Modeling of postseismic deformation following the 2019 Ridgecrest earthquake sequence

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**Introduction**

Based on our previous year’s effort, this project aims to characterize the spatial and temporal distributions of postseismic deformation spanning nearly two years after the 2019 Ridgecrest earthquake sequence using Satellite Radar Interferometry (InSAR) of multiple SAR satellites and Global Navigation Satellite Systems (GNSS). The primary goal of this project is to model the underlying postseismic deformation observed during the first two years after the mainshock. This is important not only for understanding how strain and stress evolve, but also for evaluating the impact of the 2019 earthquakes on the surface deformation field represented by SCEC’s Community Geodetic Model (CGM), both in the near field of the rupture and across southern California.

**Data**

We have produced an initial set of time series using SAR data (including Sentinel-1, ALOS-2, CSK) acquired from both ascending and descending tracks for ~2 years after the mainshock, which together with all available GNSS data form the basis of our exploration of postseismic deformation processes. Atmospheric noise is one of the major error sources in InSAR measurement, particularly for low-amplitude deformation processes, such as postseismic deformation. We performed the InSAR time series analysis by implementing different approaches to mitigate the atmospheric noise. Specifically, we used the ECMWF Re-Analysis version 5 (ERA-5) numerical weather model and Zenith Total Delay (ZTD) products derived from GNSS observations within the SAR images to correct for the tropospheric delay in each SAR acquisition. We found that the corrections using both the ERA-5 weather model and the GNSS-based ZTD products can significantly reduce the scattering in the resulting time series, while still well preserving the decaying feature expected from a postseismic deformation process. An example time series at a point near the uplift feature of the mainshock epicenter (close to the GNSS station CLR2 in Figure 1e) is shown in Figure 1f.

![Figure 1. InSAR observations of postseismic deformation following the 2019 Ridgecrest earthquake sequence. (a) and (b) cumulative line-of-sight (LOS) displacements ~two years after the mainshock derived from Sentinel-1 data of the ascending track ASC64, and descending track D071, respectively. The red and magenta stars in (a) represent the epicenters of the Mw 6.4 foreshock and the Mw 7.1 mainshock, respectively. (c) and (d) show the cumulative postseismic displacements along the East-West and vertical directions, respectively, by decomposing the LOS displacements from both the ascending and descending tracks. The North-South component is ignored in the decomposition for visualization, given that its contribution to the LOS displacement is small compared to the E-W and vertical components, although the N-S motion is significant. (e) Zoom-in of the vertical component of postseismic InSAR observations near the fault complexities. Green triangles in this panel show the locations of campaign-mode GNSS sites deployed by USGS shortly after the mainshock.](image-url)
earthquake (f) example of the InSAR LOS displacement time-series at a point near the Mw 7.1 epicenter (magenta star in (a)) with different processing strategies. Black and orange curves denote the fitting to the resulting time series after corrections combining GNSS-based ZTD products and the CSS with a logarithmic and exponential function, respectively. Shaded areas represent the uncertainties of the fitting. (g) average postseismic LOS velocity spanning the period of 2019/09/22-2020/12/23 derived from stacking of multiple ALOS-2 interferograms along the descending track 167. (f) baseline plot of the ALOS-2 SAR data. Blue lines represent the interferograms used to obtain the average velocity shown in (g). Red dash line represents the time of the 2019 Ridgecrest mainshock.

For the GNSS data, we analyzed the daily position time series produced by the Central Washington University (CWU) at >400 continuous stations within 300 km from the 2019 Ridgecrest earthquake in the first two years. To minimize the potential contamination due to postseismic deformation from the 1992 Landers and the 1999 Hector Mine earthquakes, we used data from only three years before the 2019 Ridgecrest earthquake to estimate the preseismic (interseismic) velocity at each station and subtract it from the postseismic recordings. The remaining GNSS time series at each station is then fitted with a logarithmic function \( y = A \log(1 + t/\tau) \) to obtain the cumulative displacement at each station for a given time period, where \( t \) represents the time since the mainshock, and \( \tau \) the relaxation time that characterizes the decay of the surface deformation.

Figure 1 shows the cumulative postseismic deformation ~2 years after the 2019 Ridgecrest earthquake derived from Sentinel-1 and ALOS-2 InSAR. The horizontal displacement field revealed by both GNSS and InSAR observations is characterized by south-to-southeastward motion on the eastern side of the fault and north-to-northwestward motion on the western side of the fault, a deformation pattern similar to the coseismic displacement field. The vertical displacement field however is rather complex, with most deformation being concentrated around the rupture tips and the fault geometric complexities, including the releasing-bend fault step-over near the mainshock epicenter and the fault junction between the Mw6.4 foreshock and the Mw 7.1 mainshock (Fig. 1e).

**Models**

**Viscoelastic relaxation**

One challenge of modeling postseismic deformation is that multiple relaxation mechanisms (e.g., afterslip, viscoelastic relaxation, and poroelastic rebound) are coupled and it is often not straightforward to separate the contributions of surface transients from each other, especially for strike-slip fault, where the surface deformation due to viscoelastic relaxation and afterslip can be quite similar. For the 2019 Ridgecrest earthquake, the surface deformation due to both afterslip and viscoelastic relaxations is clear in the GNSS data. Specifically, many far-field GNSS stations of up to more than 100 km from the mainshock epicenter (e.g., those in the Mojave Desert to the south) capture clear postseismic transients following the mainshock. Deformation at this distance is unlikely to originate from afterslip, as that would require the afterslip to take place in the upper mantle at a depth well below in the coseismic rupture. Instead, we found that a viscoelastic relaxation model based on the rheological model of Liu et al. (2020), which was obtained by modeling the postseismic transients following the 1992 Landers and the 1999 Hector Mine earthquakes, can fit both the magnitude and temporal evolution of postseismic deformation recorded at stations in the far-field reasonably, particular for those in the Mojave Desert to the south. The viscoelastic relaxation model, however, significantly underpredicts the observed deformation at stations close to the mainshock rupture (e.g., <50 km from the mainshock epicenter). Similar to many previous studies, postseismic deformation in the relatively near field is best explained by afterslip taking place mainly downdip of
the coseismic rupture. To avoid the potential trade-off between contributions from afterslip and viscoelastic relaxation, in this study, we used the model of Liu et al., (2020) to calculate the deformation due to viscoelastic relaxation and substrate it from both the GNSS and InSAR data before they are used to explore relaxation mechanisms.

**Afterslip**

The observed InSAR and GNSS postseismic displacements after subtracting the contributions from viscoelastic relaxation are then used to invert for the distribution of afterslip. As discussed below, poroelastic rebound also made a significant contribution to the observed InSAR LOS displacements near the fault geometry complexities, and mainshock rupture tips. Numerical simulations show that at those places, surface deformation along the vertical direction due to poroelastic rebound is significantly larger than that along the horizontal direction. So to reduce the possible bias in the resulting afterslip model, we only used the horizontal component of the InSAR and GNSS measurements in the inversion. The fault geometry is based on the coseismic model of Wang et al., (2020), while extending all fault segments to a depth of ~40 km.

One striking feature of the afterslip model is that similar to the coseismic rupture, most of the afterslip moment concentrates in a relatively shallow depth range (0-10 km) (Figure 2). We note that this feature appears to be robust, since models with slip concentrated at relatively greater depths (e.g., > 20 km) would produce larger surface displacements in the middle-to-far field, while they underpredict the motion in areas close to the fault. In addition, the maxima of afterslip seem to be mostly collocated at or close to areas of high coseismic slip. We run the inversion with different model regularizations and data selections, e.g., smoothing and relative weighting between the GNSS and InSAR datasets. The resulting afterslip models are overall similar to what is shown in Figure 2, despite some small-scale variations. While horizontal displacements predicted by the afterslip model match the observations reasonably well, the afterslip model predicts the opposite sign of the vertical displacements in the areas of major vertical deformation, suggesting that the vertical displacement is mainly controlled by other relaxation mechanisms. Although viscoelastic relaxation can predict the same signs of quadratic vertical deformation, the deformation due to viscoelastic relaxation is distributed in a much wider area compared to what the data reveal. In addition, the predicted magnitude of vertical displacement due to viscoelastic relaxation based on the rheological structure of (Liu et al., 2020) is <5 mm during the observation period, which is about one order smaller than the maximum vertical displacement inferred from the InSAR observation. Therefore, we suggest that vertical postseismic deformation observed in this study is mainly due to poroelastic rebound.

*Figure 2. Distribution of cumulative afterslip ~1.5 years after the mainshock. Grey dots in panels to the right represent the aftershocks during ~2 weeks after the mainshock (Shelly, 2020). Blue contours represent the coseismic slip contours at 1-meter interval (from Wang et al., 2020). The red star represents the hypocenter of the mainshock. Green star denotes the approximate location of the Mw 5.5 aftershock on 06/30/2020.*
Poroelastic rebound

A widely used approach to model the poroelastic rebound is by differencing the coseismic displacement fields calculated with different Poisson's ratios under undrained and drained conditions (Peltzer et al., 1998; Jónsson et al., 2003; Fialko, 2004). This method is simple to implement and can provide the first-order spatial pattern and final magnitude of the surface deformation by varying the contrast in Poisson’s ratios from undrained to drained conditions. However, it lacks the capability to model the temporal variation of surface deformation due to poroelastic rebound, thus does not provide much information about the hydraulic properties of the fault zone and surrounding crust. To take advantage of the high temporal resolution of the InSAR and GNSS data, we model the poroelastic rebound using the software PEGRN/PECMP (Wang and Kümpel, 2003), which solves for the fully coupled poroelastic diffusive problem in a layered half-space. By comparing the model predicted surface deformation time series with observations, one may draw inference about the hydrological properties, particularly, the hydrological diffusivity of the shallow crust, which controls the speed of the fluid flow in the porous medium, and the corresponding temporal evolution of surface deformation.

To this regard, we used the GNSS time-series recorded by a campaign network deployed shortly after the earthquake (Brooks et al., 2020), and Sentinel-1 InSAR LOS displacement time series from the ascending track ASC64 after correcting for the contributions from viscoelastic relaxation and afterslip for each time epoch. For GNSS data, we only used the vertical components at stations within the ‘uplift’ feature near the mainshock epicenter (clr1, clr2, clr7), as the horizontal displacements may include significant contributions from the afterslip. To account for the contribution due to afterslip in the InSAR LOS displacements, we assume that afterslip everywhere on the fault follows the same temporal evolution pattern, so its temporal characteristics can be approximated by that of the surface displacements. We perform a Principal Component Analysis (PCA) to the GNSS time series at stations of intermediate distance (<80 km) from the rupture to extract the temporal evolution of afterslip. We then compute the LOS displacement at each SAR acquisition epoch using the afterslip model shown in Figure 3 whose temporal evolution follows the best-fitting logarithmic function of the PC1 temporal response.

Figure 3. Modeling of the poroelastic rebound in the area close to the mainshock epicenter as a function of hydraulic diffusivity. The top row is based on the vertical displacement time series at the GNSS site clr1. The bottom row is based on the average LOS displacement time series of pixels around the mainshock epicenter uplift feature. Magenta lines for both cases represent the best-fitting exponential functions to the respective displacement time series.
Figure 3 shows the comparison of displacement time series in the area of clear postseismic uplift near the mainshock epicenter between observations and model predictions due to poroelastic rebound as a function of the hydrological diffusivity. Both the GNSS and InSAR LOS displacement time series best match with the model with a hydraulic diffusivity on the order of 0.01 m²/s, which is comparable to in-situ estimates of the fault zone diffusivity based on tidal response data (Xue et al., 2013, 2016), but is at least one order lower than that estimated with the propagation of seismicity accompanying fluid pressure diffusion through fractured rocks (e.g. Shapiro & Dinske, 2009, Yu et al., 2019).

Discussion and Conclusions

Using InSAR and GNSS data collected during the first 2 years after the mainshock, we have developed an initial set of models to characterize the early postseismic deformation following the 2019 Ridgecrest earthquake sequence. We show that the surface deformation 2 years after the 2019 Ridgecrest earthquakes consists of contributions from all three commonly considered relaxation mechanisms, including afterslip, viscoelastic relaxation, and poroelastic rebound. Specifically, the InSAR deformation observed in the near-to-medium field can be well explained by a model combining both afterslip and poroelastic rebound, while the GNSS displacements in the far-field require the involvement of viscoelastic relaxation from the upper mantle. The postseismic models derived in this study offer a unique perspective to probe the mechanical properties of the fault zone and surrounding rocks, e.g., the hydrological properties of the shallow crust discussed in the section of modeling of poroelastic rebound. They are also helpful to evaluate the stress and strain evolution in the surrounding crusts. Last but the least, the postseismic models derived in this project can be used to evaluate and correct for the impact of recent large earthquakes on the geodetic observations made after the 2019 Ridgecrest earthquake sequence, e.g., the ongoing effort on the Community Geodetic Model (CGM) development.

However, one must also admit that the current InSAR data are still too noisy to robustly distinguish the contributions from the viscoelastic relaxation, particularly from the ascending satellite tracks. Modeling of viscoelastic relaxation based on the rheology structure of Liu et al., (2020) predicts that the range change for both ascending and descending tracks will be on the order of ~5 mm/yr for the next few years, so one should expect to see the long-wavelength signals of viscoelastic relaxation more clearly in the next 3-4 years. Also, we may need to adjust some of the model assumptions to better reflect the local geology. For instance, in our current effort to model the poroelastic rebound, we have assumed a confined boundary condition (p=0) at the surface. However, several recent studies suggested a no-flow boundary condition (dp/d=0) might be more appropriate in modeling the groundwater flow after a big earthquake. We will test these model setups and compare them with data for an improved understanding of the selection of boundary conditions in the modeling of poroelastic rebound. In addition, as we discussed above, current data are indicative of spatial heterogeneity in the mechanical properties, e.g., hydrological properties, along the fault, as well as the lithospheric rheology north and south of the 2019 rupture. We still need to quantitatively characterize these heterogeneities and associate them with local geology. We anticipate that with more SAR image acquisitions over the next 2-3 years, and an updated algorithm we have recently developed to account for the long-wavelength atmospheric noise in InSAR measurements using the GNSS zenith delay products, the results, including both measurements of the surface deformation and model constraints will be further improved.
References


