GNSS measurements of postseismic deformation and updating of site positions in the Mojave Desert in the aftermath of the 2019 Ridgecrest earthquake sequence for the Community Geodetic Model

Final Report

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Introduction

Scientists from UCR were among the first to respond to the 2019 Ridgecrest earthquakes. We travelled to the epicentral region within hours of the first event (on the afternoon of July 4th) and deployed survey GNSS equipment at five sites – all of which were in place and running, and importantly, remained standing, when the second, larger event occurred on July 5th, enabling us to distinguish the deformation that occurred in each event (Floyd et al., 2020).

In the days that followed the events, we significantly densified the survey GNSS coverage in the area to around 30 sites in collaboration with colleagues from Scripps Institute of Oceanography, the University of Nevada, Reno and the US Geological Survey. Many of these sites were measured, episodically or continuously, for up to three and a half years afterward, in order to measure any transient postseismic deformation resulting from the earthquakes. In this report, we describe how we continued this program of GNSS survey measurements in the region, and also began to remeasure sites further afield in the Mojave desert that we had neglected during the earthquake response.

Field surveys in the Ridgecrest area

The main focus of the project was to measure the ongoing postseismic transient deformation in the epicentral region of the Ridgecrest earthquakes. We made four survey visits during the project period, in March 2022, June 2022, July 2022 and March 2023, measuring 15 sites that were either previously measured by UCR or Scripps. Details of the site locations and occupation dates are given in Table 1. The majority of the sites were measured in campaign mode, i.e. for short temporary occupations, typically of 18-24 hours. At three sites, GS04, 0914 and GS25, we occupied the benchmarks semi-continuously, i.e. the equipment was left out in the field continuously, with solar panels for power – we adopted this strategy, as the sites were in remote, out of the way locations, and if the equipment were left out, we only needed to visit each site once per trip, compared with twice for campaign measurements. The equipment used was the PI's own, a mixture of Trimble receivers (R7s, NetRSs and NetR9s) and Topcon receivers (GB-1000s), with Trimble Zephyr Geodetic or Topcon PG-AI antennas.

Table 1: Details of Ridgecrest area survey data acquisitions. For campaign measurements, date given is the equipment set-up date. Unless otherwise noted, sites were occupied in campaign mode, and previously measured by UCR.

Station code	Coordinates	Dates visited	Notes
0806	35.36615, -117.6142	2022/07/13	Scripps site
0914	35.97792, -117.32864	2022/06/07, 2023/03/11	Semi-continuous
ATOL	35.31313, -117.60938	2022/03/23, 2022/06/06	
BM25	36.04457, -117.94402	2022/06/07	
GS04	36.20353, -117.90658	2022/06/07. 2023/03/11	Semi-continuous
GS11	35.42877, -117.58484	2022/03/23, 2022/06/08	Scripps site
GS16	35.47028, -117.70649	2022/07/13	
GS17	35.56939, -117.55676	2022/03/24, 2022/06/08	Scripps site
GS18	35.58376, -117.87032	2022/03/24, 2022/06/08	
GS25	35.91323, -117.28912	2022/07/13, 2023/03/11	Semi-continuous
H701	35.60906, -117.80036	2022/03/23, 2022/06/08, 2023/03/11	
J701	35.57444, -117.78389	2022/06/08	
PASO	35.51302, -117.70636	2022/03/24, 2022/07/13	
PNCL	35.60077, -117.39360	2022/03/24, 2022/07/13, 2023/03/11	
V511	36.06141, -117.86567	2022/06/07, 2023/03/11	

Remeasuring sites further afield in the Mojave Desert

Our final campaign trip, in April 2023, involved measuring sites in the Mojave Desert that had been previously measured by UCR, in SCEC-funded campaigns in 2014 and 2019, or sites that had been measured by other groups and included in the SCEC Crustal Motion Map. Each site was measured in campaign mode, as for the Ridgecrest surveys, and using the same equipment. Seven sites were measured in total; details of the occupations are given in Table 2.

Table 2: Details of sites measured in the central Mojave desert area in April 2023.

Station code	Coordinates	Previous measurement
GS36	35.16783, -11704248	2002 (MIT)
HAW0	34.94807, -117.41448	2019 (UCR/SCEC)
HEC2	34.78468, -116.42188	2019 (UCR/SCEC)
NORM	35.22677, -117.60716	2019 (UCR/SCEC)
PT65	34.45401, -117.06797	2019 (UCR/SCEC)
RAIN	34.97258, -117.21577	2019 (UCR/SCEC)
SUNH	34.74946, -117.29740	2019 (UCR/SCEC)

Preliminary results of data processing

With help from Michael Floyd at MIT, who had SCEC support for GNSS data processing and analysis work in the past year, we processed preliminary GNSS time series incorporating the data from 2022. The total time span of the data from this preliminary processing effort is approximately 3 years, from July 2019 to July 2022. We presented the preliminary findings below at the 2022 AGU Fall meeting (Funning et al., 2022).

The map pattern of horizontal displacements as a function of time is shown in Figure 1; both survey and continuous GNSS stations are plotted. The inclusion of survey sites approximately doubles the number of observations, and is particularly important for densifying the coverage in the near field (within 50 km of the source faults). As time increases, the displacement increases, but at a decreasing rate – at many stations, the incremental displacements from the last 400 days are similar in amplitude to the displacements from the first 30 days. We note that there is some asymmetry in the amplitudes of displacement across the fault; stations to the NE of the Ridgecrest mainshock fault typically have larger displacements than the stations to the SW. We hypothesize that this may be due to variations in surface elevation decreasing the distance to the deformation source (potentially a lower crustal shear zone undergoing afterslip) to the NE (the location of the low elevations of Death Valley), and increasing distance to the SW (the location of the higher elevations of the Sierra foothills).

The majority of stations show a change in the direction of movement over time, with a counter-clockwise rotation of the displacement vectors discernable in Figure 1. We suspect that this represents a change in the primary postseismic deformation mechanism, from deep afterslip to viscous relaxation, but we will need to confirm this with modeling.

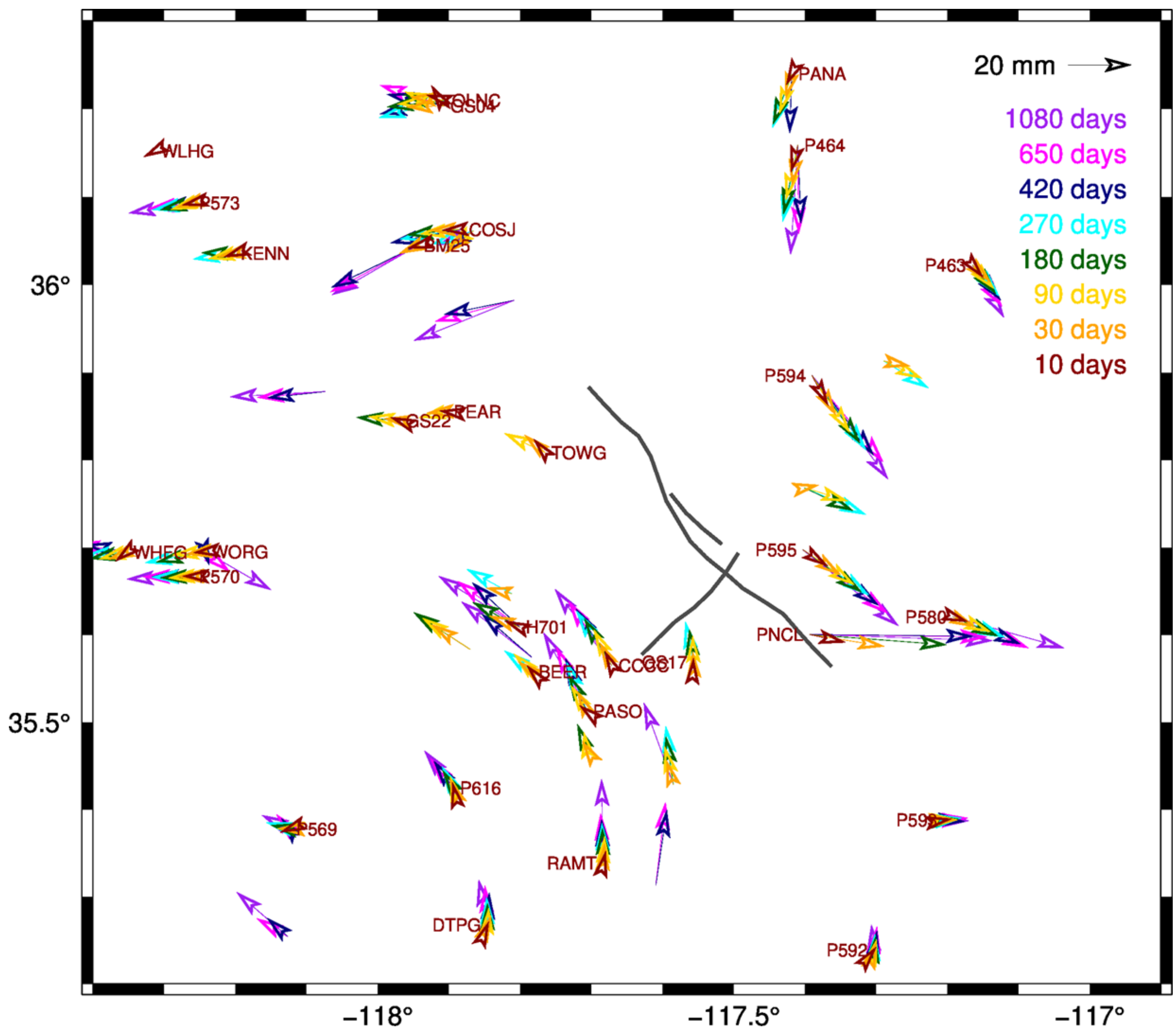

Figure 1: Map pattern of postseismic displacements as a function of time following the M7.1 July 5th Ridgecrest mainshock. Vectors show surface displacement and are color-coded by time. The NW-striking M7.1 source fault and SW-striking M6.4 source fault are shown as black solid lines. Overall, the pattern of displacements is consistent with deep, right-lateral afterslip on the M7.1 source fault, but rotations of most of the vectors as time increases suggests that a different deformation mechanism may be influencing the later period of displacement. Displacements to the NE of the M7.1 source fault are typically larger in amplitude at a similar distance to the fault compared with sites to the SW of the fault, suggesting a possible influence of the surface elevation – which varies by ~3 km from SW to NE – on the measured displacement.

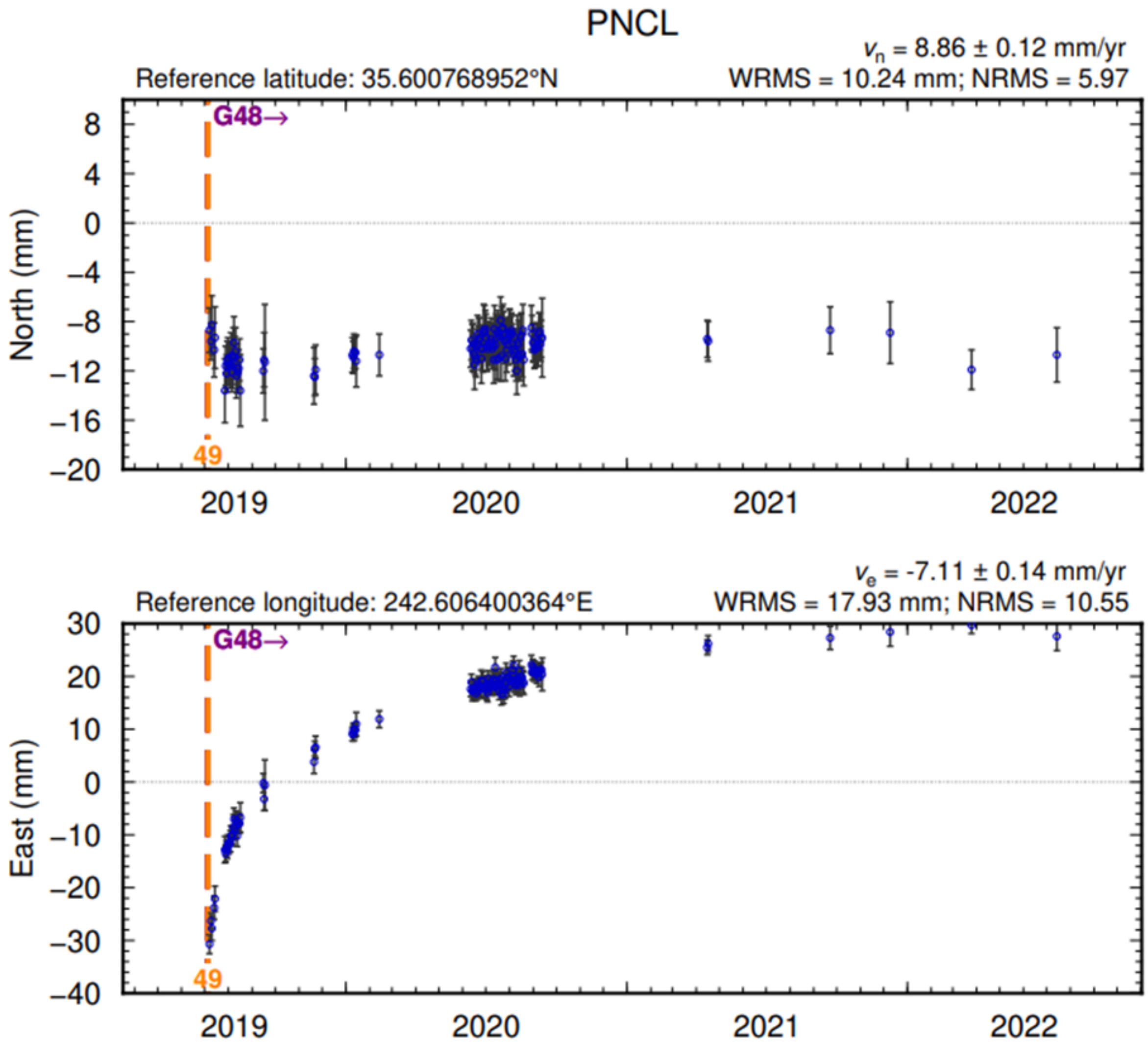

Figure 2: North (top) and East (bottom) components of the displacement time series of station PNCL (Pinnacles), located close to the M7.1 earthquake surface rupture. Time series have been detrended by the pre-earthquake secular rates estimated by Floyd et al. (2020). We infer a total postseismic displacement of ~60 mm over the three year period spanned by the data; the flattening of the time series in late 2021 and 2022 suggests that the postseismic deformation transient may be coming to an end.

An example of the horizontal time series of a site with one of the most complete survey records, PNCL, is shown in Figure 2. PNCL is located ~600 m east of the M7.1 surface rupture, near the Trona Pinnacles, and has the largest postseismic displacements of any of the survey sites measured by UCR. The total postseismic displacement of the site is of the order of 60 mm, with about half of that displacement occurring in the first three months. In late 2021 and 2022, the time series flattens out, suggesting that the postseismic transient is finishing

Data archiving and documentation

We are currently writing the results up for publication, and as part of that effort, will submit all of the RINEX files for the GNSS data, along with scanned log sheets and site photos to the EarthScope Campaign Data Archive. The processed time series will be included as supplemental material and made publicly available.

References

M Floyd, G Funning, Y Fialko, R Terry and T Herring, 2020, Survey and Continuous GNSS in the vicinity of the July 2019 Ridgecrest earthquakes, Seismol. Res. Lett., 91, 2047-2054, https://doi.org/10.1785/0220190324

G Funning, M Floyd, K Rivera, R Rivera, 2022, Postseismic deformation following the 2019 Ridgecrest earthquakes from 3 years of survey GNSS data, AGU Fall Meeting Presentation G22A-08