3 SURFACE FAULT RUPTURE ASSOCIATED WITH THE M6.0 SOUTH NAPA EARTHQUAKE OF AUGUST 24, 2014

Tim Dawson (CGS), Keith Kelson (USACE), John Wesling (OMR), Ken Hudnut (USGS), and Dan Ponti (USGS)[1]

3.1 Introduction

The M6.0 South Napa earthquake of August 24, 2014 was the first earthquake in the San Francisco Bay Region (SFBR) to produce significant, through-going surface rupture since the 1906 San Andreas Fault earthquake and the first earthquake in northern California to rupture through a densely populated area. The South Napa earthquake rupture affected residential structures, roads, and lifelines, and provides information on the possible effects of future surface-rupturing earthquakes on other faults in the region. The occurrence of surface rupture within the densely populated SFBR prompted a large number of earth scientists representing government, academia, and the private sector to document the rupture in the hours and days immediately after the main shock. This summary report documents some of the key observations made by these workers following the earthquake.

Surface rupture associated with the South Napa earthquake occurred on parts of the West Napa fault, a zone of discontinuous faults that extends from American Canyon to the north along the west edge of Napa Valley, and is thought to be a relatively minor strike-slip fault within the system of northwest-trending dextral faults in the SFBR (Figure 3-1). The surface rupture extends approximately 12 to 15 km from the town of Cuttings Wharf in the south to beyond the northern boundary of Alston Park in the city of Napa, in the north (Figure 3-2). The surface rupture is expressed largely to the west of most mapped Quaternary traces of the West Napa fault, and is only coincident with the western-most previously mapped trace of the West Napa fault zone, which is depicted in the U.S. Geological Survey (USGS) Quaternary Fault and Fold Database (Bryant, 2000) as a 4 km long, northwest trending fault and assigned a Late Quaternary age.

Field reconnaissance began almost immediately following the earthquake; some observations of surface deformation were made within 2.5 hours of the main shock. As of September 12, 2014, field teams were still evaluating the extent of rupture in the north, so the total rupture length is not yet known precisely. Most ruptures were located by the field teams driving roads across the area, looking for disrupted or offset cultural features and then following those features into areas on either side of the road. Also, several aerial overflights were completed along the rupture and adjacent areas; the overflights were accomplished via helicopter as part of the California Highway Patrol (CHP) earthquake response. Field teams were later aided in their search for surface rupture by the acquisition of Synthetic Aperture Radar (SAR) data, initially by satellite-based COSMO-SkyMed (X-band) interferograms using data provided especially by the Agencia Spaziale Italiana and prepared by scientists of NASA's Jet Propulsion Laboratory (JPL) and the Advanced Rapid Imaging and Analysis (ARIA) Center for Natural Hazards, and a week later by L-band interferograms from NASA/JPL's airborne uninhabited aerial vehicle system acquisition system, UAVSAR and the European Space Agency's C-band satellite, Sentinel-1A. These images revealed additional lineaments, formed by discrete line-of-sight changes between pre- and post-earthquake missions. Many of these lineaments have been verified in the field (Figure 3-3).

[1] Agency Abbreviations: California Geological Survey (CGS), United States Army Corps of Engineers (USACE), California Office of Mine Reclamation (OMR), United States Geological Survey (USGS)

Other lineaments observed from the UAVSAR imagery most recently still need to be field checked, and those lineaments initially field checked and/or thought to be connected to mapped tectonic ruptures are shown on Figure 3-2.

Displacements along the surface rupture are predominantly right-lateral and amounts are variable along strike, both in the near-field (on the order of tens of meters perpendicular to strike), as well as along the entire length of the rupture, as shown on Figure 3-4. The rupture is highly variable in terms of expression at the surface, but is typically expressed as a zone of *en echelon* left-stepping fractures (Figure 3-5) varying from less than a meter in width to tens of meters, or more, wide. The expression of surface rupture varies where the fault crosses paved roads, in some cases being complex, with some fractures oriented nearly orthogonal to the orientation of the fault trace (Figures 3-6a-b) and others oriented along strike.

The following sections summarize the key observations of surface rupture related to this earthquake collected by the field teams, although we note that this is still largely a work in progress, as field teams are still in the area mapping the details of the rupture and filling in gaps.

3.3 **Cuttings Wharf to Congress Valley Road**

The epicenter of the M6.0 main shock is located near Cuttings Wharf and nearly continuous surface rupture was mapped for about 7 km from the west bank of the Napa River, at Cuttings Wharf, to Congress Valley Road. In the area north of Cuttings Wharf, the fault trends about 340°, crossing numerous vineyards that provide abundant opportunities to collect offset data along the rows of grapes. Measureable lateral displacements along this stretch of the rupture are typically in the 20-25 cm range (Figure 3-7), but there are right-lateral displacements as high as 40-45 cm measured between Henry and Congress Valley Roads. The surface rupture through alluvium, colluvial deposits and agricultural fields is notably wider than that observed across asphalt roads, and the amount of surface offset recorded by vineyard rows appears greater than that recorded by roadway asphalt.

3.4 **Congress Valley Road to Browns Valley**

Near the intersection between Buhman and Congress Valley Roads, surface rupture has not been completely mapped, although surface rupture in the area has been inferred based on a lineament interpreted from the UAVSAR. To the north the rupture is strongly expressed on the Buhman Ranch Property, west of Buhman Road (Figure 3-8), with right-lateral offsets in the range of 40-45 cm.

3.5 **Browns Valley to Alston Park**

Within Browns Valley, fault offset is in the range of 10 – 20 cm (Figure 3-3), as the fault steps to the east. The Browns Valley area is developed, consisting largely of residential units, and the fault cuts numerous cultural features including roads, sidewalks and residential structures (Figures 3-9). At the latitude of Browns Valley Road, a subparallel, northwest trending fault (herein referred to as the Eastern Strand) is approximately 500 meters east of the principal rupture (labeled Western Strand on Figure 3-2), and has a subordinate amount of right-lateral displacement, typically 2-8 cm (Figure 3-10). North of Browns Valley, the eastern and western strands merge in the vicinity of the Hendry Winery, located south of Alston Park. The northern end of the field-verified rupture has been traced as far as the northern boundary of Alston Park (Figure 3-11), and likely continues for a least several kilometers more, which will be confirmed as field teams continue to map the rupture.

On the eastern strand, rupture was verified as far south as Browns Valley Road. South of Browns Valley Road, limited access has hindered field teams in verifying the rupture trace, although a lineament interpreted from the UAVSAR, appears to connect surface deformation on the eastern strand to rupture observed in the vicinity of Thompson Road. Near Thompson Road, the rupture is mapped through a residential neighborhood crossing Thompson and Congress Valley Roads, before going into areas that are predominantly vineyard. In the vicinity of Thompson Road, the rupture is weakly expressed in soil, but shatters asphalt driveways (Figure 3-12), illustrating the variation in response to surface rupture of different materials even at apparently very small total offsets (these were not easily measureable, but likely < 5 cm).

3.6 **Southeast of Napa River: Napa County Airport**

South of Cuttings Wharf, previously mapped traces of the West Napa fault step about 2 km to the east, and trend from the Napa County Airport to the southeast through American Canyon. Minor surface rupture and offset was observed on Taxiways “C” and “E” at the Napa County Airport, expressed as warping and left-stepping, *en echelon* cracking in the asphalt, suggestive of right-lateral movement (Figure 3-13). The surface rupture is coincident with the mapped trace of the West Napa fault (Bryant, 2000; Wesling and Hanson, 2008), which is expressed at the airport as a low scarp and is visible in aerial imagery as a vegetation lineament adjacent to the taxiway (Figure 3-13). At the time of this writing, the origin of the airport deformation is not known, and could be related to either surface rupture or triggered slip. On August 27, 2014, evidence of surface rupture or triggered slip was not present across Green Island Road, or across features south of Green Island Road. An aerial overflight on August 27 showed an absence of perceptible ground cracking along the eastern banks of the Napa River, south of Green Island Road. Subsequent analysis of the UAVSAR data suggested the presence of possible surface deformation in this area, but this has not yet been field checked.

3.7 **Afterslip Observations**

Afterslip was documented within the first 24 hours and was expressed as the continued development of the rupture on the ground and the growth through time of observed offsets on roads and other cultural features (Figure 3-14). The USGS was able to establish four alignment arrays across the fault in order to monitor afterslip. Although results are not yet available, based on episodic field observations, afterslip appears to be common in the primary, 7-km-long epicentral part of the rupture. Little to no offset was observed within a few hours of the main shock at some locations that exhibited as much as 20 cm of right-lateral slip 48 hours after the mainshock. From qualitative observations made by the field teams, the majority of afterslip occurred within about 36 to 48 hours of the main shock, and the amount of afterslip was probably in the range of about 30 - 60% of the total slip. Additional time-series analyses of imagery and digital topographic data, using repeat mobile LiDAR, campaign and continuous GPS data acquired by the USGS, may provide information to define the pattern, timing, and amount of afterslip along the various sections of the surface rupture.

3.8 **Discussion**

The 2014 South Napa earthquake was notable as M6.0 earthquake with complex pattern of surface faulting that involved multiple fault strands over a length of about 12 to 15 km. Further, the maximum net surface offset of about 45 cm, is somewhat atypical for this magnitude. The surface rupture pattern corresponds to seismological interpretations of a south-to-north rupture of a very steeply west-dipping fault, and the maximum surficial displacement measured north of Henry Road, ~45 cm, spatially correspond with a zone of high subsurface slip in the preliminary finite fault models (USGS, 2014). Fundamental questions regarding the causative fault for this earthquake relevant for basic seismic hazard parameters such as slip rate, recurrence, timing of past events, are unknown at this time. Investigations into this earthquake are ongoing and much work still needs to be done in order to fully document the extent, complexity, and surface offsets produced by this earthquake, as well as basic data that feeds into regulatory zone and seismic hazard maps.

This earthquake offers a rare opportunity to study the effects of surface rupture using modern techniques such as aerial and ground based LiDAR, Structure from Motion (SfM) imaging, and various SAR techniques, all of which were deployed by various groups following this earthquake. These techniques will likely offer an unprecedented look into the effects of surface rupture and near-field ground deformation across the fault. Given the dense array of cultural features and new technological advancements, this earthquake rupture will provide much insight into the effects of surface rupture on the built environment and inform engineers regarding mitigation of surface rupture hazard imposed by active faults.

References

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Contributors

Nikita Avdievitch (USGS)
Mike Bennett (USGS)
Dave Branum (CGS)
Jonathan Bray (UCB)
Ben Brooks (USGS)
Cooper Brossy (Fugro)
Bill Bryant (CGS)
Mike Buga (Fugro)
Julien Cohen-Waeber (UCB)
Brian Collins (USGS)
Clif Davenport (CGS)
Tim Dawson (CGS)

Marc Delattre (CGS)
Steve DeLong (USGS)
Andrea Donnellan (NASA JPL)
Todd Ericksen (Univ. of Hawaii)
Eric Fielding (NASA JPL)
Margaret Glasscoe (NASA JPL)
Craig Glennie (Univ. of Houston)
Wayne Haydon (CGS)
Les Harder (HDR)
Suzanne Hecker (USGS)
Chris Hitchcock (InfraTerra)
Tom Holzer (USGS)
Ken Hudnut (USGS)
Michael Jewett (Miller Pacific)
Keith Kelson (USACE)
Jeremy Lancaster (CGS)
Jim Lienkaemper (USGS)
Andy Lutz (InfraTerra)
Max Mareschal (CGS)
Alexander Morelan (UC Davis)
Mike Oskin (UC Davis)
Susan Owen (NASA - JPL)
Jay Parker (NASA – JPL)
Ante Perez (CGS)
Alexandra Pickering (USGS)
Dan Ponti (USGS)
Carol Prentice (USGS)
Jared Pratt (RGH Consultants)
Cindy Pridmore (CGS)
Ron Rubin (CGS)
Carla Rosa (USGS)
David Schwartz (USGS)
Gordon Seitz (CGS)
Robert Sickler (USGS)
Mike Silva (CGS)
Nicholas Sitar (UCB)
Jenny Thornburg (CGS)
Jerry Treiman (CGS)
John Tinsley (USGS)
David Trench (Fugro)
Chad Trexler (UC Davis)
Donald Wells (AMEC)
John Wesling (State of California, Office of Mine Reclamation)
Mark Wiegers (CGS)
Sang-Ho Yun (NASA - JPL)
Dana Zaccone (GeoVit)

Figures:

Fig. 3-1 Map showing historic and Holocene mapped traces of the various right-lateral branches of the San Andreas Fault system. Red lines are historic surface ruptures, orange lines are Holocene faults. Those traces recently activated in association with the M 6.0 South Napa earthquake have been added, and are included as an update to previously mapped faults for the region. Faults from USGS Quaternary Fault and Fold Database, base from U.S. Geological Survey.

Figure 3-2. Map showing location of observed and inferred South Napa Earthquake fault rupture. Note: Due to scale issues, not all roads and place names listed in text are labeled. Readers are encouraged to use published road maps and online map resources for locating place names not included on Figures 3-2 and 3-4. Image base from Google Earth.

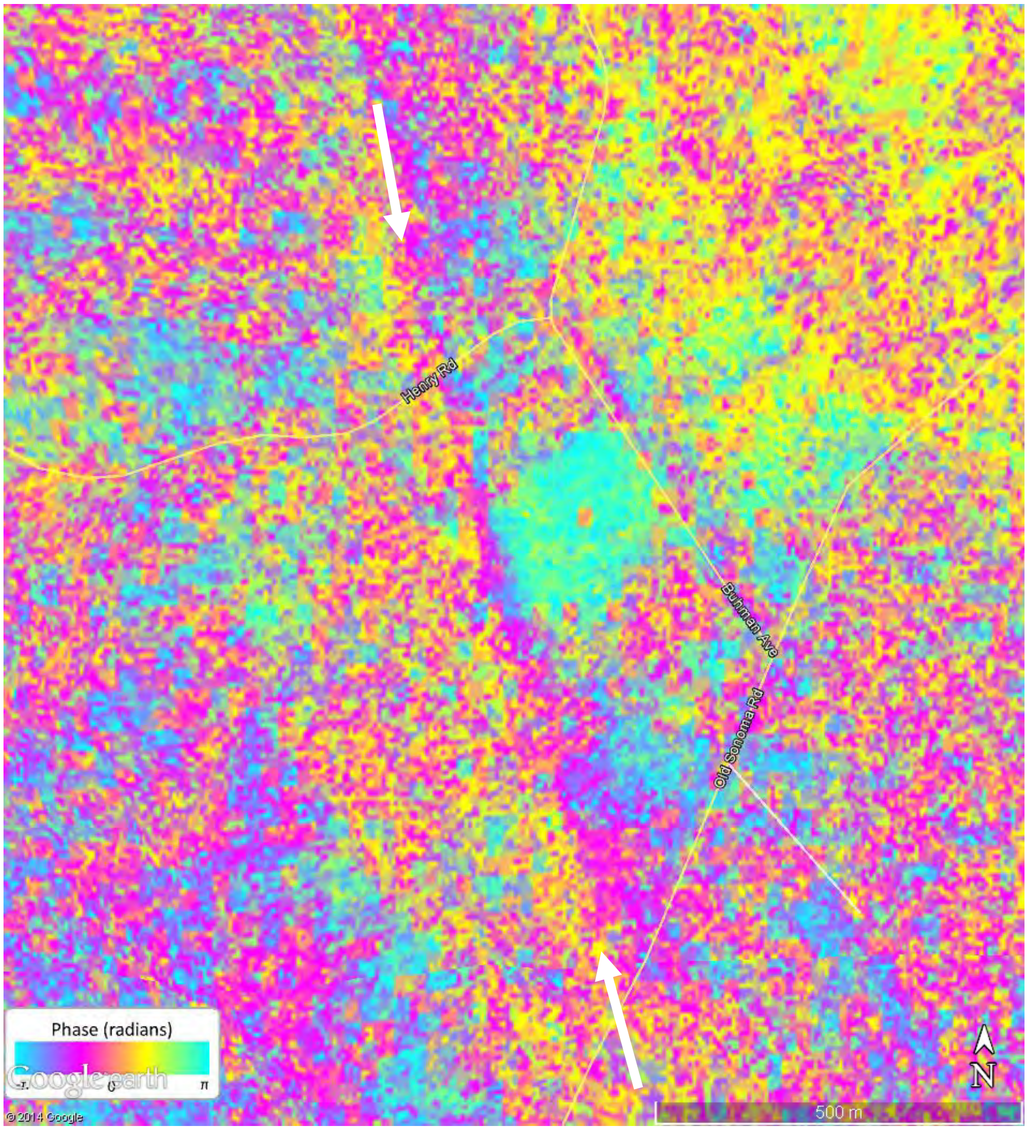

Figure 3-3. Image showing lineament observed on UAVSAR (denoted by white arrows) coincident with surface rupture in the vicinity of Old Sonoma and Henry Roads (UAVSAR image provided by NASA/Jet Propulsion Laboratory, California Institute of Technology).

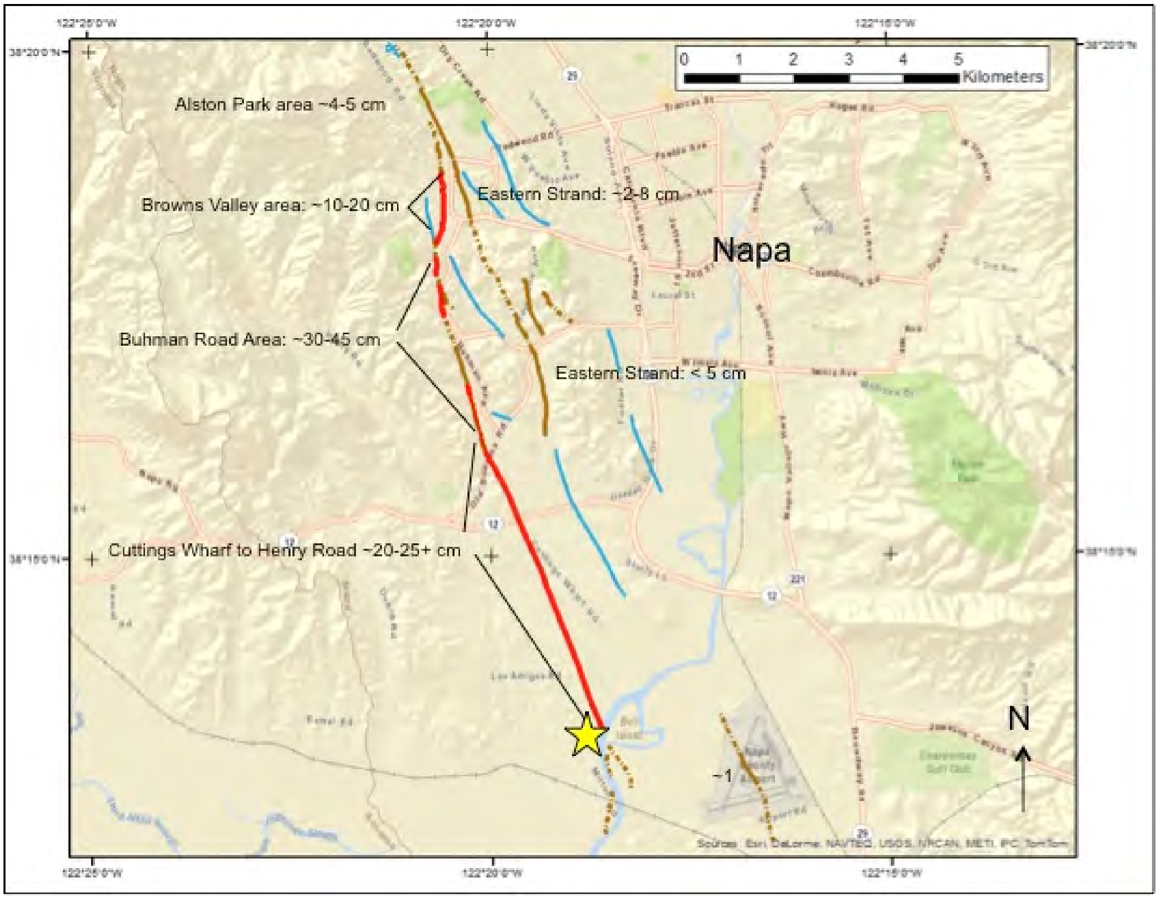

Figure 3-4. Map showing generalized right-lateral offsets along the surface rupture (in cm), measurements may include afterslip. Ruptures shown as red and brown lines, brown lines show areas of lesser, or distributed slip, or areas not yet field verified, but are likely areas of rupture, based on UAVSAR. Blue lines are lineaments identified from UAVSAR, and are still being field verified. Star shows approximate location of epicenter. Note how the surface rupture is located at, and north of the epicenter, and that the majority of the rupture involves about 20 to 25 cm of right-lateral offset at the surface, with slip decreasing in the vicinity of Browns Valley as the fault steps to the east.

Figure 3-5. Left-stepping pattern of surface fault rupture crossing horse corral near Cuttings Wharf Road. Note variation in width of zone. Offset at this location was initial on the order of ~10 - 20 cm, although offsets later grew due to afterslip. [NSF-GEER; GPS: 38.2555°, -122.3270°; 08/24/2014]

3-6a 3-6b

Figure 3-6a-b. Photos showing complexity of surface rupture as it crosses paved roads: 3-6a shows a broad zone, with fractures oriented nearly orthogonal to trend of fault at Middle Avenue [NSF-GEER; GPS: 38.2517°, -122.3251°; 08/24/2014]. The expression in 3-6b is narrower and fault-parallel, located where fault crosses Los Carneros Ave [NSF-GEER; GPS: 38.2431°, -122.3207°; 08/24/2014].

Figure 3-7. Surface fault rupture at northern part of Clos du Val Vineyard near 2121 Buhman Avenue (6.7 km NW of epicenter), showing measurement alignment along azimuth 090. Yellow engineer's scale shows measurement of 40 to 45 cm from base of thick wooden post; tape placed along southern edge of wooden posts aligned on east side of fault zone. [NSF-GEER; GPS 38.2776, -122.3377; 08/25/14: kik027]

Figure 3-8. Rupture west of Buhman Avenue. Right-lateral displacement was on the order of 40 cm, with a small amount (~12 cm) of up-on-the-west vertical displacement. [NSF-GEER; GPS: 38.2924°, -122.3432°; 08/25/2014]

Figure 3-9. Surface rupture disrupting sidewalks and curb on Twin Oaks Drive in Napa. Right-lateral displacement was on the order of 10 – 20 cm at this location [NSF-GEER; GPS 38.3024°, -122.3438°; 08/26/2014]

Figure 3-10. Surface rupture forming moletrack on asphalt road, tented concrete curb and displaced sidewalk in right-lateral sense on Partrick Road along eastern strand of the surface rupture. Right-lateral offset is on the order of between 5 - 10 cm. [NSF-GEER; GPS 38.3069°, -122.3374°; 08/24/2014]

Figure 3-11. Surface rupture near northern boundary of Alston Park. Note left-stepping pattern of extensional cracking, suggestive of right-lateral displacement, which was about 4-5 cm at this location. [NSF-GEER; GPS 38.3263°, -122.3459°; 09/01/2014]

Figure 3-12. Shattering of asphalt along southern part of eastern strand on driveway near Thompson Road. Rupture was difficult to see in soil on either side of driveway, but obvious on asphalt. Right-lateral offsets were around 5 cm in this area, although difficult to measure at this location [GEER-NSF; GPS: 38.2866°, -122.3259°; 8/25/2014].

Figure 3-13. Left-stepping en-echelon fractures without measurable displacement but of likely tectonic origin observed crossing only one of several runways at the Napa County Airport and located on the previously mapped section of the West Napa fault. Note vegetation lineament in grass, on trend with cracks on taxiway. [NSF-GEER; GPS: 38.2127°, -122.2814°; 8/27/2014].

Figure 3-14. Offset painted stripe on the side of Highway 12 is shown by these two photos taken approximately 24 hours apart on Aug. 24, 2014 and Aug. 25, 2014. The fracture opening is narrower and the paint stripe offset by a lesser amount on the day of the earthquake. During the ensuing day, the fracture grew and the offset of the paint stripe increased. The increase of offset along the surface rupture of an earthquake has been observed in previous earthquakes. What is different in the case of the South Napa earthquake is that in this case, afterslip in the first day after the earthquake was rapid, but then afterslip appeared to stop in the following days. In the southern half of the surface rupture zone, the initial evidence for rapid afterslip was pronounced, whereas in the northern portion there was little to no afterslip [NSF-GEER; GPS: 38.2559°, -122.3272°; 08/24/2014 and 08/24/2014.

Appendix B

The intent of this appendix is to provide a forum for the contributors to this report a place for additional figures, observations, and interpretations collected in the field not included in Section 3. The appendix sections are organized by field team and include additional figures and downloadable files. For further information regarding the individual subsections, please contact the field team lead.

Appendix B-1: Kelson and Wesling Detailed Observations
Appendix B-2: Fugro observations
Appendix B-3: U.C. Davis observations, made available on SCEC Earthquake Response site via Dropbox: https://ucdavis.app.box.com/s/9zsz84638fp90grhikzx