Refining slip distribution in moderate earthquakes using Sentinel-1 burst overlap interferometry: a case study over 2020 May 15 $M_w$ 6.5 Monte Cristo Range Earthquake

Yan Cui,¹ Zhangfeng Ma,¹ † Yosuke Aoki,² Jihong Liu,³ Dongjie Yue,¹ Jia Hu,¹ Cheng Zhou⁴ and Zhen Li⁵

¹School of Earth Sciences and Engineering, Hohai University, Nanjing 211100, Jiangsu, China. E-mail: jspcmazhangfeng@hhu.edu.cn; yuedongjie@163.com
²Earthquake Research Institute, The University of Tokyo, Tokyo 113-0032, Japan
³School of Geosciences and Info-Physics, Central South University, Changsha 410083, Hunan, China
⁴SINOPEC Geophysical Research Institute, Nanjing 211103, Jiangsu, China
⁵College of Surveying and Geo-informatics, North China University of Water Resources and Electric Power, Zhengzhou 450046, China

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SUMMARY
Azimuth and range measurements from Synthetic Aperture Radar (SAR) images are commonly used to depict the coseismic deformation of large earthquakes. Azimuth measurements associated with moderate-sized earthquakes are hardly applicable due to their limited accuracy. In this paper, we first explored the capability of Sentinel-1 azimuth measurements to map the coseismic deformation of a moderate earthquake. We used both range and azimuth offset measurements to map the coseismic deformation of the 2020 $M_w$ 6.5 Monte Cristo Range earthquake in Nevada. Optimal dip angles of the two main faults and the slip model were obtained. By adding azimuth displacements as constraints, the inverted slip model reveals shallower and more refined slip than models only constrained by InSAR and GPS data, highlighting the importance of introducing the azimuth measurements to the moderate earthquake. The preferred fault model shows a mixture of left-lateral and normal faulting on the western segment and a left-lateral slip on the eastern segment. We found that the inferred faults might verify the clockwise rotation block model, which has been proposed to accommodate fault slip across the Mina deflection. Moreover, a shallow alluvial basin and the young left-lateral fault within the left bend can potentially be responsible for the orientation and normal slip components in the western fault segment, respectively.

Key words: Space geodetic surveys; Interferometry; Earthquake hazards.

1 INTRODUCTION
An $M_w$ 6.5 earthquake struck the west of Monte Cristo Range in Nevada on 2020 May 15 at 11:03:27 UTC, leading to a strong shaking at regional distances (up to Mercalli Modified Intensity VIII; https://earthquake.usgs.gov). Preliminary focal mechanism solutions for this earthquake released by the U.S. Geological Survey (USGS) indicate that the slip occurred on a steeply dipping fault striking either east-west (left-lateral) or north-south (right-lateral). Over 1100 and 47 aftershocks of $M_w > 2.5$ and $M_w > 4.0$, respectively, within one month after the main shock mainly extended along a WSW-ENE trending fault structure, implying that the seismogenic fault likely strikes eastward (Fig. 1). An inspection of the seismicity seemingly reveals that the rupture occurred on an east–west striking plane with a left-lateral motion. Discrete and ambiguous surface ruptures made the depicting of the fault trace difficult. As noted, several studies focused on estimating the fault parameters of this earthquake using geodetic and teleseismic data (Table 1). Hammond et al. (2020) used GPS data to constrain the fault parameters on a single fault with a fault dip of 90° and a strike of 11°, and reported that a left-lateral slip of ~1 m on a plane fault well explains near-field GPS displacements. Zheng et al. (2020) used InSAR and teleseismic data to estimate the slip distribution on the two fault segments with the fault dips of 63° and 83°. As Nevada’s largest event in the past 66 yr, this event reminds us to refocus on this third most tectonically active state in the United States behind Alaska and California (Anderson & Miyata 2006).
Figure 1. The study area of the Monte Cristo Range earthquake and three generated interferograms from the ascending orbit (top) and the descending orbit (middle and bottom). The W-phase moment tensor solution from the USGS is also shown. Red solid lines are the surface trace of the inferred faults, and the red frames indicate the ground projection of the two-segment fault model. The aftershocks within one month after the main shock are plotted in circles with the colours corresponding to the focal depths. IHF: Indian Head fault; BSF: Benton Springs fault; PSF: Petrified Springs fault; MCVF: Monte Cristo Valley fault; RFF: Rattlesnake Flat fault; EMF: Excelsior Mountains fault; CF: Coaldale fault; WMF: White Mountains fault; FLVF: Fish Lake Valley fault; EPF: Emigrant Peak fault; LMF: Lone Mountain fault; CDF: Crescent Dunes fault. Three insets on the left show wrapped interferograms acquired by Sentinel-1 in ascending track 64 and descending tracks 71 and 144. White dashed frames in these three insets represent the areas where undesired phase discontinuities happened, and the red star is the epicentre. The inset on the top-right shows the broader view of the location of the study. Pacific-North American relative plate motion vector is 50 mm yr$^{-1}$ at 323$^\circ$ (DeMets & Dixon 1999). The light magenta, blue and green boxes outline ascending track 64, descending track 71 and 144 SAR frames. The MD is shown in orange. Other element abbreviations are SAFS: San Andreas fault system; SNGV: Sierra Nevada/Great Valley; WLB: Walker Lane Belt; ECSZ: Eastern California shear zone; CA: California; NV: Nevada.

Interferometric Synthetic Aperture Radar (InSAR), a rising geodetic tool, has been successfully used to study earthquake deformations (Peltzer et al. 1999; Fialko et al. 2005; Fielding et al. 2009; Li et al. 2009; Raoucles et al. 2010; Elliott et al. 2013; Xu et al. 2016; Xu et al. 2018; Zhou et al. 2018; Liu & Xu 2019). Wide coverage and high accuracy of SAR images benefit investigating the coseismic deformation and inverting for the fault slip model from the obtained deformation field, which are also essential for understanding fault geometry and earthquake mechanism (Xu et al. 2010; Prats-Iraola et al. 2012; Xu et al. 2018). However, a key limiting factor of the differential InSAR (D-InSAR) technique is that it only measures displacements along the radar line-of-sight (LOS, Shrivastava et al. 2016) direction and misses the along-track displacements. Using only LOS displacement in fault source modelling frequently leads to misinterpretation of the actual coseismic motion and substantial trade-offs between model parameters (Hu et al. 2014; Wang & Jónsson 2015). For example, Fielding et al. (2013) and Elliott et al. (2013) both found that the 2011 Mw 7.1 Van (Eastern Turkey) earthquake occurred on a steep north-dipping thrust fault, but the obtained fault slip distributions are significantly different from each other even if they employed a similar data set. This difference indicates that interferograms from only one viewing angle are not enough to constrain the slip distribution of an earthquake.

Existing studies have demonstrated the significance of simultaneously using InSAR measurements from different viewing geometries, particularly the along-track deformation measurement, to the model inversion (Wright et al. 2004; Funning et al. 2005; Hu et al. 2012; Wang & Jónsson 2015; Grandin et al. 2016; Liu et al. 2019). The measurements from the pixel offset tracking (POT, Michel et al. 1999), multi-aperture InSAR (MAI, Bechor & Zebker 2006; Jung et al. 2009), and burst overlap interferometry (BOI) (Grandin et
Table 1. Fault parameters retrieved by different scholars and institutions. * indicates two fault segments solutions.

| Source | Data used | Central Location (E, N) | Strike (°) | Dip (°) | Rake (°) | Depth (km) | Length (km) | Width (km) | Max Slip (m) | Moment (10^18 N m) | Magnitude (w) |
|--------|-----------|-------------------------|------------|--------|---------|------------|-------------|-------------|-------------|----------------|------------------|--------------|
| USGS Teleseismic | −117.85,38.16 | 73/168 | 78/67 | 24/−167 | 11.5 | – | – | – | 6.774 | 6.49 |
| GCMT Teleseismic | −117.85,38.21 | 75/168 | 81/74 | 16/−171 | 12 | – | – | – | 6.34 | 6.5 |
| Hammond et al. (2020) | −117.921,38.161 | 90.02 | 10.9206 | 4 | 17/017 | 10.47 | 24 | 24 | 6.31 | 6.41 |
| Zheng et al. (2020) | − | – | – | – | – | – | – | – | – | 2 | 0.7 |
| Our solution* | −118,38.167 | 78.536 | 65 | 28.560 | 40 | 0.57 | 24 | 24 | 6.5 | 6.5 |

2 REGIONAL CONTEXT

The complex tectonic settings of the Monte Cristo Range earthquake are governed by the interaction between the Pacific and North American plates. Up to 25 per cent of the 50 mm yr⁻¹ Pacific–North American relative right-lateral plate motion is accommodated by the Walker Lane Belt and Eastern California shear zone, and the rest is mainly accommodated by the San Andreas fault system (Dokka & Travis 1990; Dixon et al. 1995, 2000; Bennett et al. 2003). Those northwest-trending dextral faults in WLB that are subparallel to the plate motion are interrupted by zones of east-northeast trending sinistral faults (Wesnousky 2005a; Nagorsen-Rinke et al. 2013). This diffuse region may combine into a major transform boundary to replace the San Andreas fault to accommodate the tectonic motion in the future (Faulds et al. 2005).

The MD, where the Monte Cristo Range earthquake occurred, is a right stepover and consists of sinistral, dextral, and normal faults (Bradley 2005; Wesnousky 2005b; Lee et al. 2006, 2009; Tincher et al. 2009; Nagorsen-Rinke et al. 2013; DeLano et al. 2019). Several different kinematic models have been proposed to explain the slip transfer across the MD. Oldow & Craig (1992) and Oldow et al. (1994) suggested that the dextral slip transferred...
into the MD via the normal slip. Subsequently, Oldow (2003) proposed a transtensional model, whereby oblique-slip (sinistral and normal) along connecting faults accommodates the dextral slips. Conversely, Wesnousky (2005a) and Nagorsen-Rinke et al. (2013) explained the deformation mechanism across the MD region using a clockwise block rotation model with sinistral slips along connecting faults. Previous large earthquakes, including the 1932 \( M_s 7.2 \) Cedar Mountain and the 1954 Fairview Peak–Dixie Valley (\( M_s 7.2 \) and 6.8) earthquake sequence, took place in the northwest-striking right-lateral faults to the north of Monte Cristo Range earthquake. However, the Monte Cristo Range earthquake ruptured near the east-trending fault within MD for the first time. Therefore, because the historical seismicity is concentrated along the NW-trending faults, trending fault within MD for the first time. Therefore, because the historical seismicity is concentrated along the NW-trending faults, so, due to the near-polar orbit of SAR satellites, the along-track deformation effect on cm-dm coseismic along-track deformations seems negligible, we can ignore it effect. Only the along-track deformation can be estimated and removed by the enhanced spectral separation of \( \sim 5000 \text{ Hz} \) between consecutive bursts. Any cross-track deformation of ascending and descending tracks can be formed by

\[
d = d_1 \cos \theta + d_2 \sin \theta + \delta
des(1)
\]

where \( \theta \) and \( \alpha \) respectively represent the radar incidence angle and the orbital azimuth angle (positive clockwise from the North), \( \alpha - \frac{\pi}{2} \) represents the angle between the ground range direction and the North (positive clockwise from the North). \( \delta \) represents the residual error. Subscripts asc and des denote the ascending and descending geometries, respectively.

From the east–west displacement field (Fig. 2a), a roughly ENE-trending fault trace separates deformation at opposite directions nearly throughout the entire rupture zone. In contrast to the east–west displacement field, an area of negative displacement representing obvious subsidence occur merely western of the epicenter (Fig. 2b).

### 3.2 Along-track ground displacements

Cross-track deformation of ascending and descending tracks can provide measurements from two different viewing geometries. Even so, due to the near-polar orbit of SAR satellites, the along-track component of deformation is almost missing (Wright et al. 2004; Grandin et al. 2016). The offset tracking and multiple-aperture InSAR techniques measure along-track deformation exceeding \( \sim 50 \text{ cm} \), promoting their applications in large-scale earthquakes (Jung et al. 2014; Grandin et al. 2016). Hence, we attempt to use BOI to compute along-track deformation caused by the moderate earthquake.

In the Sentinel-1’s TOPS mode, the satellite keeps electronically steering beam in the azimuth direction, resulting in a high spectral separation of \( \sim 5000 \text{ Hz} \) between consecutive bursts. Any along-track signals can further introduce a phase inconsistency in the burst overlaps. Assuming no stochastic phase noise, this phase inconsistency (we named it as burst overlap interferogram below) \( \phi \) can be formed by

\[
\phi = 2\pi \Delta f \Delta x
\]

where \( \Delta f \) is the spectral separation and \( \Delta x \) denotes the along-track shift related to three possible elements: orbital uncertainty, ionospheric disturbance and along-track deformation.

The orbit of the Sentinel-1 constellation can be ever maintained within a \( \sim 150 \text{ m} \) tube. The azimuth shift induced by orbital uncertainty can be estimated and removed by the enhanced spectral density (ESD, Prats-Israola et al. 2012) technique in advance. After ESD, only ionospheric disturbance and along-track deformation should be further considered in the residual burst overlap interferograms. Given less ionospheric disturbances occur in mid-latitude regions than low-latitude areas, and this mm–cm level ionospheric effect on cm-dm coseismic along-track deformations seems negligible, we can ignore it effect. Only the along-track deformation is left in the final burst overlap interferogram. However, in real cases, phase noise always exists and is hard to get rid of. To obtain a clean along-track deformation field, a strategy (Ma et al. 2019) in which elite pixels with high coherence are first selected could

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**3 DATA PROCESSING AND INVERSION STRATEGY**

### 3.1 D-InSAR and 2-D displacements

In order to obtain the surface deformation field associated with the Monte Cristo Range earthquake, we generated coseismic interferograms (Fig. 1) from the C-band Sentinel-1 TOPS mode from three tracks (descending track 71 and 144 and ascending track 64). Pre-seismic images of ascending track 64 and descending track 71 were both acquired on May 11, and their post-seismic images were acquired on May 17; the interferograms include deformation by eight \( M_s > 4 \) aftershocks and 2 d of post-seismic motion. We registered images from all tracks to their respective reference with a geometrical co-registration method (Sansosti et al. 2006) and a following Enhanced Spectral Diversity to mitigate the residual misregistration (Ma et al. 2020). In the interferometric processing, we simulate the topographic phase with the 1-arcsec Shuttle Radar Topography Mission (Farr et al. 2007) Digital Elevation Model. After flattening the interferogram and eliminating the topographic phase, a multilooking was applied with factors of 5 by 20 in the azimuth and range directions, respectively. The interferograms were filtered by an adaptive filtering algorithm (Goldstein & Werner 1998) and unwrapped using the SNAPHU software (Chen & Zebker 2001). Due to the occurrence of the unknown fault geometries of this earthquake along with complex surface ruptures, it is difficult to accurately identify the fault traces through a direct visual inspection on the interferograms. Therefore, we decomposed the displacements along the LOS direction into two orthogonal components of the surface displacements as follows.

It is challenging to obtain a 3-D displacement field from three interferograms in this study because the azimuth angles of two descending tracks are very similar. We just derived east–west and vertical displacements (Fig. 2) by decomposing LOS displacements through a least-square method. The relationship between the 2-D ground displacement vector \( d = [d_x, d_y] \) and the InSAR displacement vector \( D = [D_{asc,LOS}, D_{des,LOS}, D_{des,2LOS}] \) can be expressed as (Hu et al. 2012):

\[
\begin{align*}
D_{asc,LOS} & = \begin{bmatrix} \sin \theta_{asc} \cdot \cos \alpha_{asc} & \cos \theta_{asc} \\ -\sin \theta_{asc} \cdot \cos \alpha_{asc} & \cos \theta_{asc} \end{bmatrix} \cos \alpha_{asc} \\
D_{des,LOS} & = \begin{bmatrix} \sin \theta_{des1} \cdot \cos \alpha_{des1} & \cos \theta_{des1} \\ -\sin \theta_{des1} \cdot \cos \alpha_{des1} & \cos \theta_{des1} \end{bmatrix} \cos \alpha_{des1} \\
D_{des,2LOS} & = \begin{bmatrix} \sin \theta_{des2} \cdot \cos \alpha_{des2} & \cos \theta_{des2} \\ -\sin \theta_{des2} \cdot \cos \alpha_{des2} & \cos \theta_{des2} \end{bmatrix} \cos \alpha_{des2}
\end{align*}
\]

\[
\times \left( \begin{bmatrix} d_x \\ d_y \end{bmatrix} + \begin{bmatrix} \delta_{asc,LOS} \\ \delta_{des,LOS} \end{bmatrix} \right)
\]

\[
\left( \begin{bmatrix} D_{asc,LOS} \\ D_{des,LOS} \\ D_{des,2LOS} \end{bmatrix} \right)
\]

\[
(1)
\]
be borrowed. An unbiased coherence estimation is a premise with this method. Because only two images are used in this case, the statistically homogeneous pixel (SHP) selection (Jiang et al. 2014) is not applicable because it requires many images. Therefore, the stationary condition provided by SHP in the coherence estimation window cannot be satisfied. To improve the coherence estimation accuracy, Minimum Spanning Tree-ESD and Efficient ESD (Ma et al. 2020) provide us a clue. Because the TOPS mode senses the burst overlap region twice, the number of samples in this overlap region doubles. Even though the stationarity is hard to satisfy, the double number of samples can benefit the coherence estimation, leading to bias mitigation (Bamler & Hartl 1998). The commonly used Boxcar coherence estimator is defined as

\[ 
\gamma = \frac{\left| \sum_{i=1}^{k} m_{i,up}s_{i,up}e^{-\sqrt{\nu}\phi_{ramp,up}} \right|}{k} 
\]

where \( up \) denotes the upper burst overlap, \( m \) and \( s \) respectively represent referenced and secondary image, \( \phi_{ramp} \) is the linear phase ramp estimated by the maximum-likelihood fringe estimator, which aims to remove the local fringe, and \( k \) is the \( i \)th pixel in \( k \) pixels.

By introducing the doubled samples, the coherence is now written as

\[ 
\gamma = \frac{\left| \sum_{i=1}^{k} m_{i,up}s_{i,up}e^{-\sqrt{\nu}\phi_{ramp,up}} + \sum_{i=1}^{k} m_{i,lo}s_{i,lo}e^{-\sqrt{\nu}\phi_{ramp,lo}} \right|}{2k} 
\]

where \( lo \) denotes the lower burst overlap. This method improves the estimation accuracy of coherence; see Ma et al. (2020) for further discussions.

Fig. 3 shows the along-track displacement field. In contrast to the east–west and vertical displacements (Fig. 2), the along-track displacements show a more complex pattern, with both negative and positive displacements peaking at ±11 cm. Apart from the slight deformation in the far-field, Fig. 3 identifies three deformation zones around the epicentre. The ascending images yield the maximum positive (northward) displacement about 13.7 km to the west of the epicentre, contrasting to the opposite (southward) motion closer to the epicentre. It is worth noting that the southern burst in the descending track 71 yields negative displacements in many areas (Fig. 3, top-right inset).

### 3.3 Inversion strategy

Three differential interferograms, GPS-derived displacements (Hammond et al. 2020), and azimuth displacements in the burst overlap area can be used to retrieve fault parameters and slip distribution at depth. A quadtree-based method was applied to subsample the InSAR and BOI data sets (Jo´nsson et al. 2002). We subsampled the InSAR data of each track because the InSAR measuring points are continuous in space. While BOI measuring points are only spatially continuous in each burst overlap area, so we subsampled the BOI data of each overlap area. The final InSAR datasets consist of ~7700 points in InSAR LOS displacements and ~9500 points in azimuth displacements. The covariance between subsampled data is estimated by semi-variogram. An error-variance-based weighting method was adapted to set up weights of individual data sets by considering the covariance between subsampled data. We applied the weight ratio 1:1:3 for GPS data, InSAR data and BOI data. A uniform weight was used for each data point within an individual data set. We used a single rectangular dislocation model (Okada 1985) in a homogeneous and isotropic elastic half-space (Poisson’s ratio \( \nu = 0.25 \)).

Focal mechanism solutions for this earthquake provided by USGS indicate that the slip probably occurred on a steeply dipping fault striking east–west or north–south. Moreover, aftershocks mainly extended along a WSW-ENE trending fault structure (Fig. 1). Given the above outlined consideration, we back up the opinion that the slip occurs on an ENE-trending left-lateral fault. We supposed that strike slip with some oblique components causing the subsidence of the vertical displacement field (Fig. 2b). Through further investigating east–west displacement field and focal mechanism solutions, we outlined a single ENE-trending fault segment trace (Fig. S1, Supporting Information). From the predicated east–west displacement field (Fig. S2b, Supporting Information), this ENE-trending single fault trace only separates deformation at opposite directions in the eastern area. A shortage fault segment with smaller strike (ENTrending) would be appropriate to separates displacements towards
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4 SLIP DISTRIBUTION RESULT OF DIFFERENT DATA SETS

To highlight the significance of introducing the azimuth measurements to the slip inversion, we use the constraints of different data types to calculate the slip distribution (Fig. 8). Root-mean-square error (RMSE) of each model are summarized in Table 2. Figs 8(a) and (b) show the inverted coseismic slip distributions constrained by GPS-derived displacements and InSAR data, respectively. The western segment in Fig. 8(a) (WS8a) suggests that oblique slips almost concentrated in the shallower crust, with a maximum value of approximately 0.65 m at about 4.2-km depth. The slip peak of approximately 0.52 m occurs at a depth of ∼3.7 km on the eastern segment (ES8a). The maximum oblique slip of 0.47 m is located on the western segment in Fig. 8(b) (WS8b) at a depth of 3 km, while other minor oblique slips occur at depth of 5–13 km. The peak left-lateral slip on the eastern segment (ES8b) is 0.55 m at about 9-km

Figure 3. The along-track component of coseismic displacements from the ascending (track 64) Sentinel-1 TOPS data. The light magenta and dark blue dashed frames, respectively, indicate the coverage of azimuth displacements mapped from the descending track 71 (inset on the top-right) and 144 (inset on the low-right). Black arrows represent the positive direction of displacements. White solid lines indicate the top traces of the inferred faults. The yellow star represents the epicentre.
depth. Both results share similar slip motions and mean rake angles. The slip distribution, however, shows different patterns. Comparison between Figs 8(a) and (b) shows that slip distribution inverted by InSAR coseismic displacements is generally deeper than that inverted by GPS. Although the coverage of InSAR data is denser than that of GNSS, nearly zero values which generated during the subsample procedure may let the slip distribution go wrong. Therefore, we attribute the deeper slip distribution inverted by InSAR to the subsample errors of near-filed measured points. Dense spatial coverage of InSAR data produced different and more complex slip distribution. WS8b contains two oblique-slip asperities while WS8a has only one slip asperity but larger slip peak. We also find that left-lateral slip in ES8a has a more concentrated distribution, different from the extent of the slip in ES8b. Fig. 8(b) shows that fewer coseismic fault slips are obtained near the surface which is consistent with the existing study (Zheng et al. 2020). Through a comparison between these two results, we can infer that the slip distribution constrained by GPS data is shallower than that constrained by InSAR. In contrast, complex slip distribution constrained by InSAR data have several slip asperities different at the depth, indicating that the main slip in the event is mostly blind. This slip distribution pattern is more consistent with the field survey (Koehler et al. 2021).
The observations of GPS and InSAR were applied to accomplish a joint inversion. Oblique slips of the western segment in Fig. 8(c) have a maximum value of approximately 0.58 m at about 3-km depth, while eastern segment has the largest left-lateral slip of 0.57 m at about 7-km depth. By combining these two complementary data sets, the joint inversion for slip exploits the strengths of each (Fig. 8c). More complex slip distribution occurs on the western segment, while eastern segment slips fewer near the surface. We then added the azimuth displacements in burst overlap areas as data constraints to invert the fault slip distribution. The slip distribution inversion (Fig. 8d) constrained by three different data types suggests the western segment has concentrated high-slip patches at a depth of 2–10 km, with a peak slip of 0.57 m occurs at a depth of ~4 km. We also identified a fishtail slip distribution at a shallower depth of 0–15 km on the eastern segment. The maximum value of this area is ~0.53 m at depth of ~7 km. The mean rake angle of slip on the western segment is ~49.1°, implying a left-lateral strike-slip with some normal dip-slip motion. The slip on the eastern segment is characterized by mainly left-lateral strike-slip with slight thrust dip-slip component with a mean rake angle of approximately 5°. The coseismic moment release of this model is approximately $4.87 \times 10^{18}$ N-m, corresponding to an $M_w 6.43$ earthquake. Based on seismic data, GPS, and geological estimates of surface rupture length and maximum displacement overlap, an inferred magnitude
range of M 6.3–6.4 was given by Hammond et al. (2020). Thus, the $M_w$ 6.43 estimated by adding azimuth displacements constrains is nearest to this range.

Three primary mechanisms, namely afterslip, viscoelastic relaxation and poroelastic rebound, are responsible for causing transient post-seismic deformation (Evans & Meade 2012; Zhao et al. 2017). Afterslip has been proposed as predominant post-earthquake mechanism to dominate early post-seismic deformation spanning from several days to months (Segall et al. 2000; Ding et al. 2015; Shrivastava et al. 2016). Hammond et al. (2020) also indicated that afterslip was the likely mechanism to cause early post-seismic deformation after this earthquake. In order to simplify the process and directly compare with coseismic slip, here we assume afterslip dominantly lead to post-seismic displacements. Near-field post-seismic displacements (7–93 d) measured by GPS stations are selected for afterslip inversion. We carry out the afterslip inversion using the same fault parameters in the coseismic slip inversion because post-seismic displacements had a similar manner to the coseismic displacements. One dominant post-seismic slip patch occurred in the western fault segment. Another two patches with larger amount of slip ($\sim$0.1–0.13 m) were found in the eastern fault segment. The total moment released by the afterslip in this post-seismic period is about $5.62 \times 10^{17}$ N-m, corresponding to a moment magnitude of $M_w$ 5.8. Afterslip majorly concentrates adjacent to the coseis-
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Figure 8. Slip distribution estimated from different data sets. (a) is derived from GPS only. (b) is derived from InSAR only. (c) is derived from GPS and InSAR. (d) is derived from GPS, InSAR and constraints from burst-overlap interferometry in azimuth. White slip contour lines show afterslip distribution inferred from the post-seismic GPS displacements. Yellow star is the hypocentre of the earthquake. The plotted aftershocks (black dots with white edges) are selected by time, which occurred between the period of post-seismic GPS measurements.

Table 2. RMSE of each model.

<table>
<thead>
<tr>
<th>Data used</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>0.0024</td>
</tr>
<tr>
<td>InSAR</td>
<td>0.0140</td>
</tr>
<tr>
<td>GPS + InSAR</td>
<td>0.0105</td>
</tr>
<tr>
<td>GPS + InSAR + BOI</td>
<td>0.0136</td>
</tr>
</tbody>
</table>

mic rupture zone, indicating that coseismic slip and afterslip occur on complementary parts of the area. Comparison between all slip distribution patterns (Fig. 8) demonstrate that coseismic slip distribution inverted by constraints with azimuth displacements are more coincided with the afterslip distribution.

5 DISCUSSION

5.1 Model resolution improvement by the BOI measurement

Deriving the coseismic displacement filed from more viewing geometries is significant to constrain fault slip models, especially for blind faults. Different data types such as InSAR data alone (Wright et al. 2004), InSAR and azimuth pixel offsets (Fialko et al. 2005), InSAR and optical image offsets (Barnhart et al. 2011), as well as InSAR and multiple aperture interferometry (MAI, Bechior & Zebker 2006; Jonsson 2012) have been used by pioneers to estimate 3-D displacements. However, neither pixel offsets nor MAI can provide suitable azimuth deformation from Sentinel-1 images for this $M_w$ 6.5 earthquake with small-magnitude deformation since they are only suitable for cases of large coseismic displacements. Due to the near-polar orbit, azimuth displacements in the burst overlap areas of Sentinel-1 data are strongly sensitive to the north–south component of motion. The azimuth displacements derived from the BOI technique show evident deformation pattern in each track (Fig. 3). Moreover, we find the obvious negative displacements which mean opposite direction of the satellite’s flight in the southernmost descending burst overlap area. These deformation patterns also follow the extended line of the western fault segment and correspond to the strike-slip direction. Azimuth displacement maps in burst overlap regions can provide near-field measurements at a higher density than GPS, therefore they can be combined with the conventional D-InSAR results to identify deformation details near the causative faults.

The main drawback of the BOI is that the measurements are only practicable in burst overlap regions. Nevertheless, within these regions only with a ~1.5 km NS length, the azimuth displacement is available at dense spatial sampling and is not influenced by tropospheric phase screen (Grandin et al. 2016). Benefiting from this substantial improvement of SAR acquisition mode, we identify the clean north–south displacement of this moderate earthquake, which can help imply the complex fault structure beneath the MD and benefit the inversion of more detailed coseismic slip distribution (Fig. 8d).

The uncertainty of slip model stems from two main sources, error in observations as well as incompleteness of Green’s functions. Regarding the error in observations, it is hard to quantitatively calculate the slip model uncertainty due to the lack of true values. The second source of model uncertainty is associated with the incompleteness of the Green’s functions which relates the surface displacements to fault dislocations. The factors including simplified fault model, medium elastic properties and observations distributions can jointly cause the incompleteness of the Green’s functions (Khoshmanesh
In the case of using additional azimuth displacements, Fig. 9(b) and (c) respectively show the standard deviation and distribution of the fault slip as the model resolution improves. This map reflects the ability of model and data in resolving slip standard deviation associated with inverting InSAR and GPS data. (c) The model resolution improvement following the use of additional data set (azimuth displacements derived from BOI) on the model resolution in this quantitatively investigate the impact of additional data set (azimuth displacements derived from BOI) on the model resolution in this study. (Koehler et al. 2021). To further investigate the impact of InSAR and GPS data on the model resolution in this moderate earthquake case, we use a model uncertainty test, in which InSAR and GPS data are used to solve the slip with or without azimuth displacements data. We used the following equation based on the variance–covariance analysis of the unknowns to evaluate the effect of the Green’s functions: \[
Q_i^d = \left( [G, s(x)]^T (G, s(x)) + \lambda^2 H^T H \right)^{-1}
\] in which \(i = 1\) denoting the InSAR and GPS displacement, and \(i = 2\) denoting the InSAR, GPS and the azimuth displacement derived from BOI. \(G, s(x), \lambda\), and \(H\) are the Green function, the slip vector, the smoothing factor, and the Laplacian operator in eq. (2), respectively. The square root of diagonal components in the variance–covariance matrix (eq. 6) represents the standard deviation of the inverted slip for each patch. Fig. 9(a) shows the distribution of slip standard deviation associated with inverting InSAR and GPS data. This map reflects the ability of model and data in resolving distribution and amplitude of the fault slip as the model resolution improves. Figs 9(b) and (c) respectively show the slip standard deviation and the improvement in the case of using additional azimuth displacements data. One can see that the substantial BOI data, particularly, improves the model resolution up to 30 per cent at the deep zone of the western fault, as well as at the middle-deep zone of the eastern fault.

5.2 Surface rupture and slip distribution

The Monte Cristo Range earthquake surface rupture has been presented in details and the detected ruptures seem to tell a complex story (Koehler et al. 2021). The surface rupture was divided into two distinct domains with distinctly different styles and orientations of displacements. In the western part of the rupture, sinistral-oblique slip along northeast-striking faults and normal right-oblique slip along NNE-striking faults coincided with the east-striking mapped trace of the Candelaria fault and extended to the northeast direction. In the eastern domain, normal and right-oblique slip along north-striking faults occurred in vicinities of several mapped northwest-striking faults. Most of the rupture observations were inspected in the western rupture zone. The epicenter location indicates that the earthquake began in the eastern part of region, and that the rupture proceeded bidirectionally east and west. When the slip propagated westward, it shallowed and tapered upward at the surface, causing most of the observed western zone of surface rupture. The fractures of ~3 cm of displacement occurred when the slip propagated eastward. As it happens, our preferred modelling results (Fig. 8d) also indicate that slip patterns differ in two inferred fault segments. The ranges of western and eastern segments are coincident with two surface rupture domains. Sinistral-oblique slip along northeast-striking western fault segment and almost pure left-lateral slip along east-striking eastern fault segment were inverted by GPS and InSAR data sets. In the western fault segment, the areas with large amounts of slip were confined to the uppermost 9 km and shallowed from east to west. Slip in the eastern segment concentrated in a region that was nearly coupled between ranges of 0–20 km east from the westernmost edge of the plane. Owing to discrete and mostly blind surface rupture, we set 1 km as the top edge depth of each fault segment. From the slip depth of each fault segment, however, we can roughly consider that the main slip occurs in the western segment and partially extend to the surface, with the eastern segment accommodating residual slip which is mostly blind. These distributions of slip depth are consistent with two distinct surface rupture domains.

There are two main discrepancies between the model results and mapped surface rupture (Koehler et al. 2021). The first is that western fault segment and majority of surface rupture in the western zone share similar strike angle, while surface rupture bifurcates and spans farther north. Moreover, we see that both sinistral-oblique and normal right-oblique slip occur in the western surface rupture domain, while the western fault segment only shows the left-oblique slip. The second discrepancy is that the surface rupture mapping in the eastern zone finds north-trending ruptures that exhibit predominantly normal and right-oblique slip deformation. Appreciable left-lateral surface displacements were not observed along the eastern domain of the rupture, while the eastern fault segment showed the left-lateral slip. We can attribute these disagreements to the deep and mostly blind slip. From the location of epicentre, we suggest the earthquake initiated the east region, and that the rupture propagated bidirectionally east and west. When the slip propagated westward, it shallowed and tapered upward at the surface, causing most of the observed western zone of surface rupture. The fractures of ~3 cm of displacement occurred when the slip propagated eastward. As it happens, our preferred modelling results (Fig. 8d) also indicate that slip patterns differ in two inferred fault segments. The ranges of western and eastern segments are coincident with two surface rupture domains. Sinistral-oblique slip along northeast-striking western fault segment and almost pure left-lateral slip along east-striking eastern fault segment were inverted by GPS and InSAR data sets. In the western fault segment, the areas with large amounts of slip were confined to the uppermost 9 km and shallowed from east to west. Slip in the eastern segment concentrated in a region that was nearly coupled between ranges of 0–20 km east from the westernmost edge of the plane. Owing to discrete and mostly blind surface rupture, we set 1 km as the top edge depth of each fault segment. From the slip depth of each fault segment, however, we can roughly consider that the main slip occurs in the western segment and partially extend to the surface, with the eastern segment accommodating residual slip which is mostly blind. These distributions of slip depth are consistent with two distinct surface rupture domains.

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segment to invert the coseismic displacements. The results suggest a modelled left-lateral plane in the eastern region is necessary (Fig. S7, Supporting Information). We conjecture the existence of left-lateral slip along east-trending fault buried beneath the eastern region.

5.3 Implications for regional tectonics

The northeast MD, where this earthquake occurred, is characterized by a series of east- to northeast-striking left-lateral and normal-oblique faults, as well as low historical seismicity (Faulds et al. 2008). Pioneering studies, which were conducted primarily to the southwest of the MD, indicate that transtension ranges from extension-dominated transtension of the northeastern MD probably has a tendency to evolve into the extension-dominated transtension. In addition, there is no evidence for normal slip component on the NE-striking sinistral faults despite the slip transfer occurring in the MD (DeLano et al. 2019). Therefore, there are two main discrepancies between the modelled results and previous regional context. The first is that the extension occurs in the wrench-dominated transtension zone. The second discrepancy is the normal fault slip on the NE-striking sinistral faults. We can reconcile these apparent disagreements by recalling a clockwise rotation block model bounded by left-lateral east trending faults as follows.

DeLano et al. (2019) described various block models which have been proposed to accommodate slip transfer across the MD. In Wesnousky (2005b, 2020) model for the accommodation of northwest-directed right-lateral shear, clockwise rotation of crustal blocks bounded by left-lateral east trending faults resulted in the formation of basins. In this model, the Excelsior fault to the north and Candelaria fault to the south bounding the clockwise rotation block (Teels Marsh Block) resulted in the development of the Teels Marsh basin. Block rotations between the Candelaria fault and Coaldale fault (Columbus Block) likewise resulted in the relatively mature Columbus Marsh basin. Moreover, the east ends of some of these faults bended to strike NNE along range fronts and expressed a component of extension due to basin facing scarps across alluvial fan and piedmont surfaces (Wesnousky 2005b). The Candelaria fault and its eastern extending part are unlikely to be mature, since MD tectonic context limits maximum fault length and possibly maximum offset (Lomax 2020). Young sinistral displacements extending away from the bend expect to express normal slip on the fault within the left bend (Crowell 1973). Therefore, the unmapped east ending of Candelaria fault within left bend is generally coincident with our modelled sinistral-oblique NE-striking western fault segment. Based on the geodetic inversion, we hypothesize that the Teels Marsh Block between the Candelaria fault and Excelsior fault has a southeast edge characterized by sinistral-oblique NE-striking fault (Fig. 10). In this sense, range fronts located northeast end of the Candelaria fault might be responsible for the orientation of the western fault segment. Basin development corresponding to a clockwise rotating block may force the east part of the weakly developed Candelaria fault to bend left and express additional normal slip component. We contribute the extension to a shallow alluvial basin located immediately northeast of the Candelaria fault.

6 CONCLUSIONS

In this study, we derived the InSAR displacement field of the 2020 \( M_w 6.5 \) Monte Cristo Range earthquake which occurred in the northeast edge of MD, Nevada. Evident azimuth displacements in the burst overlap areas demonstrate the capability of BOI for extending the interferometric measurements to the moderate earthquake. We determined the source fault model which comprises two main fault segments with different orientations and faulting patterns. Our results show that the SW-NE trending western fault contains the sinistral and normal-faulting components, whereas the ENE-striking eastern fault exhibits a left-lateral slip pattern. The total geodetic moment release estimated by the preferred model is approximately \( 4.87 \times 10^{18} \) N-m, corresponding to an \( M_w 6.43 \) earthquake. Seismogenic structure of the northeastern MD revealed...
by the 2020 earthquake coincides with the existing clockwise rotation block model. We attribute the orientation and normal slip components in the western fault segment to the occurrence of a shallow alluvial basin and the expression of young left-lateral fault within the left bend, respectively. Through an analysis of the relationship between modelled faults and regional tectonics, we reveal possible accommodation of slip transfer across the northeast edge of the MD and an immature basin consistent with clockwise rotating block between the Candelaria and Excelsior faults. In addition, the east part of the Candelaria fault has bent along the range fronts and become the southeast edge of the clockwise rotating block.

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DATA AVAILABILITY

Coseismic and early post-seismic GPS displacements were provided by Hammond et al. (2020). The location and character of the surface rupture and displacement measurements were provided by Koehler et al. (2021). This work also used Copernicus data from the Sentinel-1 satellite constellation provided by the European Space Agency (https://scihub.copernicus.eu). All processed InSAR data are available from the authors upon request. The information of aftershocks was provided by USGS-NEIC (https://earthquake.usgs.gov/earthquakes/search/). The Generic Mapping Tools 6.1.0 software developed by Wessel et al. (2019) was used to plot several figures. CiSent software for Sentinel-1 interferometric processing used in this paper is available online (https://zenodo.org/record/4774694).

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SUPPORTING INFORMATION

Supplementary data are available at GJI online.

**Figure S1.** (a) 3-D display of the single-segment fault model. (b) is the trade-off curve between the dip angles and the RMSEs in static inversion trials. The red solid circle shows the preferred fault dip.

**Figure S2.** Coseismic 2-D surface displacement fields derived from Sentinel-1 interferograms for (a) and (d) the observed displacement fields, (b) and (e) the modelled displacement fields using single-segment fault model, and (c) and (f) the residuals. The dim grey solid line is the top trace of the fault.

**Figure S3.** (a) and (b) represent the horizontal and vertical coseismic GPS displacements (blue vectors), single-segment fault (green lines) that best fit the data, and predicted coseismic displacements (orange vectors) from the single fault model, respectively.

**Figure S4.** Coseismic InSAR LOS surface displacement fields derived from Sentinel-1 interferograms for (a), (d) and (g) the observed displacement fields, (b), (e) and (h) the modelled displacement fields using single-segment fault model, and (c), (f) and (i) the residuals. The dim grey solid line is the top trace of the fault.

**Figure S5.** Coseismic InSAR azimuth surface displacement fields derived from Sentinel-1 interferograms for (a), (d) and (g) the observed displacement fields, (b), (e) and (h) the modelled displacement fields using single-segment fault model, and (c), (f) and (i) the residuals. The dim grey solid line is the top trace of the fault.

**Figure S6.** The afterslip distribution inverted by the post-seismic GPS displacements. Yellow star is the hypocentre of the earthquake. The plotted aftershocks (black dots with white edges) are selected by time, which occurred between the period of post-seismic GPS measurements.

**Figure S7.** The slip distribution only inverted by the single western fault segment. The plotted aftershocks (black dots with white edges) are selected by time, which occurred between the period of post-seismic GPS measurements.

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