future earthquake potential to both the northwestern and southeastern end of the rupture, for instance, the afore mentioned Kangding earthquake happened in 2014 does occur on the XYMF to the southeast direction of the 2010 Yushu event (Figure 1). We should pay close attention to such earthquake triggering or migration phenomenon.

6 Conclusions

We investigate the 3D surface deformation, coseismic fault slip and after-slip of the 2010

Yushu earthquake, using InSAR and MAI techniques and under elastic half-space assumption. We find that:

- (1) The LOS InSAR deformation shows condense fringes at south-eastern segment and continuous fringes at north-western segment of the coseismic rupture. The azimuthal displacements detected by MAI technique shows northward movement on northern side of the rupture and southward movement on southern side.
- (2) The resolved horizontal deformation of the 2010 Yushu event shows consistency with a left lateral strike slip event; whereas the resolved vertical component shows more complexity, which we argue may exhibit local variations of the source fault geometry.
- (3) The inversion of coseismic fault slip finds no shallow slip deficit at the SE segments of the rupture; yet does show such shallow slip deficit at the NW segments of the rupture. The largest coseismic fault slip of the 2010 Yushu earthquake reaches 1.5 m and the seismic moment reaches 1.8×10^{19} N.m, equivalent to a magnitude event of Mw6.8.
- (4) Accumulated after-slip model based on inversion of InSAR measurements gives a complementary pattern with the coseismic fault slip. No slip gap left by the Yushu earthquake under 20 km depth. Future earthquake potential on the Yushu segment has been reduced; yet earthquake potential to the northwestern end and southeastern end of the rupture has been increased.

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Figures

Figure 1. InSAR coverage and tectonic boundary of the 2010 Yushu Earthquake. Upper right inset shows the main strike-slip faults and thrust faults within and around Tibet (red lines). White arrows show schematic block motion observed by GPS data (Gan et al, 2007). BHB and XYMF stand for the secondary Bayan Har Block and the

Xianshuihe-Yushu-Manyi fault, respectively. Two blue stars are epicenter locations for the 2014 Kangding earthquake (KD) and the 2008 Wenchuan earthquake (WC). The main figure shows InSAR coverage area. Red curves show surface ruptures obtained by field investigation (Chen et al., 2010). The blue and white rectangles are the coverage area of ALOS L band PalSAR and Envisat C band ASAR, respectively. Blue arrows are the GPS velocity after Gan et al (2007). Red star and the beach ball are the epicenter and focal mechanism of the 2010 Yushu earthquake from USGS, respectively. White circles are aftershocks, also from USGS.

Figure 2. InSAR coseismic measurements and the derived 3D deformation of the 2010

Yushu Earthquake. Figure 2A is the coseismic deformation detected by Envisat C band ASAR data under descending mode. Each fringe is a color cycle from red to blue, which equals 5.6cm surface deformation in the LOS direction. We rewrap it with 5.6cm, one wavelength of C-band data. Figure 2B is the coseismic deformation detected by ALOS L band PalSAR data under ascending geometry. Each fringe is also a color cycle from red to blue, rewrapped with 23.6cm, one wavelength of L-band data. Figure 2C is the azimuthal displacements detected by MAI technique. Figure 2D/2E/2F are the resolved components of the vertical, the north-south and the east-west, respectively. Black lines are the surface ruptures from offset tracking (Zhang et al., 2013).

Figure 3. Postseismic deformation and 3D coseismic deformation of the Yushu event. Figure 3A is the postseismic deformation after around 5 months of the Yushu event, detected by ALOS L band PalSAR data. Figure 3B is the 3D coseismic deformation resolved based on 3 components of InSAR data. Arrows are the horizontal displacements and color denotes the vertical components. Blue rectangles are the fault model we determined and used for fault slip inversion. See more details in the main text and Table 2.

Figure 4. Geometric relation between ascending observing InSAR and the 3D displacement. θ and α are the incidence angle and azimuthal angle (AZ), respectively. AZ also is the observing direction of MAI. ALD means stands for Azimuth Look Direction. More details in the main text. This figure is modified based on Hong (2010).

Figure 5. Trade-off between data misfit (NRMS) and slip roughness for coseismic data inversion. Each blue circle stands for a separate inversion using a specific smoothing factor. The optimal smoothing factor is chosen according to the trade-off line.

Figure 6. Coseismic fault slip and after-slip model. Figure 6A and Figure 6B are the coseismic fault slip inverted from without and with the azimuthal data included, respectively. Figure 6C is the after-slip model. For comparison, we add the coseismic slip contours above and we can find a clear complementary slip distribution between the coseismic fault slip and postseismic after-slip. Arrows are rakes with coseismic slip larger

than 0.5m and rakes with after-slip larger than 0.1m, respectively. Note that, for clarity the 3 segments have been jointed together.

Figure 7. Simulated 3D coseismic deformation and the residuals. Figure 7A, 7B and 7C are the simulated vertical, north-south and east-west coseismic deformation, respectively. Figure 7D, 7E and 7F are the residuals between the observed and the simulated, for the

vertical, north-south and east-west component, respectively.

Tables:

Table 1. SAR data description

Acquisition phase	Data type	Acquisition dates	Method	Incidence angle (°)	Azimuthal angle (°)
coseismic	ALOS-1	2010-01-15	InSAR	39	-13
	PALSAR	2010-04-17	MAI	90	-13
	Envisat	2009-11-03	InSAR	23	-168
	ASAR	2010-06-01			
postseismic	ALOS-1	2010-04-17	InSAR	39	-13
	PALSAR	2010-09-02			

Table 2 Fault model parameters used during inversion

No	NW point/ °	Strike/ °	dip angle / °	length/km	width/km
NW segment	(33.23, 96.44)	109	75	26	30
Middle segment	(33.16, 96.70)	128	83	14	30
SE segment	(33.08, 96.82)	125	85	36	30

Table 3. Inversion residual and Normalized RMS

Inversion	Mean	NRMS	Linear correlation	Scalar Moment
phase	residual(cm)		(%)	(N.m)
Cosesismic	9.8	0.4	95	1.8×10^{19}
Postseismic	1.1	0.28	93	7.0×10^{17}