

Ground Deformation Data from GEER Investigations of Ridgecrest Earthquake Sequence

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22 Abstract

23 Following the Ridgecrest Earthquake Sequence, consisting of a **M6.4** foreshock and **M7.1**
24 mainshock along with many other foreshocks and aftershocks, the Geotechnical Extreme
25 Events Reconnaissance (GEER) Association deployed a team to gather perishable data. The
26 team focused their efforts on documenting ground deformations including surface fault rupture
27 south of the Naval Air Weapons Station China Lake, and liquefaction features in Trona and
28 Argus. The team published a report within two weeks of the **M7.1** mainshock. This paper
29 presents data products gathered by the team, which are now published and publicly accessible.
30 The data products presented herein include ground-based observations using GPS trackers,
31 digital cameras, and hand measuring devices, as well as UAV-based imaging products using
32 Structure from Motion to create point clouds and digital surface models. The paper describes
33 the data products, as well as tools available for interacting with the products.

34 Introduction

35 The 2019 Ridgecrest earthquake sequence began with a **M6.4** foreshock at 10:33 am local time
36 on July 4, followed by a **M7.1** main shock at 8:19 pm local time on July 5. These events were
37 the first earthquakes centered in southern California to rupture the ground surface since the
38 1999 Hector Mine earthquake. Considering the importance of quantifying surface rupture and
39 gathering perishable data from the Ridgecrest earthquake sequence, the NSF-funded
40 Geotechnical Extreme Events Reconnaissance (GEER) Association, with co-funding from the B.
41 John Garrick Institute for the Risk Sciences at UCLA and support from the Southern California
42 Earthquake Center (SCEC) and NASA Jet Propulsion Laboratory (JPL), deployed several teams
43 of researchers to the Ridgecrest area. The first team arrived in Ridgecrest on July 5th to
44 document perishable data on the **M6.4** event effects, and the team experienced the **M7.1** event

at a hotel in Ridgecrest. Work then continued for several weeks after the earthquake sequence, during which investigators identified major effects, performed detailed mapping of ground failure features, and conducted unmanned aerial vehicle (UAV) imaging.

The GEER team is multi-disciplinary, with expertise in geology, seismology, geomatics, geotechnical engineering, and structural engineering. GEER collaborated extensively with other reconnaissance teams operating in the region, including a fault mapping team comprised of the U.S. Geological Survey (USGS), California Geological Survey (CGS), and U.S. Navy personnel. The team released version 1 of their report on July 19 and version 2 on August 3 (Stewart et al. 2019). These reports are publicly available. Although the GEER reports have been published, the bulk of the data gathered during the reconnaissance missions were not published at the time of the release of the reports. In fact, reports are often the only products published after a GEER mission, while the majority of the data gathered during the missions is often not published.

This paper presents data gathered during the GEER missions that has now been published and assigned a digital object identifier (DOI). Data that has been published to date includes (i) ground-based observations gathered during field deployments several days after the earthquake sequence, with specific focus on mapping surface fault rupture south of the Naval Air Weapons Station China Lake (NAWSCL), (ii) ground-based observations of liquefaction effects in Trona and Argus, (iii) UAV imaging of the surface ruptures south of NAWSCL, and (iv) UAV imaging of liquefaction effects in Trona and Argus. With the intent of facilitating application by other researchers, in this paper we document details regarding the data types that are available, the location of the data files, and tools for interacting with the data.

Additional data products being published by researchers affiliated with GEER, and presented by Stewart et al. (2019), include measurements of the surface rupture that occurred on the NAWSCL (Ponti et al. 2019), where the largest fault offsets were measured. Additionally, UAV

images of the length of the **M6.4** and **M7.1** surface rupture south of NAWSCL were gathered by Koehler et al. (2020), and are being published separately. The amount of data available through these efforts is simply too large to fit into a single paper. We therefore focus our attention in this paper on specific missions conducted to study surface rupture south of NAWSCL, and liquefaction features in Trona and Argus.

Field Reconnaissance Missions

The various field reconnaissance efforts are organized into missions, while data products for each mission are organized into collections. Table 1 summarizes the missions, dates, activities, team members, and DOI's for these deployments. This paper includes five separate missions conducted between July 5th and 22nd, 2019. Two of the missions, GEER Field Reconnaissance and SCEC Field Reconnaissance, involved ground-based measurements using digital cameras, GPS trackers, tape measures, and rulers. Three of the missions, JPL UAV Imaging, UCLA UAV Imaging, and UW RAPID UAV Imaging, involved unmanned aerial vehicles (UAV's) equipped with digital cameras to perform Structure from Motion (SfM) processing to obtain point clouds and digital surface models. A map showing the locations studied during these missions is provided in Figure 1. Details of the data products from each mission are discussed in the sections that follow.

86 **Table 1.** Summary of reconnaissance missions.

Mission	Dates in Field	Description of Activities	Team Members	DOI
GEER Field Reconnaissance	July 5-7	Ground-measurements of M6.4 and M7.1 surface ruptures, and liquefaction features in Trona and Argus.	Ahdi, Brandenburg, Davis, Goulet, Hudson M., Hudson K., Nweke, Stewart, Wang	10.17603/ds2-vpmv-5b34
JPL UAV Imaging	July 9, 11, 15, 22	UAV imaging of M6.4 and M7.1 surface ruptures immediately south of Highway 178 over repeated dates	Donnellan, Lyzenga, Wang, Pierce	10.5967/5sq2-rs60
UCLA UAV Imaging	July 10-11	UAV imaging of M7.1 surface rupture, and liquefaction features in Trona and Argus	Brandenburg, Delisle, Kim, Lucey, Winters	10.17603/ds2-wfgc-a575
SCEC Field Reconnaissance	July 11	Ground measurements of surface fault rupture and ground cracks near the Trona Pinnacles	Goulet, Meng	10.17603/ds2-c5z3-wy42
UW RAPID UAV Imaging	July 16-18	UAV imaging of M6.4 surface rupture south of Highway 178	Lyda, Yeung, Buckreis, Issa, Yi	10.17603/ds2-tyca-se83

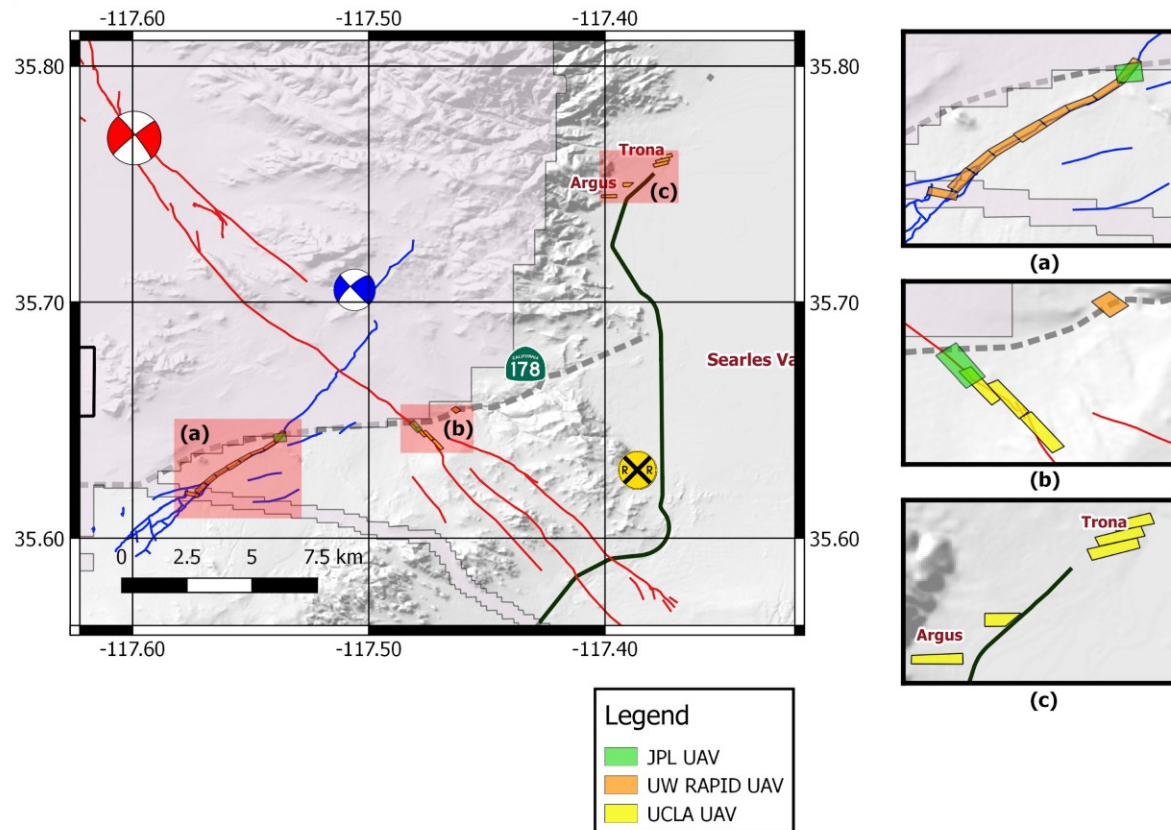


Figure 1. Map of the **M6.4** (in blue) and **M7.1** (in red) fault ruptures as given in Stewart et al. (2019) with shapefiles obtained from D. Ponti 7/17/2019, along with polygons flown during UAV missions. Reconnaissance efforts in this paper focused on the locations south of NAWSCL where the fault ruptures cross Highway 178, and liquefaction effects in Trona and Argus.

GEER Field Reconnaissance Mission

The initial field reconnaissance mission team was formed after the **M6.4** event through the NSF-funded Geotechnical Extreme Events Reconnaissance (GEER) Association, with co-funding from the B. John Garrick Institute for the Risk Sciences at UCLA and support from the Southern California Earthquake Center (SCEC). The team experienced the **M7.1** event at the motel in Ridgecrest where they stayed. Work then continued for two days, and involved initial

reconnaissance to identify major effects, and detailed mapping of ground failures. Two members of the GEER initial reconnaissance team were able to access the Naval Air Weapons Station China Lake (NAWSCL), but most team members focused their attention on features south of the NAWSCL using GPS trackers, digital cameras with GPS geotagging capabilities, and hand-held measuring devices including tape measures and rulers.

Data from the GEER Field Reconnaissance mission (Brandenberg et al. 2019) are published in DesignSafe (www.designsafe-ci.org, Rathje et al. 2017), which is a cyber-infrastructure tool for the natural hazards community. The “Field Research Project” data model was utilized to organize the data within a mission into collections. The GEER Field Reconnaissance mission data are organized into 9 separate collections. Eight of the collections are specific to the researcher who gathered the data, and are named “GEER Team Observations - NAME” where NAME is an identifier for the researcher, and includes the following {Ahdi, Brandenberg, Goulet, Hudson K., Hudson M., Nweke, Stewart, Wang}. The remaining collection is called “QGIS Products” and contains base maps and shape files from all of the researchers involved in the mission.

The individual collections contain GeoJSON files that organize each researcher’s track logs and photos into a file format that can be viewed using the HazMapper tool in DesignSafe. An example view of a GeoJSON file viewed using the HazMapper tool is shown in Figure 2 for the “GEER Team Observations - Brandenberg” collection, and shows a pipe that ruptured at the location where it crosses the **M6.4** surface rupture, and was subsequently repaired. Each photo appears as a thumbnail, and a reduced resolution version of the photo appears when a user clicks on the thumbnail. We recognize that users might want to view the full resolution versions of the images, so we also included a zip file in each collection that contains the full resolution images. We suggest that users begin by viewing the GeoJSON files in the HazMapper tool to

identify specific photos of interest, and subsequently download the relevant zip file to locate the full resolution version of the photo.

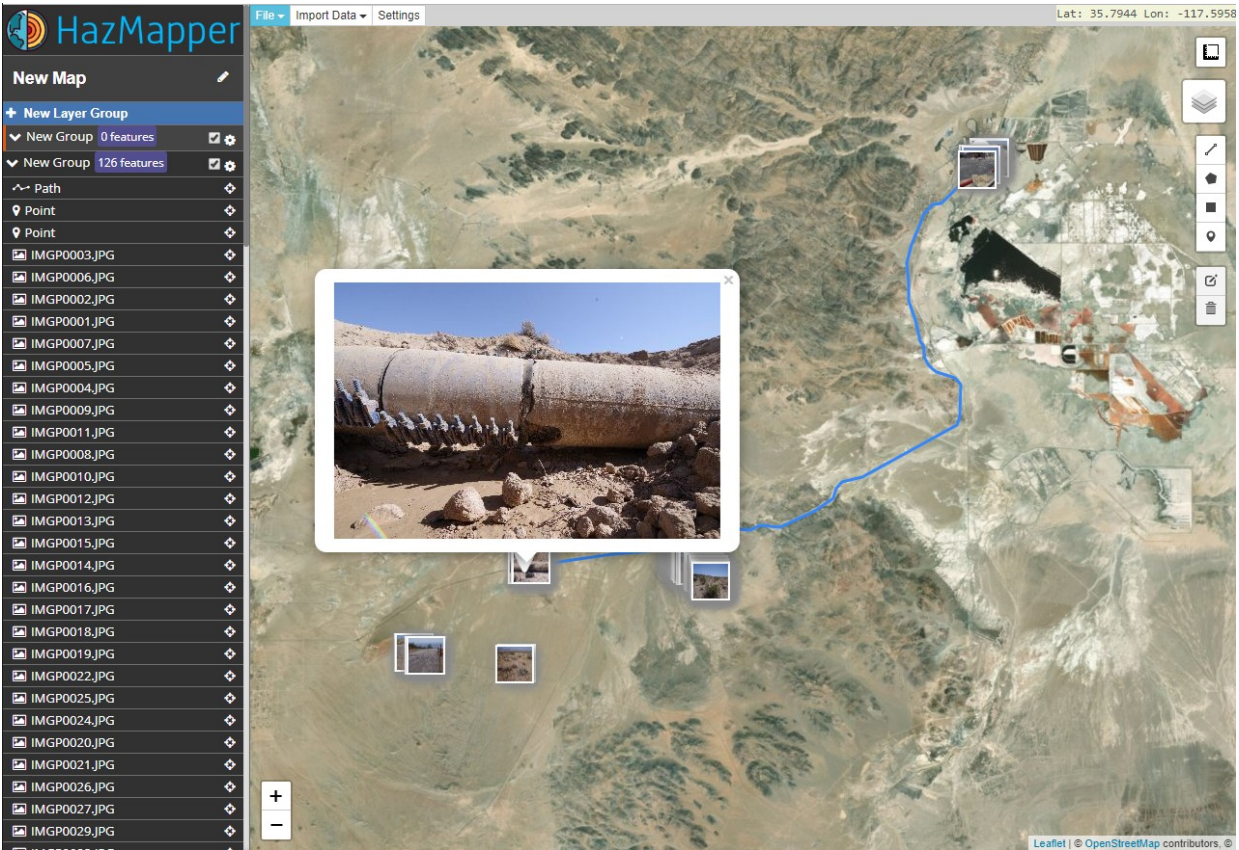


Figure 2. Visualization of “Brandenberg_July_6_2019.geojson” file using the HazMapper tool in DesignSafe.

The collection “QGIS Products” synthesizes information from multiple researchers into a single data object that is also viewable using the QGIS app in DesignSafe. The individual products available in the QGIS Products collection are also available in the individual researcher collections, but we believe that synthesizing these products together into a single collection is

beneficial for data re-use because users can obtain a more immediate understanding of the activities performed by the entire team.

Figure 3 shows measurements of ground cracks at the location where the surface rupture from the **M6.4** event crosses Highway 178. The purple lines were obtained by walking along each visible ground crack while recording a GPS track log, and subsequently importing the track logs to QGIS. These lines were gathered at this location because we observed that the surface rupture was spread over a broad region, with the slip accommodated by many splays. The green lines are transects along which detailed measurements of ground crack position and width were made. Measuring these ground cracks soon after the earthquakes proved to be important because they degraded quickly due to foot traffic, roadway repair efforts, wind-blown sand and dust, and collapse of the soil along the vertical crack walls. These ground measurements also provide an important benchmark against which the resolution and accuracy of Structure from Motion (SfM) and LiDAR point clouds and digital surface models can be evaluated. The ground crack measurements for the M6.4 surface rupture have not yet been processed, and are not included as part of the published dataset at the time of submission of this paper. Once the ground crack measurements are processed, they will be published as part of this project. Highlighted in red in Figure 3 is the region where a water pipe was broken at the locations where it crossed the surface rupture, disrupting water supply to Trona. Repair activities were ongoing during the reconnaissance mission.

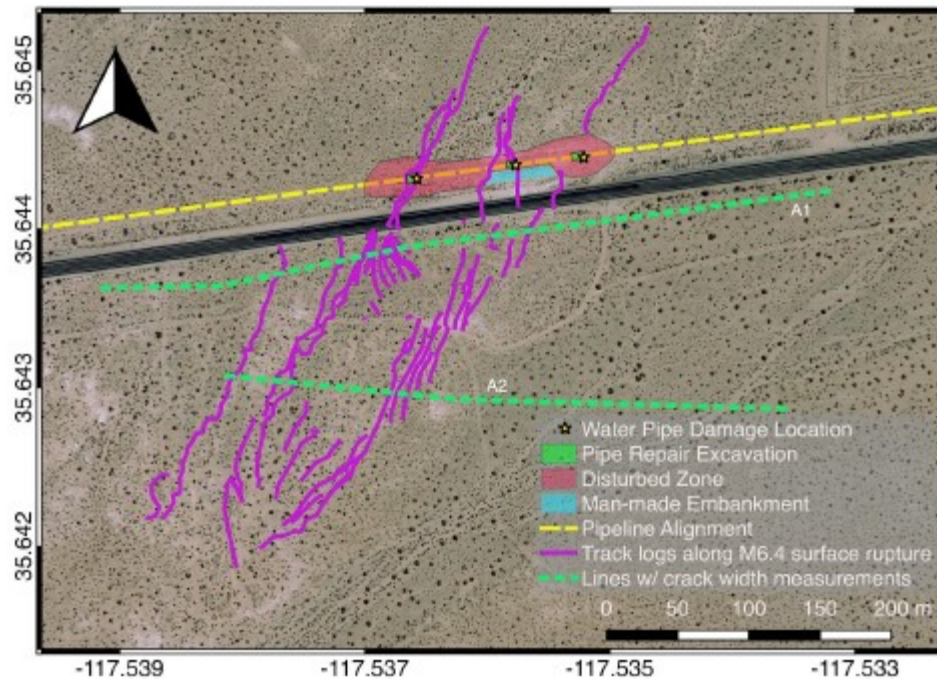
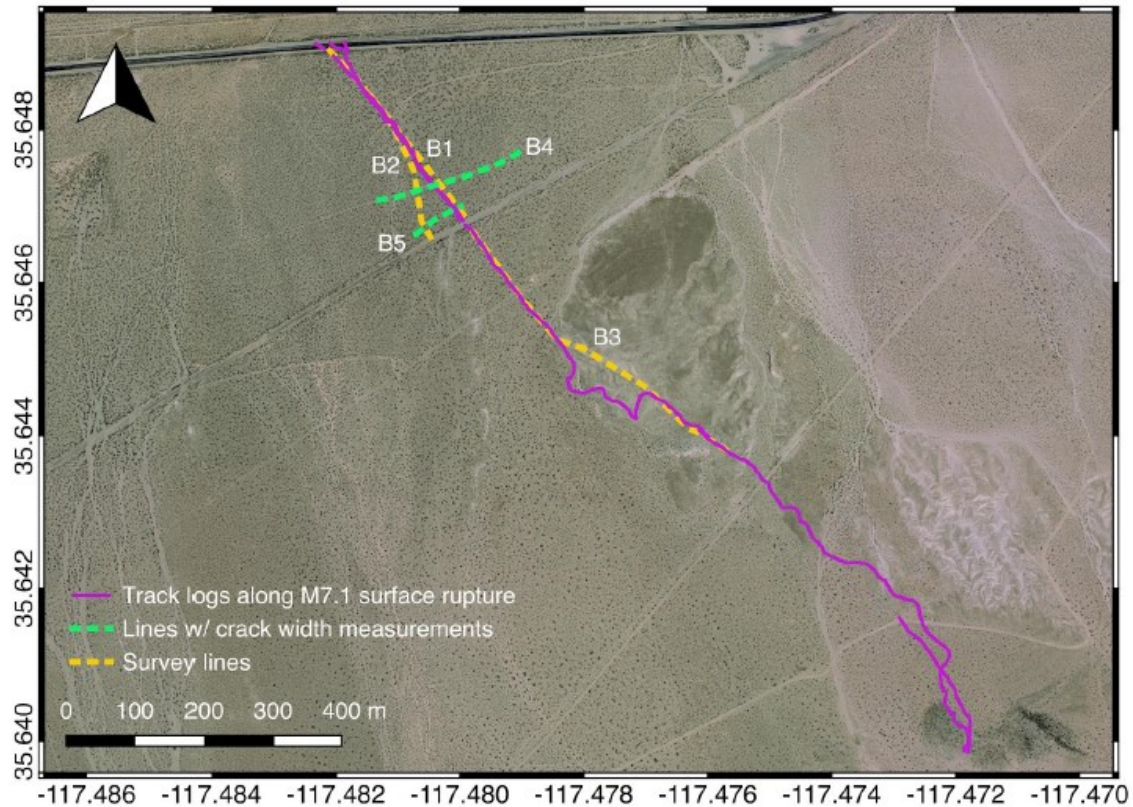


Figure 3. Map showing locations of measured ground cracks at location where **M6.4** fault rupture crosses highway 178 (Stewart et al. 2019).

Figure 4 shows reconnaissance measurements at the location where the surface rupture from the **M7.1** event crosses Highway 178. The **M7.1** surface rupture at this location was concentrated in two main strands, and our efforts focused on characterizing these strands. The purple line is a GPS track log obtained by walking along the surface rupture from Highway 178 toward the southeast. The green lines are transects along which ground cracks were measured. The ground crack measurements for the **M7.1** surface rupture have not yet been processed, and are not included as part of the published dataset at the time of submission of this paper. Once the ground crack measurements are processed, they will be published as part of this project. At location B5, the ground in the extension zone is about 40 cm lower relative to the ground outside the fault strands. The yellow lines are survey lines along which the fault crack

165 widths were measured at regular intervals. Lateral offsets along these survey lines were as
166 large as 40 cm, and crack widths were as large as 50 cm.



167
168 **Figure 4.** Map showing locations of measured ground cracks at location where **M7.1** fault
169 rupture crosses highway 178 (Stewart et al. 2019).

170 UCLA UAV Imaging Mission

171 A DJI (SZ DJI Technology Company, Shenzhen, China) Phantom 4 Pro unmanned aerial vehicle
172 (UAV) with a 20 million pixel camera was used to capture aerial photos of the surface rupture
173 zone east of Ridgecrest, as well as liquefaction features in Trona and Argus areas on July 10th
174 and 11th, 2019. Flight parameters were managed using the DJI GS Pro iOS application wherein
175 the autonomous flight path was based upon user-defined survey extents and a suggested

specified image overlap of 80% (Haala et al., 2013). A Stonex S900A GNSS receiver was used to geolocate ground control points (GCPs) spanning the survey region. GCPs were constructed of 0.3 m x 0.3 m x 1.3 cm ($\frac{1}{2}$ ") plywood with a high contrast (black/white) pattern. GCP locations were recorded in World Geodetic System 1984 (WGS84), UTM Zone 11N using network Realtime Kinematic (RTK) position corrections from Scripps Orbit and Permanent Array Center (SOPAC) base station P618, approximately 100 km away. GCP density ranged from 0.6-1.9 GCP/hectare above the 0.5 GCP/ha recommendation for highly accurate DEM and orthomosaics (Coveney and Roberts, 2017).

Eight flights were conducted (Table 2) on July 10th and 11th. Three flights were flown at the M7.1 rupture location (Figure 1b), three flights at the Trona liquefaction site (Figure 1c) and two at the Argus location (Figure 1c). Ambient temperatures were approximately 40° C and winds calm. Flights were constrained to 55 m above ground level (AGL) and covered approximately 6 ha each. The UAV camera was angled 90 degrees from the flight direction (i.e., perpendicular to the flight path) with the lens facing directly downward for all flights. In flights covering the surface rupture, the UAV was flown in lines parallel to the fault.

Automatic photogrammetric image processing Pix4Dmapper (version 4.4.12, Pix4D S.A., Prilly Switzerland) software and RTK surveyed ground control points (GCPs) were used to generate georectified point clouds, orthomosaics, and digital surface models (DSMs) from UAV data. GCPs were imported into Pix4D, where target centers were manually identified. Pix4D utilizes binary descriptors to photo-match points (Kung et al., 2011). The matched points are then used, along with the image positions and orientations, to obtain georectified three-dimensional coordinates. The point clouds were interpolated to a triangulated irregular network (TIN), and the DSMs and orthomosaics were generated. The DSMs were not filtered for vegetation, vehicles, people or other surface objects. Average ground sampling distance (GSD) range from

200 1.3-1.7 cm. Root mean square error (RMSE) estimates range from 7-13 cm depending on the
201 individual flight (Table 2). The coordinate system is WGS 1984 UTM Zone 11N.

202 **Table 2.** Summary of UAV flights for UCLA UAV Imaging mission.

Flight #	Date	Location	Time (UTC)	Flight Area (ha)	Flight Altitude (m, AGL)	Duration (min)	NTRIP Base	# GCPs	GCP / Hectare	RMSE (cm)	GSD (cm)
1	07/10/2019	M7.1 Rupture	19:30	6.65	54.86	15.5	P618	4	0.60	10.8	1.3
2	07/10/2019	M7.1 Rupture	21:10	6.77	54.89	16.0	P618	6	0.89	10.8	1.3
3	07/10/2019	M7.1 Rupture	23:15	5.56	59.47	10.5	P618	6	1.08	10.8	1.3
13	07/11/2019	Trona	15:35	5.55	54.89	13.0	P618	8	1.44	7.3	1.4
14	07/11/2019	Trona	16:45	6.49	54.89	15.0	P618	9	1.39	7.3	1.4
15	07/11/2019	Trona	18:00	3.11	54.89	8.0	P618	6	1.93	7.3	1.4
16	07/11/2019	East Argus	19:00	5.15	54.89	12.5	P618	7	1.36	7.7	1.4
17	07/11/2019	West Argus	20:05	5.37	54.89	12.5	P618	8	1.49	13.2	1.7

Data from this mission (Winters et al. 2019) are organized into three collections titled “M7.1 Fault Rupture - UAV Survey”, “Argus Liquefaction - UAV Survey”, and “Trona Liquefaction - UAV Survey”. Data included in each collection include the following: (i) a digital surface model (DSM) in .tif format, (ii) an ortho-mosaic image in .tif format, (iii) a point cloud in .las format obtained from SfM processing, and (iv) a folder containing data files to enable viewing the point cloud data using the Potree viewer in DesignSafe. The DSM and ortho-mosaic can be viewed using QGIS in DesignSafe, and Figure 5 shows an example of the DSM viewed in QGIS using the Hillshade rendering option.

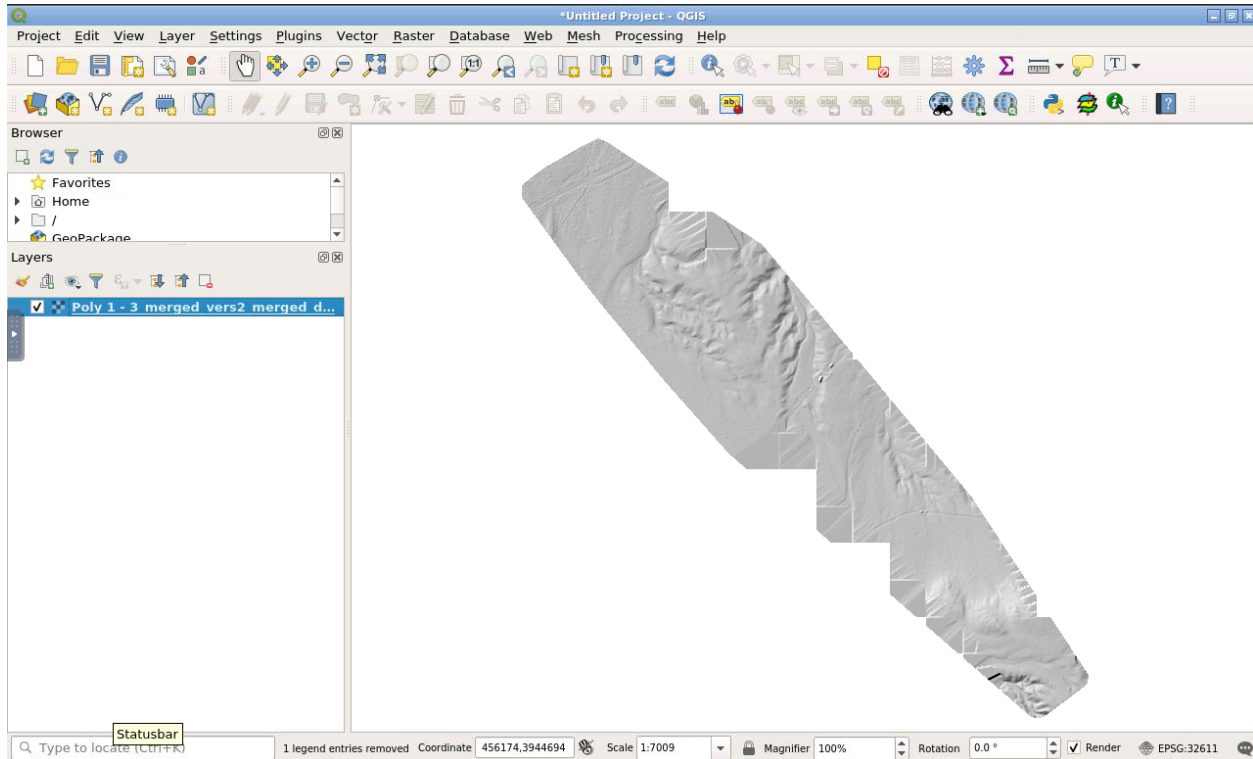


Figure 5. Digital surface model “Poly 1-3_merged_vers2_merged_dsm.tif” viewed in QGIS in DesignSafe.

The Potree point cloud converter in the DesignSafe discovery workspace was utilized to convert all of the .las files into an object that can be viewed using the Potree viewer, also available in the discovery workspace. Figure 6 shows the point cloud from the UAV survey over Trona. Liquefied sand ejected from the subsurface flowed over the parking lot at the Family Dollar store (near left center of Figure 6), and sand boils are visible in the point cloud to the south of Highway 178 in the foreground of the image. Ground cracks and compressional features indicative of liquefaction-induced lateral spreading are also visible throughout the imaged area.

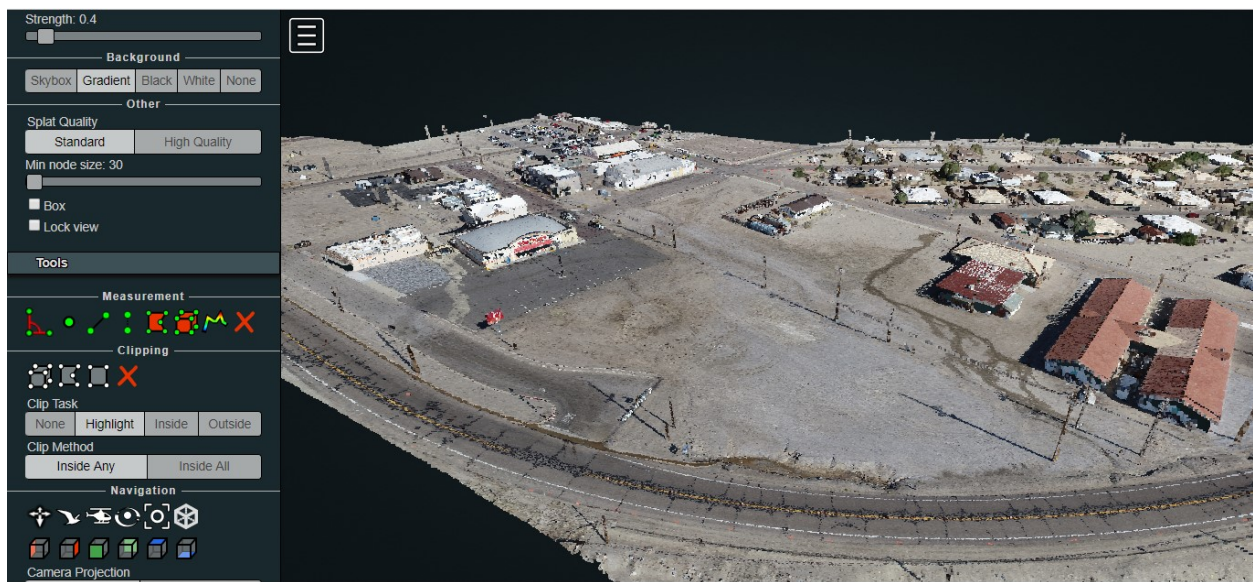


Figure 6. Point cloud “TronaLiquefactionSurvey/point_cloud_potree” viewed using Potree viewer in DesignSafe.

JPL UAV Imaging Mission

Five days after the mainshock, Andrea Donnellan and Gregory Lyzenga of the Jet Propulsion Laboratory, California Institute of Technology performed targeted surveys of the **M6.4** and **M7.1**

228 ruptures based on guidance from Christine Goulet of the Southern California Earthquake
229 Center, University of Southern California and the GEER team (Donnellan et al, 2019, Donnellan
230 et al, submitted). The two locations included a 480 x 410 m area just south of and including
231 Highway 178 over the **M6.4** rupture and a 460 x 640 m area over the **M7.1** rupture, also just
232 south of and including Highway 178 (Figure 1). Double grids were flown on July 9th, 11th, and
233 15th at the **M6.4** and **M7.1** locations, and on July 22nd at the **M6.4** location using a Parrot Anafi
234 vehicle with an integrated 21 megapixel camera and GPS for low accuracy geotagging. Iron
235 cross ground control targets were placed and left at each site and surveyed each visit with a
236 Septentrio Real Time Kinematic (RTK) GPS system. A base station broadcast corrections, so
237 that the ground control points (GCPs) are precise relative to each other. Data are recorded at
238 the base station and later downloaded and processed using the National Geodetic Survey Opus
239 system. Absolute accuracy of the GCPs is ± 2 cm. Point clouds, orthomosaics, 2 cm digital
240 surface models, and quality reports for each survey are posted at GeoGateway under the 3D
241 imaging tab (<http://geo-gateway.org>). We are working to share our products to
242 OpenTopography, DesignSafe, and GeoCollaborate. Figure 7 shows the point cloud for the
243 **M7.1** rupture.

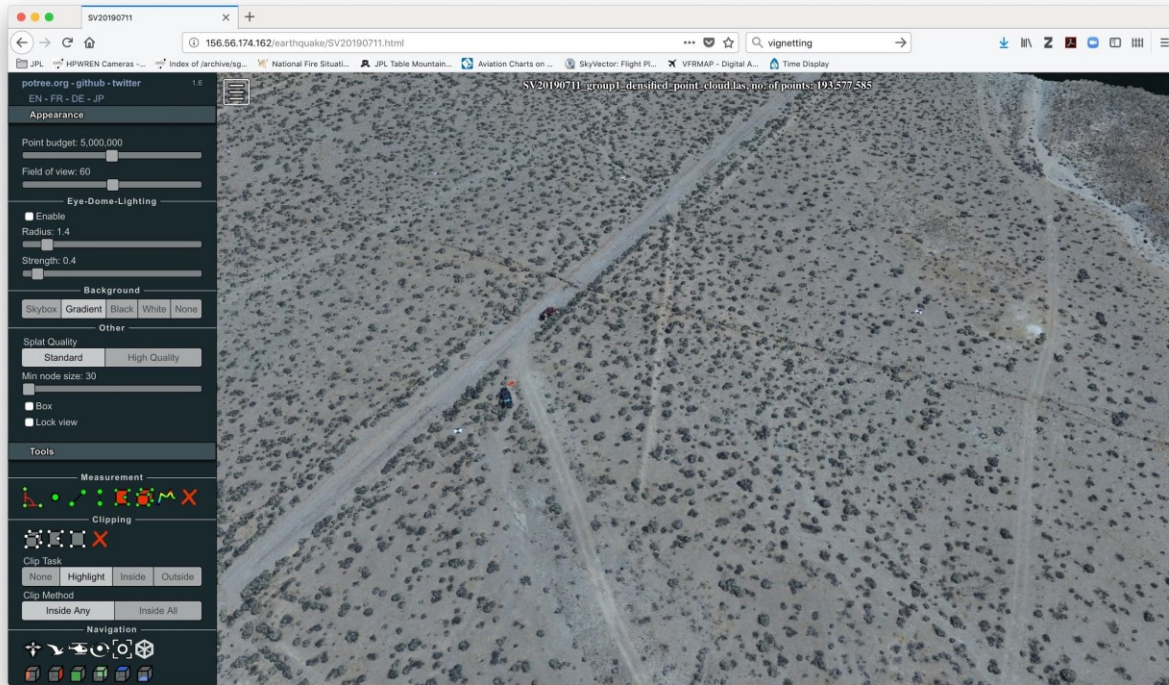


Figure 7. View of **M7.1** pointcloud in Potree from the GeoGateway (<http://geo-gateway.org>) 3D Imaging tab. This oblique view is to the northeast. The **M7.1** rupture can be seen in the image. The fault branches in the right of the image, at the south end of the point cloud.

SCEC Field Reconnaissance Mission

On July 11, 2019, Christine Goulet and Xiaofeng Meng conducted the SCEC Field Reconnaissance Mission to gather additional ground measurements at the location of the **M6.4** and **M7.1** surface ruptures, observe ground cracks near the Trona Pinnacles, and visit Argus and Trona (Goulet and Meng 2019). Observations from this mission are organized into a collection titled “SCEC Recon Observations - Goulet”. Goulet was a member of the GEER team, and observations from this mission are included in the GEER report. However, this mission and

collection use the SCEC title to reflect the primary affiliation of Goulet and Meng. Within the collection are a GeoJSON file titled “SCEC.geojson” that contains all of the geotagged images from the mission, and a zip file containing the full-resolution images from the mission. A screenshot of the GeoJSON file viewed in DesignSafe is shown in Figure 8, along with a photo of a ground crack near the Trona Pinnacles.

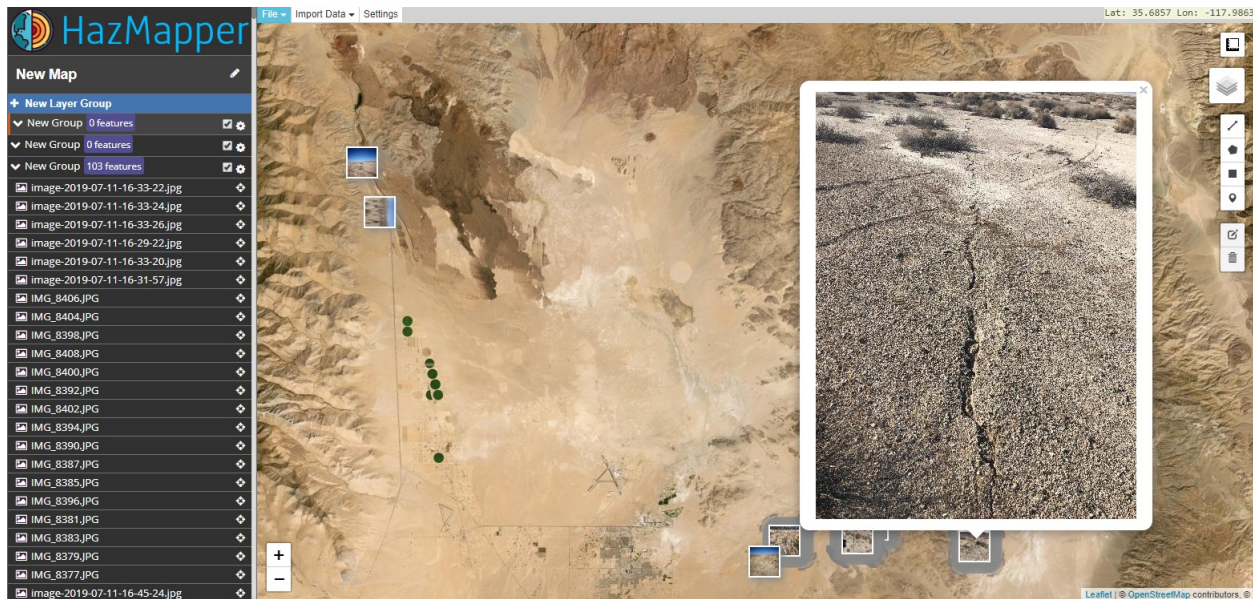


Figure 8. Screenshot from HazMapper showing “SCEC.geojson” file, with reduced-resolution image of a ground crack near the Trona Pinnacles.

UW RAPID UAV Imaging Mission

The RAPID facility is sponsored by the National Science Foundation through the Natural Hazards Engineering Research Infrastructure (NHERI) program, and provides investigators with equipment, software, and support services needed to collect, process, and analyze perishable data from natural hazards events. The RAPID facility is headquartered at the University of

Washington (UW), and is a collaboration between UW, Oregon State University, Virginia Tech, and the University of Florida. Members of the RAPID team, Andrew Lyda and Sean Yeung, conducted the UW RAPID UAV Imaging Mission on July 16-18 with help from UCLA students Tristan Buckreis, Omar Issa, and Zhengxiang Yi. Aerial imagery was gathered using a DJI Matrice 210 UAV with ground control provided by a Leica GS18 in base rover setup. A total of 10 separate polygons were flown over the **M6.4** surface rupture, and aerial imagery was processed in five batches titled “Ridgecrest1” through “Ridgecrest4” for the area south of Highway 178, and titled “Highway178” for the polygon near the highway. Data from this mission (Lyda et al. 2019) are organized in DesignSafe into a collection titled “M6.4 Fault Rupture - UAV Survey”. Data products available for each processing batch from this mission include (i) a digital surface model in .tif format, (ii) an ortho-mosaic in .tif format, (iii) a point cloud in .las format, and (iv) a folder for each point cloud created using the Potree Converter in DesignSafe. Figure 9 shows a point cloud for the **M6.4** surface rupture at a location where the road is being repaired.



Figure 9. Screenshot of point cloud “M6.4_Ridgecrest1_point_cloud_for_potree” showing location where **M6.4** surface rupture crosses a rod that is being repaired.

Conclusions

This paper presents ground deformation data collected by the Geotechnical Extreme Events Reconnaissance (GEER) team following the 2019 Ridgecrest earthquake sequence. Five separate missions were performed to collect data using GPS trackers, digital cameras, hand-held measuring devices, and unmanned aerial vehicles equipped with digital cameras. The GEER team published their report within two weeks of the **M7.1** mainshock event. This paper presents the data that have been published in the time since the GEER reports were released. All of the data presented in this paper are publicly available through the five digital object identifiers in Table 1. In addition to making the data available, resources are also available for users to interact with the datasets in the cloud. The following apps available in the DesignSafe discovery workspace can be used to interact with the data: HazMapper can be used to view the GeoJSON files, QGIS can be used to view the mapping products synthesized from numerous different researchers, and the Potree viewer can be used to visualize point clouds produced from UAV Structure from Motion surveys. The Potree viewer is also available in the GeoGateway site where the JPL UAV Imaging data are located. Our intention is that other researchers will be able to access the data resources presented herein, and integrate the data into their own workflows to learn about ground deformations from the Ridgecrest earthquake sequence.

305 Data Resources

306 The data presented in this paper are publicly available, and have been assigned a digital object
307 identifier, as summarized in Table 1.

308 Acknowledgments

309 The work of the GEER Association, in general, is based upon work supported in part by the
310 National Science Foundation through the Geotechnical Engineering Program under Grant No.
311 CMMI-1826118. Any opinions, findings, and conclusions or recommendations expressed in this
312 material are those of the authors and do not necessarily reflect the views of the NSF. Any use of
313 trade, firm, or product names is for descriptive purposes only and does not imply endorsement
314 by the U.S. Government. The GEER Association is made possible by the vision and support of
315 the NSF Geotechnical Engineering Program Directors: Dr. Richard Fragaszy and the late Dr.
316 Cliff Astill. GEER members also donate their time, talent, and resources to collect time-sensitive
317 field observations of the effects of extreme events. Sponsorship of this GEER deployment was
318 also provided by the Natural Hazards Risk and Resilience Research Center (NHR3), the
319 Southern California Earthquake Center, and the NASA Jet Propulsion Laboratory. Portions of
320 this work were carried out by the Jet Propulsion Laboratory, California Institute of Technology
321 under contract with NASA. The authors would like to thank the following individuals for their
322 support during the various GEER missions: Shawn Barker (Shawn Barker Construction, Argus,
323 CA), Priscilla Benadom (Trona resident), Dale Fuller (Ridgecrest resident), Raymond Becker
324 (Searles Valley Domestic Water), Ken Santini (Santini & Associates, Tucson, AZ), Albert Kottke
325 (PG&E), Jeff Keaton (Wood.), Wyatt Iwanaga (Wood.), Chris Madugo (PG&E), David Frost
326 (Georgia Tech), Fangzhou (Albert) Liu (Georgia Tech), Niket Agrawal (Ridgecrest Super 8),
327 Pinkal Panchal (Ridgecrest Super 8), and Gabriel Martinez (Ridgecrest Super 8).

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