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Key Points:
- Coseismic and postseismic displacements due to the Monte Cristo earthquake are mapped using interferometric synthetic aperture radar and global positioning system measurements.
- The shallow slip deficit caused by the coseismic rupture is largely compensated by rapid afterslip.
- The aftershocks are triggered by the stress change caused by both coseismic slip and rapid postseismic afterslip.

Supporting Information:
Supporting Information may be found in the online version of this article.

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Abstract
The 2020 Mw 6.5 Monte Cristo earthquake occurred in the northeastern Mina deflection of the central Walker Lane Belt (WLB) in Nevada, USA. The Mina deflection represents a typical stepover zone that transfers the dextral slip in the northern Eastern California Shear Zone onto the dextral faults in the central WLB. The Monte Cristo earthquake provides a rare opportunity to investigate the strain accumulation and stress transition mechanisms in the WLB. In this study, ascending and descending Sentinel-1 images were utilized to generate coseismic and early postseismic deformations associated with this earthquake. Combined with global positioning system measurements, these images were inverted for the coseismic slip and afterslip of the Monte Cristo earthquake. The preferred coseismic slip model suggests that the causative fault is characterized by two fault segments with southward dips of 64° and 79°. The coseismic rupture was dominated by sinistral slip with obvious normal slip components in the western segment of the source fault. The coseismic slip was mainly concentrated in the 3–12 km depth range and decreased at shallower depths, suggesting a moderate amount of shallow coseismic slip deficit. Rapid afterslip was mainly confined to the 0–3 km depth range, largely compensating for the shallow slip deficit caused by the mainshock. The widely distributed normal slips in the northeastern Mina deflection revealed by the Monte Cristo earthquake suggest the transtensional model is more applicable due to its ability to account for the slip transition kinematics in the Mina deflection.

1. Introduction
The Walker Lane Belt (WLB), located between the eastern Sierra Nevada/Great Valley microplate and the western margin of the basin and range province, defines a complex NW-trending shear zone in the Pacific-North America plate boundary (Bellier & Zoback, 1995; Wesnousky, 2005). Geodetic measurements indicate that the WLB shear zone accommodates ~25% of the dextral motion between the Pacific and North American plates, and the remaining fraction of the motion is mainly accommodated by the San Andreas fault system (Bennett et al., 2003; Dixon et al., 2000). The WLB is characterized by widely distributed, young, developing transform, and transtensional fault structures with a total near-constant slip rate of 8–10 mm/yr across the ~100-km-wide belt zone (Bormann et al., 2016; Kreemer et al., 2009). Throughout the WLB, extensional and dextral motions were identified on well-defined NNW-striking normal faults in the western part of the domain and the major subparallel NW-striking right-lateral strike-slip faults in the eastern part (Angster et al., 2019; Sturmer & Faulds, 2018; Wesnousky, 2005). The structural activity in the complex fault zone results in strong strain accumulation related to the WLB domain. Numerous neotectonic (Angster et al., 2019; DeLano et al., 2019), paleomagnetism (Carlson et al., 2013; Rood et al., 2011), and geodetic (Bennett et al., 2003; Bormann et al., 2016; Hammond et al., 2011) studies on the WLB have reported conflicting interpretations of how strain is accumulated and released across the belt, resulting in various kinematic strain accumulation and displacement transfer models on the WLB (Oldow, 2003; Surpless, 2008; Unruh et al., 2003; Wesnousky, 2005). Meanwhile, the seismic activity in the WLB, which can provide critical insights into the regional tectonic stress buildup and partitioning, exhibited a relatively low level in the past decades (Ichinose et al., 2003; Zeng et al., 2018). The relative paucity of the historical seismic data,
particularly for moderate and large earthquakes, impedes our understanding of the strain accumulation mechanism and seismic hazards in the WLB.

The Mw 6.5 Monte Cristo earthquake occurred on May 15, 2020, west of the Monte Cristo range in the central WLB, representing the largest earthquake in the central WLB in the past 65 years. The most recent large earthquakes were the 1954 Ms 7.2 Fairview Peak and Ms 6.7 Dixie Valley earthquakes (Hodgkinson et al., 1996). The preliminary focal mechanism solutions of the U.S. Geological Survey and Global Centroid Moment Tensor agree that the Monte Cristo earthquake occurred due to a strike-slip on either an EW or NS-trending fault (Figure 1a). More than 6,500 aftershocks were recorded by the Nevada Geodetic Laboratory (NGL) within 3 weeks of the mainshock, exhibiting high aftershock productivity similar to that of the 2019 Ridgecrest earthquake sequence that occurred in the northern part of the Eastern California Shear Zone (ECSZ) (Koehler et al., 2021; Li et al., 2020; Liu et al., 2019; Ross et al., 2019). The focal mechanisms of the aftershocks (Mw > 5.0) in the western and eastern segments are characterized by normal and sinistral strike-slip components, respectively, and show obvious spatial variations along the trend of the aftershock cluster (Figure 1b), implying a complicated source rupture process of the mainshock.

The Monte Cristo earthquake occurred in the Mina deflection deformation zone, where the dextral slip in the major strike-slip faults within the northern ECSZ are transferred northward onto the NW-striking dextral faults of the central WLB (Nagorsen-Rinke et al., 2013). The wide slip transition zone within the Mina deflection acts as a stepover that accommodates fault slip propagation from the northern ECSZ to the central WLB faults. In contrast to most NW-trending faults in the central WLB, the stepover zone in the Mina deflection consists of a series of sinistral strike-slip en-echelon faults, including the Candelaria, Excelsior Mountain, and Rattlesnake fault systems (Figure 1a). Geological and geodetic studies indicate that extension-dominated transtension and clockwise block rotations play important roles in accommodating the accumulated strain in the Mina deflection (DeLano et al., 2019; Oldow, 2003).

The development of the global positioning system (GPS) and interferometric synthetic aperture radar (InSAR) techniques have made it possible to precisely measure the surface deformations associated with
earthquake ruptures and further constrain the details of fault-rupture geometry and slip distribution (He et al., 2016; Wang et al., 2011). Unlike other large earthquakes in the WLB, the Monte Cristo earthquake occurred in an area of unprecedented coverage of both GPS and InSAR measurements (Figure 1a), thus providing a rare opportunity to investigate the earthquake rupture characteristics. Hammond et al. (2020) analyzed all the available GPS data during the pre-, co-, and postseismic periods of the Monte Cristo earthquake to derive a comprehensive displacement map of this event. Based on the joint inversion of the seismic and InSAR data, Zheng et al. (2020) found that the source rupture of the Monte Cristo earthquake was characterized by sinistral and oblique slips in the eastern and western segments of the source fault, respectively. In this study, the coseismic and early postseismic displacements associated with the Monte Cristo earthquake were mapped utilizing Sentinel-1 satellite InSAR measurements. In conjunction with the GPS data, the fault geometry was investigated, and the coseismic slip and kinematic afterslip of the mainshock were inverted. Furthermore, the probable physical mechanisms of the postseismic deformation and Coulomb failure stress (CFS) changes of the Monte Cristo earthquake were studied to throw light on the stress transfer mechanism and seismic risk in the Mina deflection.

2. Geodetic Measurements

2.1. GPS Data

The GPS data utilized in this study were primarily obtained from the Mobile Array of GPS for Nevada Transtension GPS network operated by the NGL since 2004 (Hammond et al., 2020). One major objective of the network is to conduct precise geodetic surveys of the displacements caused by earthquakes in the Great Basin. After the Monte Cristo earthquake, the NGL performed post-event position measurements at more than 200 continuous and campaign sites (Figure 1a), located within 250 km of the Monte Cristo earthquake epicenter. The GPS data were processed utilizing GipsyX software (Zumberge et al., 1997) to obtain the daily solutions under the ITRF14 reference frame via the Hammond et al. (2020) method. The coseismic offset at each site was estimated by determining the best-fitting lines of the 10-day preseismic and 10-day postseismic portions of the coordinate time series. For most of the sites, the offset uncertainties were less than 0.5, 0.5, and 2.0 mm for the north, east, and vertical components, respectively. The horizontal coseismic displacements are shown in Figure 2. The maximum coseismic offset occurred at the COLU site (8.3 ± 0.04, 11.7 ± 0.05, and −3.3 ± 0.2 cm, east, north, and vertical, respectively), located ∼25 km southwest of the epicenter. Overall, the GPS horizontal displacements showed significant extensional and contractional motions in the NW-SE and NE-SW quadrants, respectively, suggesting the mainshock was dominated by an east-trending sinistral or north-trending dextral fault, which is consistent with the primary focal mechanism solutions.

Distinct postseismic displacements were also recorded utilizing continuous GPS measurements. By analyzing the postseismic GPS time series of several near-field sites (Figure S1), it was determined that a significant postseismic deformation of the Monte Cristo earthquake was sustained for ~3–4 months. The cumulative postseismic displacements over an ~4-month period were estimated for the sites within 70 km of the mainshock utilizing a method similar to that utilized to estimate the coseismic offsets (Hammond et al., 2020). The sites close to the hypocenter recorded significant postseismic displacements with maximum magnitudes in the north and east directions of 1.2 ± 0.1 and 0.6 ± 0.08 cm, respectively. The directions of the postseismic displacements were consistent with those of the coseismic displacements.

2.2. InSAR Data

Sentinel-1 radar satellites, third-generation C-band synthetic aperture radar (SAR) satellites operated by the European Space Agency, have been widely utilized to capture high-quality coseismic displacements caused by moderate and large earthquakes (Elliott et al., 2016). In this study, three Sentinel-1 InSAR data image tracks, collected in the Terrain Observation by Progressive Scan acquisition mode, were selected to map the surface deformations associated with the Monte Cristo earthquake. One image track was collected during an ascending orbit from 23 April to 17 May 2020 (T064), and two image tracks were collected during descending orbits from 11–17 May 2020 (T071) and 4–16 May 2020 (T144). The two descending tracks recorded ground displacements with different sub-swaths in different tracks; therefore, the radar wave incidence
angles differed up to $\sim 11.0^\circ$. To quantify the postseismic transient deformation, a SAR data track collected from 17 May to 13 November 2020, during a descending orbit was selected to map the cumulative postseismic displacements in the first 6 months. Detailed SAR image parameters of the S1A data are presented in Table 1, and the image coverage is plotted in Figure 1a.

The data were processed utilizing the open-source InSAR software GMTSAR (Sandwell et al., 2011) with a traditional two-pass differential InSAR approach. In the detailed processing strategy, a multi-look ratio of 10:2 between the range and azimuth directions was adopted to suppress noise. The effect of the topographic phase was removed utilizing the Shuttle Radar Topography Mission 90-m-resolution digital elevation model (Farr et al., 2007). Wrapped interferograms were generated after performing a filtering operation utilizing a low-pass Gaussian filter with a 200 m cutoff wavelength to remove long-wavelength artifacts (Goldstein & Werner, 1998). The minimum cost flow algorithm in the SNAPHU software was utilized for phase unwrapping (Chen & Zebker, 2000). Low-coherence pixels (coherence $<0.1$) were masked during unwrapping, and the interferograms were finally geocoded to the Mercator coordinate system with a 90-m resolution. The possible topographically correlated atmospheric noise was removed utilizing a simple linear regression

| Sensor   | Orbit     | Track (A/D) | Master (Y-M-D) | Slave (Y-M-D) | Incidence angle (°) | Azimuth angle (°) | Perpendicular baseline (m) |
|----------|-----------|-------------|----------------|---------------|---------------------|-------------------|---------------------------|
| Sentinel-1A | Ascending | T064        | 2020-04-23     | 2020-05-17    | 37.9–43.6           | −10               | 24.88                      |
|          | Descending| T071        | 2019-05-11     | 2020-05-17    | 41.7–46.1           | 189               | −53.20                     |
|          | Descending| T144        | 2020-05-04     | 2020-05-16    | 30.7–38.8           | 190               | −36.31                     |
|          | Descending| T071        | 2020-05-17     | 2020-11-13    | 41.7–46.1           | 189               | −98.29                     |

Table 1: Parameters of Interferometric Pairs of Sentinel-1 SAR Images

Figure 2. Coseismic displacements of the Mw 6.5 Monte Cristo earthquake. In panels (a–c), the blue-to-red basemaps show the displacements in the line-of-sight (LOS) observed by ascending (a) and descending (b, c) models of Sentinel-1 satellites. The green arrows indicate the coseismic horizontal offsets inferred from global positioning system (GPS) measurements. Panels (d–f) show the comparison between interferometric synthetic aperture radar and GPS LOS displacements before (red diamonds) and after (blue circles) correcting the combined influences of orbital errors and some possible long-wavelength perturbations. The pink dashed lines have slopes of one.
between the location \((x, y)\), elevation, and error phase in the far-field areas where the surface deformation caused by the earthquake was expected to be small.

Although the orbital control of the C-band Sentinel-1 satellites is very accurate, residual orbital errors that could significantly contaminate the coseismic signals are still possible. Due to the relatively dense distribution of the GPS network, GPS-based measurements can be utilized to evaluate the combined influences of orbital errors and possible long-wavelength perturbations (e.g., residual atmospheric delay and topographic effects) on the interferograms. In this study, the GPS-derived 3D coseismic displacements were projected in the line-of-sight (LOS) direction utilizing the unit vectors pointing from the ground toward the satellite and compared with the corresponding LOS displacements of the unwrapped InSAR interferograms (Figures 2d–2f). Based on the comparison results, systematic offsets between the GPS-derived displacements and the corresponding InSAR LOS displacements were found, suggesting the aforementioned error sources slightly distorted the interferograms. Therefore, the following linear modifying function was adopted to correct the systematic offsets (Yang et al., 2014):

\[
d_{\text{gps}} - d_{\text{insar}} = A_0 + A_1\lambda + A_2\phi,
\]

where \(d_{\text{gps}}\) and \(d_{\text{insar}}\) represent the projected GPS and InSAR LOS displacements at the common pixels, respectively; \(\lambda\) and \(\phi\) denote the range and azimuth coordinates of each pixel, respectively; and \(A_0, A_1,\) and \(A_2\) are the model parameters that can be inverted via the least-squares method. For image tracks T064, T071, and T144, 20, 13, and 20 GPS sites were utilized to estimate the model parameters, respectively. The corrected coseismic interferograms that account for LOS range changes from the surface to the satellite are shown in Figures 2a–2c. After correction, the InSAR LOS displacements concurred with the GPS measurements (Figures 2d–2f), and the standard deviations between the InSAR and GPS displacements projected onto the LOS were reduced to 1.1, 0.8, and 0.4 cm for tracks T064, T071, and T144, respectively.

The differential interferograms recorded in the Sentinel-1 ascending and descending modes are highly coherent due to the dry desert weather and sparse vegetation (Figure S2). The fringes continuously spread across the epicentral region of the event and provided no significant evidence of a primary surface rupture, indicating the rupture was largely blind. The coseismic interferogram of the ascending image track T064 showed positive and negative LOS displacements (shortening and extension along the LOS direction, respectively) on the northern and southern walls of the fault, respectively, indicating a left-lateral strike-slip motion on the source fault. This is consistent with the surface displacement characteristics revealed by the GPS measurements. The coseismic LOS displacements of descending image tracks T071 and T144 showed a relatively complex fringe pattern. The non-deformation line separating the positive and negative LOS displacements was curvilinear, implying a complicated slip pattern of the seismogenic fault or a geometrical complexity for this segment. The maximum positive and negative LOS displacements observed in the image tracks were 12.5 and −30 cm for ascending track T064, 8.7 and −12.1 cm for descending track T071, and 7.3 and −15.5 cm for descending track T144, respectively. The standard deviation of each interferogram was calculated utilizing a simple 1D-covariance function (Parsons et al., 2005) to estimate the uncertainty of the LOS displacements, which were 11, 14, and 13 mm for T064, T071, and T144, respectively, suggesting a medium random noise level.

The InSAR-derived postseismic displacements presented in Figure S3 show a significant increase in the range of the northern wall of the source fault. The LOS displacements, on the other side, are characterized by a wide zone of range decrease, similar to the coseismic displacement field. The maximum negative and positive cumulative displacements, after 6 months of the Monte Cristo event, reach −3.8 and 2.1 cm, respectively, near the surface projection of the source fault, which is approximately 20%–30% of the maximum coseismic displacements. The discontinuous fringes indicate the postseismic signal is probably due to the effect of postseismic slip distribution rather than a localized phase difference caused by atmospheric disturbances. A quadtree algorithm with a gradient-based sampling method was then utilized to downsample the coseismic and postseismic InSAR datasets to reduce modeling computation costs (Bagnardi & Hooper, 2018).

A 2.5-dimensional (2.5-D) coseismic displacement field of the Monte Cristo earthquake was constructed utilizing three pairs of interferograms with different SAR acquisition geometries (Fujiwara et al., 2000). The N-S component was ignored during the calculation due to the near-polar orbital geometry of the SAR.
satellites and because the seismogenic fault of the Monte Cristo earthquake is approximately oriented E-W. The LOS displacements were decomposed into E-W and vertical components based on the widely utilized method (He et al., 2018). The retrieved E-W components showed westward and eastward displacements on the northern and southern walls of the fault, respectively, consistent with the sinistral-slip fault motion and the spatial distribution of the aftershocks. The maximum eastward and westward displacements were 16.3 and 15.5 cm, respectively, and both were concentrated on the western segment of the source fault (Figure 3).

The most notable feature of the vertical components is the significant subsidence in the western segment of the source fault with a maximum amplitude of −25 cm, which is shown by the 2D displacement vectors along two profiles (AA′ and BB′) (Figures 3c and 3d). The subsidence displacements mainly occurred at the near-field of the hanging wall, suggesting the source fault could be partly controlled by normal slip components on the fault plane.

3. Coseismic and Postseismic Deformation Modeling

3.1. Source Geometry and Modeling Approach

Based on previous geological and seismological investigations, the Monte Cristo earthquake mainly ruptured a previously unmapped NE-striking fault (Figure 1; DePolo et al., 1991; Wesnousky, 2005). The W-phase focal mechanism solution exhibited a nondouble-couple component of ~32%, implying a complex source mechanism (Zheng et al., 2020). The decomposed E-W and vertical displacement components exhibited along-strike deformation variations, suggesting the mainshock might not have ruptured on a single fault plane (Figure 3); however, the geological and seismological information is insufficient to determine the rupture geometry details because the surface ruptures of the earthquake are not apparent. It is challenging to determine whether the complex source mechanism is solely caused by slip complexity on a single fault or also involved geometrical complexity using only seismic data. With utilizing GPS and InSAR meas-

Figure 3. 2.5-D surface displacements of the 2020 Mw 6.5 Monte Cristo earthquake. (a) East-west and (b) Vertical displacements derived from the three pairs of Sentinel-1 interferograms. The green dashed frames outline the surface projections of the two-segment fault model. The pink star marks the epicenter of the mainshock. The pink dashed lines indicate the locations of selected displacement profiles. Panels (c and d) represent profile charts showing the terrain height and 2D displacement vectors across the source fault.
measurement data, we can account for the complexity of the event and image the slip distribution of the Monte Cristo earthquake. Based on the above-mentioned information, we tested two types of geometrical configurations for the Monte Cristo earthquake in our modeling, that is, the single fault model (Model I) and the two-segment fault model (Model II).

In Model I, a single ENE-striking fault was adopted to represent the source fault, and a standard two-step procedure was utilized to construct the source model. First, a uniform slip model was employed to determine the nine source parameters (longitude, latitude, length, width, depth, strike, dip, rake, and slip), assuming a rectangular dislocation embedded in a homogeneous, isotropic, elastic half-space (Okada, 1985). These source parameters, which emphasize the dimension and orientation of the coseismic slip instead of its details, were nonlinearly proportional to the surface deformations. A Monte Carlo simulation (Clarke et al., 1997) technique was utilized to constrain the preferred fault parameters and estimate their uncertainties, for which 100 initial models were constructed to perform the simplex inversion from which the source parameters were randomly sampled from Gaussian probability density functions with means corresponding to the solutions of the U.S. Geological Survey focal mechanism. The observed data were disturbed by adding simulated noises generated utilizing a full variance-covariance matrix of the sampled data points. The perturbed data were inverted, yielding 100 model solutions, which were then utilized to estimate the fault parameter errors through histogram analysis. The Monte Carlo simulation results are presented in Figure S4, and a summary of the best-fit model and the standard deviations are provided in Table 2.

Based on the fault parameters determined by the nonlinear optimization, inversion for the distributed slip on the fault plane was performed to explain the spatial variations of the fault rupture. The fault geometry was fixed based on the nonlinear inversion results, and the fault plane was extended to cover the entire aftershock area, which was further divided into a matrix of 1-km square patches. The strike- and dip-slip components of these patches were calculated utilizing a bounded-variable least squares method (Wang et al., 2011). A Laplacian smoothing operator was employed to stabilize the inversion and avoid physically unreasonable slips on adjacent patches. The preferred smoothing factor was chosen according to the trade-off between the solution roughness and the weighted residual sum of squares (Figure 4a). The GPS horizontal and vertical components were adopted for the inversion. The weight matrices for the GPS and InSAR data were constructed based on their formal errors, and the relative weights between the GPS and InSAR measurements in the joint inversion were determined via the 1D grid search method. A set of slip models of the mainshock were calculated with the weighting factor of InSAR relative to GPS varied from 0 to 500. According to the data misfits of the GPS and InSAR observations, a relative weighting factor of 100 for the InSAR data set was adopted for the joint inversion (Figure S5).

In Model II, we consider a fault-rupture structure with a NE-trending fault F1 and ENE-trending fault F2 to constrain the coseismic surface displacement better (Table 2). Neither fault was previously mapped by geologic, tectonic, or historical seismology field investigations (Wesnousky, 2005). The simultaneous estimation of all the geometric parameters for faults F1 and F2 is difficult because the surface cracks caused

| Table 2 | Source Parameters of the 2020 Monte Cristo Earthquake |
|---------|------------------------------------------------------|
| Model   | Lon. (°) | Lat. (°) | Strike (°) | Dip (°) | Rake (°) | Depth (km) | Length (km) | MinDepth (km) | MaxDepth (km) | Slip (m) | Moment (10^18Nm) | Mw |
| USGS    | −117.850 | 38.169   | 73        | 78      | −24      | 11.5       | -           | -             | -          | -       | 6.77                | 6.49 |
| GCMT    | −117.85 | 38.21    | 75        | 81      | −16      | 12         | -           | -             | -          | -       | 6.34                | 6.50 |
| One-segment Model | Uniform | −117.973 | 38.178   | 71.5    | 67.0     | −22.0      | -           | 9.4           | 2.0        | 10.2    | 1.3                 | 4.20 |
|          | ±0.005  | ±0.005   | ±0.5      | ±1.0    | ±0.3     | ±0.5       | ±1.0        | ±0.2          | ±0.5       | ±0.3    | -                   |
| Distributed | −117.973 | 38.178   | 71.5    | 67      | -        | 17         | 28          | -             | -          | -       | 1.5                 | 6.00 |
| Two-segment Model | Fault F1 | −117.992 | 38.162   | 63      | 64       | -          | 20          | 12            | -          | -       | 1.7                 | 5.78 |
|          | Fault F2 | −117.850 | 38.170   | 81      | 79       | -          | 13          | 18            | -          | -       | 1.1                 |
The slip distribution determined via Model I is shown in Figure S6. The slip was mainly concentrated at depths between 2–15 km, extending ∼15 and ∼30 km along the dip and strike, respectively. The rupture mechanism was dominated by sinistral slip, with some minor normal slips in the western segment, and most large slips (magnitude >1.0 m) occurred at two separate slip patches with different depths. One slip patch was located at the shallow portion of the western segment at a 3–7 km depth range, and the other patch was concentrated around the hypocenter at an 8–13 km depth range. A maximum slip of ∼1.5 m occurred in the shallow slip patch. The total seismic moment released was \(6.0 \times 10^{18}\) Nm, which corresponds to an Mw 6.49 magnitude earthquake, assuming a shear modulus of 30 GPa.
Model I can generally retrieve the surface displacements recorded by both GPS and InSAR measurements. The mean misfits for the GPS and InSAR observations were 0.2 and 1.9 cm, respectively. However, significant mismatches between the observations and simulations in the near-field of the coseismic rupture zone were evident. For the GPS measurements, large residuals mainly existed at sites COLU and PILO (Figure S7). The InSAR fitting results also contained some large misfits, although most of the observations were fitted satisfactorily (Figure S8). Most of the large misfits for the three InSAR data tracks were located in the western segment of the hypocenter, implying a possible oversimplified geometry for this segment.

The optimal variable slip distribution for Model II is shown in Figures 5a and 5b, and the fitness values for the GPS and InSAR measurements are presented in Figures 6 and 7, respectively. Overall, Model II provided better displacement predictions than Model I. The mean misfits for the GPS and InSAR measurements determined utilizing Model II were 0.14 and 1.5 cm, respectively, which are 30% and 20% lower than those calculated via Model I, respectively. Most of the near-fault systematic InSAR measurement residuals in Model I were corrected by Model II, suggesting the two-segment fault geometry is more accurate and could be regarded as the causative fault of the Monte Cristo earthquake.

The Model II results suggest that the slip did not rupture to the surface, which is consistent with the characteristics of the continuous surface InSAR interferograms. The slip in fault F2 behaved as a simple pattern, showing a major sinistral-slip asperity at a 3–12 km depth range, whereas the model of fault F1 displayed a relative complex slip pattern, characterized by both sinistral- and normal-slips in the 3–11 km depth range, with the peak slip of 1.7 m at a depth of ~4 km. Notably, the pure normal-slip area of fault F1 at the ~14–18 km depth range, with an average slip of ~0.4 m, was also exhibited in the jointly inverted slip
model. The significant normal-slip in fault F1 agrees with the decomposed vertical displacements of the InSAR measurements, which showed obvious subsidence displacements in the hanging wall of fault F1 (Figure 3b). The total released seismic moment of the Monte Cristo earthquake was $5.78 \times 10^{18}$ Nm, which is equivalent to an Mw 6.48 event.

Zheng et al. (2020) also inverted the source process of the Monte Cristo earthquake through the joint inversion of the broadband seismic and InSAR data. Generally, the preferred slip model results in this study (Model II) were consistent with the Zheng et al. (2020) results. For instance, both of the two-segment slip models constrained by different data sources determined the major sinistral-slip on fault F2 and the oblique-slip pattern on fault F1; however, the 1.6 m maximum slip calculated via Model II in this study is larger than the peak slip of 0.8 m calculated by the Zheng’s slip model. The general consistency between the geodetic and teleseismic inversions confirms the fault geometry complexity and slip pattern of the Monte Cristo earthquake, which contributed to generating the complicated surface displacements. The rupture nucleated on fault F2 was dominated by left-lateral slip, and then the coseismic slip translated into oblique-slip with obvious normal components on the fault F1. It is suspected that the rake change from the fault F2 to fault F1 may be related to the frictional heterogeneities at the interfaces of the two fault segments.

### 3.3. Kinematic Afterslip Model

The inverted early afterslips of the Monte Cristo earthquake are presented in Figures 5c and 5d. Generally, the kinematic afterslip model predicts the cumulative postseismic surface displacements accurately with the mean misfits of 1.8 and 4.8 mm for the GPS and InSAR measurements, respectively (Figures 6b and 7k, respectively). Within the first 6 months after the earthquake, the afterslip was mainly concentrated in the shallow parts of the coseismic slip zone with a peak slip of 0.28 m. Both the coseismic slip and early afterslip showed a consistent left-lateral strike-slip with minor normal slips. The calculated geodetic moment was $1.06 \times 10^{18}$ Nm, corresponding to 18% of the coseismic geodetic moment. The InSAR data inversion afterslip model showed similar slip characteristics to that of the joint GPS and InSAR data inversion afterslip model (Figure S9). One noticeable difference is the InSAR data afterslip model revealed a significant afterslip in the downdip of the coseismic slip zone on fault F2 although we admitted that the result reliability at this depth could be somewhat weak.
The inferred shallow afterslip has important implications for fault frictional properties and fault strain accommodation in the shallow part of the crust. The coseismic ruptures on faults F1 and F2 did not reach the surface, exhibiting a strong slip reduction within the uppermost crust depth range of 0–3 km, termed shallow slip deficit (SSD) (Fialko et al., 2005; Xu et al., 2016). The large SSD of the Monte Cristo earthquake was largely compensated by the early afterslip, although the possibility that interseismic creep along the two faults partly relieved the SSD cannot be dismissed (Kaneko & Fialko, 2011). This phenomenon was also observed in the 2014 Mw 6.1 South Napa (Floyd et al., 2016) and 2003 Mw 6.9 Boumerdes (Mahsas et al., 2008) earthquakes. Xu et al. (2016) suggested that the SSD of strike-slip earthquakes could be explained by the lack of the available data close to the surface rupture, causing the shallow portions of the slip models to be poorly resolved and underestimated. However, this explanation is not applicable for the Monte Cristo earthquake because this event did not cause severe decoherence of the InSAR data near the surface. Generally, the spatially complementary relationship between coseismic slip and afterslip suggests these afterslip patches were in the velocity strengthening friction regime and resembled the general rate-state asperity model (Avouac, 2015; Marone, 1998).

Figure 7. The observed interferometric synthetic aperture radar deformations (left-hand column), the synthetic displacements (middle column), and their residual (right-hand column) for the modeling of coseismic and postseismic fault slip distribution. The black dashed frames outline the surface projections of the two-segment fault model. The yellow star indicates the epicenter of the mainshock.
4. Discussion

4.1. Possible Physical Mechanisms of Postseismic Deformation for the Monte Cristo Event

Poroelastic rebound, viscoelastic relaxation, and afterslip are three mechanism models widely utilized to explain postseismic deformation. Poroelastic rebound is mainly caused by the pore pressure change near the causative fault due to the sudden rupture of an earthquake (Jónsson et al., 2003; Kariche et al., 2018; Peltzer et al., 1996). To analyze the effect of the poroelastic rebound mechanism, we first used the Poisson’s ratio under different conditions (0.28 for undrained state and 0.25 for drained state) to calculate the corresponding coseismic displacements. Then we calculated the differences between the two coseismic deformation fields as the cumulative postseismic displacements related to poroelastic rebound. As shown in Figure 8a, the estimated surface displacements caused by poroelastic rebound were mainly confined to the very near-field of the ruptured faults and had maximum horizontal and vertical components of ∼2 mm. The surface displacement caused by poroelastic rebound is much smaller than the observed transient deformations of the GPS and InSAR measurements. Therefore, we suggest that the poroelastic rebound mechanism may have contributed to the observed deformation in the near-field region; however, because the predicted ground displacements are small, they can be neglected in the afterslip modeling.

Viscoelastic relaxation occurred mainly in the lower crust and/or upper mantle, where the temperature and pressure are high enough to allow for ductile flow of rocks (Bürgmann & Dresen, 2008). Here we computed the surface deformation due to viscoelastic relaxation following the Monte Cristo earthquake using a finite element model (FEM). The FEM structure includes a simple three-layer rheology model, ignoring the spatially heterogeneous rheologies due to limited data resolution. The three-layer rheology model consists of an elastic upper crust and two underlying viscoelastic layers representing the lower crust and upper mantle, respectively. The thickness of the elastic upper crust is assumed to 15 km and the thickness of the lower crust is set to 15 km in a depth range from 15 to 30 km. Based on previous studies of postseismic deformation and lake unloading in the Central Nevada seismic belt (e.g., Dickinson et al., 2016; Hammond et al., 2009), we fixed the viscosities of the lower crust and the upper mantle at $10^{20.5}$ Pa s and $10^{19}$ Pa s, respectively (Figure S10). A series of rheology models with a relatively weaker upper mantle ($10^{18}$ Pa s) and a stronger upper mantle ($10^{20}$ Pa s) were also tested. The two-segment coseismic slip model was employed in the simulation. The shear moduli of the elastic body and viscoelastic upper mantle are assumed to be 45 and 56 GPa, respectively. The simulations were performed using the Pylith software (Aagaard et al., 2013). The entire model domain size is 3,000 km (east) × 3,000 km (north) × 600 km (depth), which represents an enough large domain to eliminate boundary effects (Figure S11).
Figure 8b shows the cumulative surface displacements due to viscoelastic relaxation over a 6 months period. The predicted horizontal displacements are very similar to the observed postseismic displacements while the magnitudes of surface displacements due to viscoelastic relaxation are very small (≤1 mm). The predicted surface displacements are no larger than 1.5 mm even we use a weaker upper mantle (Figure S12), which means that the viscoelastic relaxation mechanism contributes little to the cumulative postseismic displacements. In conjunction with the modeling of poroelastic rebound, it can be concluded that the afterslip appears to be the most significant mechanism of the postseismic deformation mostly at shallow depths.

4.2. Coulomb Failure Stress Change and Aftershock Triggering

Moderate and large earthquakes can influence the stress status of faults close to the hypocenter, and positive and negative stress changes increase and decrease the failure potential of nearby faults, respectively (Freed, 2005; King et al., 1994). Therefore, analyzing the CFS changes of large earthquakes has proven to be an effective method for assessing future seismic hazards around the hypocenter. CFS changes can be categorized as static or dynamic (Freed, 2005). Dynamic CFS changes, which are not discussed in this study, are always time-dependent and associated with earthquake triggering at a remote distance (Kilb et al., 2002). In this study, the static CFS change of the Monte Cristo earthquake was calculated based on the two-segment fault geometry and slip distribution utilizing the Coulomb 3.4 code (Toda et al., 2011).

According to the Coulomb-failure criterion, the CFS change on a given receiver fault plane is defined as follows (Scholz, 2002):

\[ \Delta \sigma_f = \Delta \tau + \mu' \Delta \sigma_n, \]

where \( \Delta \sigma_f \) denotes the CFS change of a specific receiver fault, \( \mu' \) is the effective friction coefficient, and \( \Delta \tau \) and \( \Delta \sigma_n \) represent the changes in shear and normal stress, respectively. Aftershock studies have demonstrated that earthquake activity can be significantly promoted when the CFS change on a fault is increased by as little as 0.1 bar, even though the CFS change following an earthquake is much smaller than the tectonic stress required for earthquake nucleation (Stein, 1999; Ziv & Rubin, 2000). First, the CFS change was calculated utilizing a simple receiver fault mechanism (strike = 73°, dip = 78°, and rake = −24°) selected based on the optimal nodal plane of the moment tensor solution, which has a similar geometry to that of Model I. We explored the effect of different values of an effective friction coefficient on the CFS change. The results reveal that the CFS change is insensitive to the value of the effective friction coefficient in the range of 0.2–0.6 (Figure S13). So the effective friction coefficient was fixed at 0.4 for all calculations. The calculated CFS changes caused by the Monte Cristo earthquake at depths of 5 and 10 km, presented in Figures 9a and 9b, respectively, indicate obvious stress loading along the two ends of the coseismic slip. Additionally, two stress shadows were revealed in the northern and southern off-fault regions and are consistent with the general CFS change features caused by typical strike-slip ruptures.

To evaluate the impact of the mainshock on regional seismic activity, the CFS change on the surrounding active faults due to coseismic slip was calculated utilizing the inverted two-segment slip distribution model of this study. The geometries of the nearby receiver faults were simplified utilizing single planes with 90° and 50° dips for the strike-slip and normal faults, respectively, determined from the United States National Seismic Hazard Maps (Petersen et al., 2019). The rakes of the dextral, sinistral, and normal faults were set at 180°, 0°, and −90°, respectively. Significant positive changes in the CFS were calculated in the Candelaria Fault (CAF), the Bettles Well Fault (BWF), the Emigrant Peak Fault (EPF) and the central segment of the Coaldale Fault (CF), indicating increased seismic hazards in these faults (Figure 9c); however, the CFS changes in the Excelsior Mountains Fault (EMF), the Rattlesnake Fault (RF), and the Lone Mountain Fault (LMF) were negative, indicating decreased seismic hazards in these faults.

The CFS changes on the source fault were calculated utilizing the distributed coseismic slip and afterslip models to analyze the triggering relationship between CFS change and aftershocks. The receiver faults are perfectly oriented for failure under the stress direction in the region, which is near the NNE-SSW compression and ESE-WNW extension (Bellier & Zoback, 1995). Compared to the map of CFS changes caused by the mainshock, it was found that most of the afterslip occurred in the positive CFS change regions (Figures 5c,
indicating the stress change redistribution within the surrounding area induced by coseismic rupture probably drove the early afterslip. Previous studies suggest that aftershocks following the mainshock mainly occur at locations with positive coseismic CFS changes (King et al., 1994; Qiu & Chan, 2019; Serpelloni et al., 2012). The Monte Cristo earthquake generally supports this spatial correlation. As shown in Figure 9d, the spatial distribution of aftershocks below a depth of 10 km is consistent with the positive stress loads, while a large portion of the aftershocks above a depth of 10 km occurred in a CFS decrease region. Interestingly, most of the aftershocks in the 3–10 km depth range are located in the region of a positive CFS change caused by the afterslip, except for a circular region near the epicenter (Figure 9e). This implies that the afterslip played a central role in triggering aftershocks (Cattania et al., 2015; Helmstetter & Shaw, 2009). Some aftershocks that cannot be explained by coseismic and postseismic CFS changes could be driven by other physical mechanisms or some unknown details of the slip distributions. Additionally, there are few aftershocks along the eastern termination of the fault F2 where the CFS change is positive (Figure 9d), which is primarily attributed to the possible truncation of the fault F2 by an NW-striking fault at the eastern termination of the rupture. A cluster of NW-trending aftershocks could outline the NW-striking fault orientation at the eastern end of the coseismic slip. The slip on the NW-striking fault was expected to be small because almost no surface displacements above the fault were observed (Figure 3). Generally, the complex rupture geometry, large SSD, and high aftershock productivity of the 2020 Monte Cristo earthquake are consistent with the characteristics of an immature strike-slip fault system, similar to the 2019 Ridgecrest earthquake sequence (Goldberg et al., 2020; Li et al., 2020).

### 4.3. Implications for Stress Transfer and Stepover Zone Failure

Three kinematic models have been proposed to account for the fault slip transfer mechanism between the dextral northern ECSZ faults and the central WLB fault zone in the Mina deflection (DeLano et al., 2019; Nagorsen-Rinke et al., 2013). In the first model, the slip across the Mina deflection is accommodated by the clockwise rotation of a series of NE-trending fault blocks, characterized by a simple left-lateral slip style in the boundary faults (Wensnousky, 2005). In the second model, the displacement in the Mina deflection is...
transferred through an extension across a pure normal fault system, identified by geological maps and the structural and seismic data (Oldow et al., 1994). In the third model, normal and sinistral slips accommodate the instantaneous deformation in the Mina deflection, resulting in an oblique-slip style along the connecting faults (also termed the transtensional model) (Oldow, 2003). The source mechanism of the 2020 Monte Cristo earthquake provides important clues for ascertaining the fault kinematics in the Mina deflection. First, the Monte Cristo earthquake shows pure left-lateral and significant normal slip components in the eastern and western segments of the source fault, respectively, suggesting the interseismic strain accumulation in the Mina deflection, at least in the northeastern part, could not be solely explained by the sinistral or normal fault slip. Second, the normal slip transfer model requires an NW-dipping detachment with an initial dip of <30° (Oldow et al., 1994), which is not supported by the source parameters of the Monte Cristo earthquake. Model II determined two SE-dipping faults with steep dips of 65° and 79°. Considering the oblique-slip characteristics of the Monte Cristo earthquake, it was inferred that the oblique-slip model more accurately explained the fault kinematics in the northeastern Mina deflection. In the western Mina deflection, DeLano et al. (2019) concluded that no normal slip occurred along the exposed NE-trending sinistral faults in the River Spring area. The contrasting fault slip style in the northeastern and western Mina deflection implies a fault slip transform from oblique-slip to pure dextral slip along the NE-striking fault system in the Mina deflection. We speculate that the fault slip that transformed from the northeastern segment of the Mina deflection to the western segment could be associated with the different degrees of fault maturity.

As illustrated in Section 3.2, the Monte Cristo earthquake ruptured two unmapped faults in the eastern Mina deflection. Based on the map view (Figure 10e), the two ruptured faults could represent the east extension of the Candelaria fault, located in an active structural stepover zone linking the ECSZ and the WLB (Nagorsen-Kinke et al., 2013; Oldow et al., 2008). The northeast segment of the stepover zone, where the Monte Cristo earthquake occurred, has exhibited low seismic activity since the Holocene, suggesting a quiescence period in the earthquake cycle (Surpless, 2008). Stepover zone ruptures, such as the Monte Cristo earthquake, have occurred globally. For example, Bie and Ryder (2014) suggested that the 2008 Mw 7.1 Yutian earthquake rupture in western Tibet was initiated by a stepover zone failure at the west end of the Altn Tagh and the Longmu-Gozha Co faults. Brothers et al. (2011) found that the stepover fault ruptures caused by tectonic loading, and the periodic flooding of the paleo-Salton Sea had the potential to promote failure of the southern San Andreas fault. These studies suggest that stepover zones play an important role in earthquake initiation.

The interseismic strain rate field was calculated via the multiscale spherical wavelet method (Tape et al., 2009) utilizing long-term geodetic measurements obtained in the Mina deflection stepover zone (Hammond et al., 2011; Lifton et al., 2013). Figures 10a and 10b show the strain rate in the Mina deflection stepover zone is moderate, with maximum shear strain and dilatational strain rates ranging of 2.5–5 × 10⁻⁸ and 0.5–1.5 × 10⁻⁶ yr⁻¹, respectively. Generally, the regional strain field of the Mina deflection is consistent with the extensional stepover characteristic that connects right-lateral fault zones (Oglesby, 2005). Based on the results of multiple studies and field mapping and numerical modeling of historical earthquakes along strike-slip faults (De Paola et al., 2007; Oglesby, 2005), it can be concluded that the extensional stepover zones, including the Mina deflection, are more susceptible to rapid stress loading and more prone to through-going ruptures than compressional stepovers linked to thrust faults. The magnitude of an earthquake in a stepover zone is largely determined by the width between the linking strike-slip faults (Duan & Oglesby, 2006). In the Mina deflection stepover zone, the Mw 6.5 Monte Cristo earthquake only ruptured the northeastern segment of the stepover zone and left a width of ~30 km in the western segment unbroken (Figure 10e). Significant positive CFS changes were calculated in the western segment of the stepover zone (Figure 9); therefore, future seismic hazards in the western segment of the stepover zone (i.e., the Candelaria Fault) should be thoroughly studied. The maximum magnitude of an earthquake that ruptures the entire width of the Mina deflection stepover zone was roughly estimated, and the interseismic GPS velocities in the Mina deflection into the stepover-parallel and perpendicular components were projected (Figures 10c and 10d, respectively). The total normal and strike-slip rates across the stepover zone were less than 1–2 mm/yr. Assuming a rupture width of 60 km, a recurrence interval of 200 years, and the total slip rate across the stepover zone is absorbed by a simple fault, the rupture of the entire stepover zone could result in an Mw 6.7 event.
5. Conclusions

Coseismic and postseismic displacements associated with the 2020 Monte Cristo earthquake were fully mapped utilizing three pairs of Sentinel-1 image tracks and ground measurements obtained from approximately 200 Mobile Array of GPS for Nevada Transtension GPS sites. The LOS displacements derived from the InSAR measurements concur with the GPS measurements after correction for the influences of orbital errors and possible long-wavelength perturbations. Surface geodetic measurements were utilized to constrain the fault geometry and slip distribution of the Monte Cristo earthquake, and the optimized fault geometry indicates that the source fault is characterized by two previously unidentified fault plane segments.
with differing fault dips. The western segment of the source fault is dominated by sinistral and normal slips, while the eastern segment is controlled by purely sinistral slips at depths of 3–12 km. The early afterslip of the Monte Cristo earthquake was also investigated utilizing postseismic geodetic measurements. The results determined the afterslip mainly occurred in the shallow portion of the source fault, showing a good spatial complementary relationship with the coseismic slip. The significant normal slip components related to the coseismic distribution suggest an oblique-slip model in relation to the kinematics and slip transfer mechanism of the northeastern Mina deflection zone. The Monte Cristo earthquake only ruptured the northeast segment of the Mina deflection stepover between the north ECSZ and the central WLB. The enhanced seismicity implied by the positive CFS changes and interseismic strain accumulation in the remaining portion of the stepover zone is also worth further attention.

Data Availability Statement

The Sentinel-1 SAR data were acquired and processed by European Space Agency Copernicus program (https://scihub.copernicus.eu/) and retrieved from the Alaska Satellite Facility Distributed Active Archive Center (https://vertex.daac.asf.alaska.edu). These data and the digital file of the coseismic slip distribution were uploaded to Zenodo (https://zenodo.org/record/4671183#.YG6Co3Zqikx). The coseismic GPS measurements used in this study were archived from the Nevada Geodetic Laboratory (http://geodesy.unr.edu/news_items/20200619/nn00725272_24hr_19-Jun-2020.txt) and the UNAVCO archive (https://www.unavco.org/data/dai/). All of the links were last accessed 2021 February 16. The figures were plotted using the Generic Mapping Tool (GMT) software (Wessel et al., 2019).

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