Report on SCEC 2013 funding, project 13151

Renewed Investigation of the Hector Mine Earthquake Surface Rupture with multi temporal field and LiDAR data

Proposal Category A: Data Gathering and Products
Focus areas: Earthquake Geology, Fault and Rupture Mechanics

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Technical Report

Summary

Our 2012 and 2013 SCEC projects provide new insight on the rupture zone of the Mw 7.1 Hector Mine earthquake, Mojave Desert, California, using two sets of LiDAR data (collected in 2000 and 2012), post-earthquake aerial photography, new field work, and new aerial imagery (Fig. 1). This earthquake produced a 48 km long surface rupture with up to 5.2 m of right lateral slip, measured by field geological investigations shortly after the earthquake (Treiman et al, 2002).

Using the 2012 LiDAR data we made a ~0.35 m DEM over a ~1 km wide swath along the entire length of the rupture (Sousa et al., 2012a). We used this for comparison with the 2000 LiDAR data and for planning for the field work. The data analysis in 2012-13, performed by graduate student Francis Sousa, concentrated on selected areas of the fault zone. We first examined a 2 km long focus zone of the Lavic Lake fault that contains both the maximum horizontal offset measurements from field study and April 2000 LiDAR DEMs and the highest density of April 2000 LiDAR DEM offset measurements. We then examined other regions such as Lavic Lake. Subtraction of congruent 0.5 m DEMS made from the 2000 and 2012 point cloud data yielded a new raster showing specific and quantifiable areas of erosion and aggradation.

Some of our major findings can be summarized as:

- Large-magnitude slip variability (over 1m difference) within short distances (less than 0.5 km) is clearly identifiable within certain parts of the maximum slip zone. This was suggested by the interpretation of the year 2000 LiDAR data (Chen et al., 2013) and was borne out by the analysis of the 2012 LiDAR data and the 2012 field work.
- Ground-truthing of LiDAR offset measurements from the year 2000 and 2012 data sets (Chen et al., 2013; Sousa et al., 2012b) has clarified the validity of individual measurements made in geomorphically complicated locations, and reinforced the need for complementary field observations such as differences in weathering of surfaces.

- Identification of two new maximum slip locations where features are offset 7.9 m /- 0.5 m (Figure 2) and 6.7 m /- 0.5 m;
- A database of >30 offset measurements (georeferenced and photo documented) made by our team on the ground;
- Clear changes in fracture visibility in the field, with some fractures more visible, and others no longer visible, compared to the 1999-2000 studies; and
- Examples of a few field checks that both strongly agree and disagree with computer based LiDAR offset measurements.
- Our final product will be a surface rupture map showing what can be seen now in the field (over a decade after the earthquake) based on our field work and the LiDAR data analysis.

LiDAR data analysis.

The 2012 LiDAR data were used to produce a ~0.35 m DEM over a ~1 km wide swath along the entire length of the rupture. The data analysis in 2012, performed by graduate student Francis Sousa, concentrated on selected areas of the fault zone, including the section with highest reported slip along the Lavic Lake fault and the region to the north where we were given permission to conduct field investigations.

Topographic features that were offset along the fault trace were identified, and their displacements measured from the 2012 LiDAR data using LaDiCaoz software (Zielke and Arrowsmith, 2012). These were then compared to the displacements determined by Chen et al. (in revision) from the April 2000 LiDAR data. In roughly half of the locations, the same geomorphic features used to measure offset in the April 2000 data are clearly identifiable in the 2012 data (e.g. Figure 3). In other locations the features are no longer preserved; this was verified by the field work discussed in the next section of this report.

Subtraction of congruent 0.5 m DEMS made from the 2000 and 2012 point cloud data enabled us to identify areas of erosion and aggradation in this arid setting. Rapid quantification of this decadal change will ultimately help us model the surface processes that lead to such changes and help us better understand the controlling mechanisms. A comparison of part of the April 2000 and May 2012 data can be visualized in a video animation that we posted at http://www.youtube.com/watch?v=SB5iuSD7Z0c . This animation shows the fault scarp evolution, fading between 3D visualizations of LiDAR derived DEM's from the April 2000 and May 2012 LiDAR scans. View is just West of North from 34.55° N, 116.2645° W. Erosion in the main channel (foreground) actively incises the 1999 Hector Mine surface rupture scarp.

Field work.

We conducted field work in fall 2012, on dates and in locations authorized by the US Marine Corps Air Ground Combat Center (US MCAGCC) at Twentynine Palms. Personnel who participated at different times in the field observations were Stock, Akciz, Hudnut, and Sousa, as well as Kate Scharer (USGS), Katherine Kendrick (USGS) and Janet Harvey (a Caltech graduate student). We were able to access more than half of the length of the rupture, including the central high-slip region of the fault in the Bullion Mountains and its northward continuation from the range front into Lavic Lake (Fig. 1). Principal field activities included 1) re-observing, wherever possible, features whose offsets had been originally reported by Treiman et al. (2002) or by others in the field in 1999; 2) identifying and measuring additional offset features; 3) evaluating geomorphic features whose offset and uncertainties had been obtained from analysis of the 2012 LiDAR data set; 4) mapping the fault traces to within ~0.1 m horizontal location accuracy using hand-held GPS (Trimble GeoXH); 5) photodocumenting the details of the rupture and evaluating its state of preservation and the geomorphic changes that had taken place. Some of the original field notes from the 1999 studies had been collected by Jerry Treiman and by Katherine Kendrick, who provided them to us so that we could identify sites of original measurements.

We evaluated both the nature of the scarp and features that could be used to determine fault offset. The scarp was still excellently preserved in the bedrock (Bullion Mountains) sector but less so in Lavic Lake and on the alluvial fan to the south of the lake. There, the original fault scarps could generally be found and tracked with the GeoXH although with much less detail than was visible in 1999. Many of the offset features measured in 1999 were no longer visible, due to either subsequent erosion/redeposition or human activity (e.g., vehicle tracks). A considerable amount of scarp modification, including development of erosional fissures > 1 m in depth within and adjacent to parts of the fault, had occurred on Lavic Lake. On the alluvial fan south of Lavic Lake and north of the Bullion Mountains, the east-side-up component of the coseismic slip had disrupted drainages and caused accumulation of fine-grained sediment on the upstream side of the fault scarp, in some cases obscuring the original rupture.

We made a total of 37 individual offset measurements, mainly within the bedrock section of the fault. In some cases these were new observations that had not been made in 1999. Several of these measurements are larger offsets than had been documented by workers immediately after the earthquake, including the new largest-displacement location (Fig. 2).

Along with our USGS collaborators we have now received clearance for further field work during calendar year 2014. Our next scheduled field work is in April 2014. This will be conducted under the budget from the 2013 project because the project window was extended one year by SCEC. The group who have already received badges for base access comprises Akciz, Hudnut, Stock, three Caltech students (Sousa, Harvey, and Ryan Witkosky) and two other USGS researchers (Kate Scharer and Dave Lynch).

Major results

Major results are highlighted in the summary on the first page of this report. Some of our major findings include:

- Dozens of offset features are still preserved along the bedrock part of the rupture and can be accurately measured.
- Although the fault rupture can still be identified in Lavic Lake, offset features measured along it in 1999 are generally not visible now, due to scarp degradation and modification of the soft sediments by erosion.
- We identified two new high-slip locations where features are offset 7.9 ± 0.5 m (Figure 2) and 6.7 ± 0.5 m. Other large offsets, not previously documented, were also identified.

- Large-magnitude slip variability (over 1m difference within short distances less than 0.5 km) is clearly identifiable within certain parts of the maximum slip zone. This was suggested by the interpretation of the year 2000 LiDAR data (Chen et al., 2013) and was borne out by the analysis of the 2012 LiDAR data and the 2012 field work.
- Ground-truthing of LiDAR offset measurements from the year 2000 and 2012 data sets (Chen et al., 2013; Sousa et al., 2012b) has clarified the validity of individual measurements made in geomorphically complicated locations, and reinforced the need for complementary field observations such as differences in weathering of surfaces.
- Our final product will be a surface rupture map showing what can be seen now in the field (over a decade after the earthquake) based on our field work and the LiDAR data analysis.

Intellectual Merit

SCEC funded us in 2012 and 2013 for comparative analysis of the two LiDAR data sets and field work along the rupture of the Mw 7.1 Hector Mine earthquake. Analysis of the LiDAR data collected along the rupture in the year 2000 (Hudnut et al, 2002; Zhang et al., 2010; Chen et al., 2013) had three main contributions to a better understanding of this rupture: (1) it increased the spatial density of horizontal displacements, (2) it suggested a new location and larger magnitude of the maximum lateral slip, and (3) it documented rapid slip variations along geometrically simple sections of the fault. In May 2012 a new LiDAR dataset was collected by NCALM under a data-only seed grant to Caltech graduate student Francis Sousa. This covered a significantly broader swath along the same length of the fault. Together these two LiDAR datasets (Fig. 1) comprise a complete, high resolution documentation of this major earthquake surface rupture and show the geomorphic evolution of the rupture in a period of 12 years. As part of his no-cost collaboration, Hudnut of the USGS was able to recover archived data from tapes to provide aerial photography taken in April 2000 after the earthquake, which had not previously been used to interpret the fault features. He also acquired new, very high resolution (1 cm pixel) georeferenced oblique aerial photos in Dec. 2012 along the ~12 km section that had slip of 4 meters or more in 1999.

Broader impacts.

Graduate student Frank Sousa was trained in LiDAR data processing, production and differencing of DEMS, and field observations of active faults. Sousa also was trained in presenting his research results at conferences in 2012-2013 (Sousa et al., 2012a and 2012b, 2013a, 2013b), and in helping to write proposals. Graduate student Janet Harvey was trained in field observations of active faults. The LiDAR data set produced by this study will be made available on the OpenTopography web site. The aerial photos shot over the fault zone will be made available on a public web site of the USGS after approval from the US Marine Corps public relations office at 29 Palms US Marine Corps Air-Ground Combat Center.

Bibliography of presentations or items produced so far by this project

Sousa, F., J. M. Stock, S. Akciz and K. Hudnut, “Evolution of the October 1999 Hector Mine Earthquake surface rupture: a decadal view,” *Abstract G23A-0906 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 Dec.*, 2012a.

Sousa, F., J. Stock and S. Akciz, Evolution of the October 1999 Hector Mine Earthquake surface rupture: a decadal view, 2012 SCEC Annual Meeting poster 238, 2012b.

Video animation of the fault scarp evolution: http://www.youtube.com/watch?v=SB5iuSD7Z0c

Sousa, F., Harvey, J.C., Hudnut, K.W., Akciz, S.O., Stock, J.M., 2013. New investigations of the October 1999 Hector Mine Earthquake surface rupture, in: Fall Meeting Program. Presented at the American Geophysical Union, San Francisco, CA, p. Abstract T23C–2595.

Sousa, F., Harvey, J.C., Hudnut, K.W., Akciz, S.O., Stock, J.M., 2013. New investigations of the October 1999 Hector Mine Earthquake surface rupture, 2013 SCEC Annual Meeting poster 10, 2013.

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Bryant, W. A. (compiler), 2005, Digital Database of Quaternary and Younger Faults from the Fault Activity Map of California, version 2.0: California Geological Survey Web Page, <http://www.consrv.ca.gov/CGS/information/publications/QuaternaryFaults_ver2.htm>; Sept. 2011.

Chen, T., S. Akciz, K.W. Hudnut, D.Z. Zhang and J. Stock, Fault slip distribution of the 1999 Mw 7.1 Hector Mine Earthquake, California, estimated from post-earthquake airborne LiDAR data. *in review, BSSA, March 2014.*

Hudnut KW; Borsa A; Glennie C; et al., High-resolution topography along surface rupture of the 16 October 1999 Hector Mine, California, earthquake (M-w 7. 1) from airborne laser swath mapping, BSSA v. 92(4), pp: 1570-1576 DOI: 10.1785/0120000934, 2002.

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Sousa, F., J. M. Stock, S. Akciz and K. Hudnut, “Evolution of the October 1999 Hector Mine Earthquake surface rupture: a decadal view,” *Abstract G23A-0906 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., 3-7 Dec.*, 2012a.

Sousa, F., J. Stock and S. Akciz, Evolution of the October 1999 Hector Mine Earthquake surface rupture: a decadal view, 2012 SCEC Annual Meeting poster 238, 2012b.

Treiman, J. A., K. J. Kendrick, W. A. Bryant, T. K. Rockwell, and S. F. McGill (2002), Primary surface rupture associated with the Mw 7.1 16 October 1999 Hector Mine Earthquake, San Bernardino County, California, Bull. Seis. Soc. Am., v 92, no 4, pp. 1171-1191.

Zielke, O., and J. R. Arrowsmith, “LaDiCaoz and LiDARimager—MATLAB GUIs for LiDAR data handling and lateral displacement measurement,” *Geosphere*, vol. 8, no. 1, pp. 206–221, Feb. 2012.

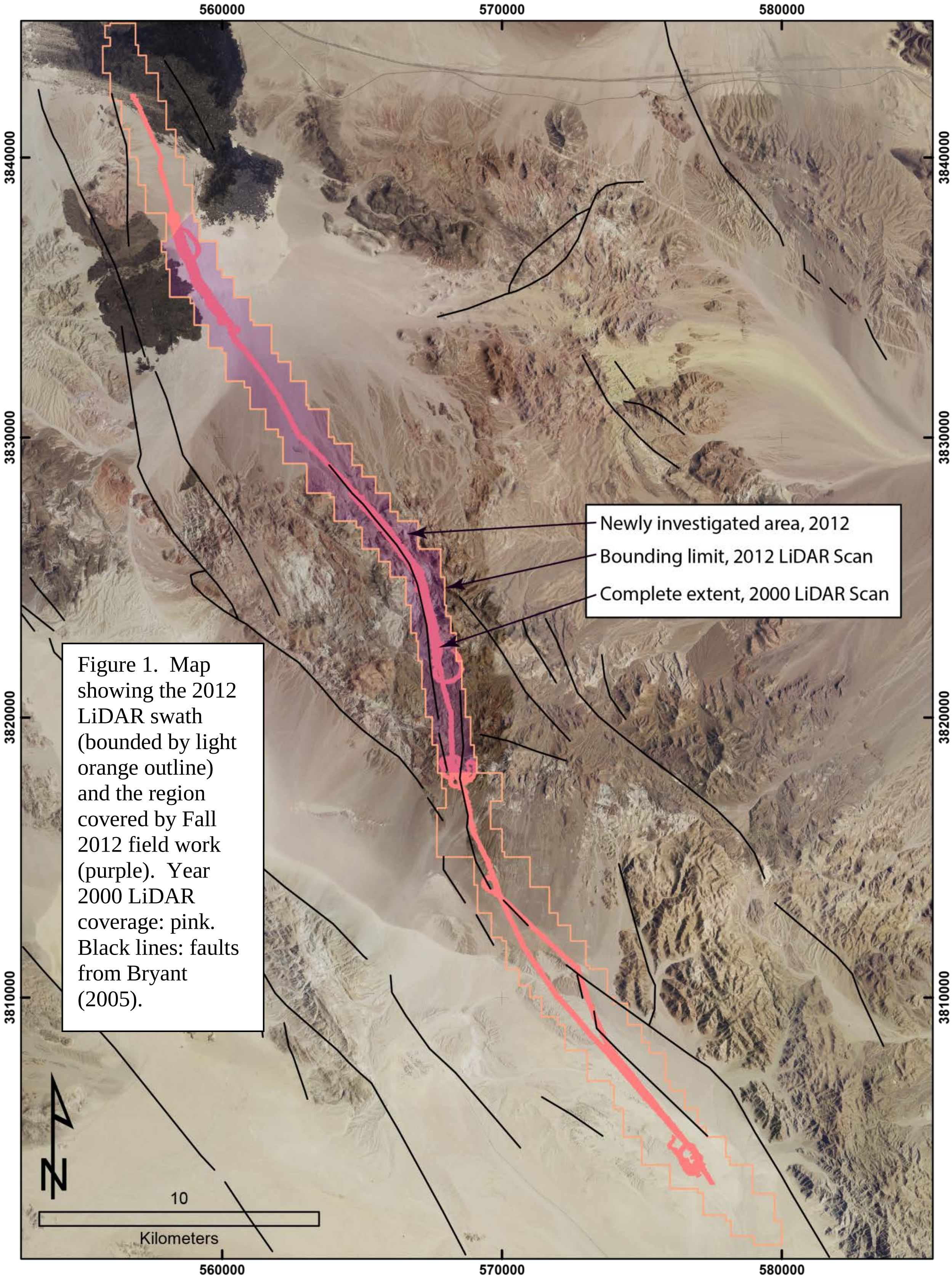

Figure 1. Map showing the 2012 LiDAR swath (bounded by light orange outline) and the region covered by Fall 2012 field work (purple). Year 2000 LiDAR coverage: pink. Black lines: faults from Bryant (2005).

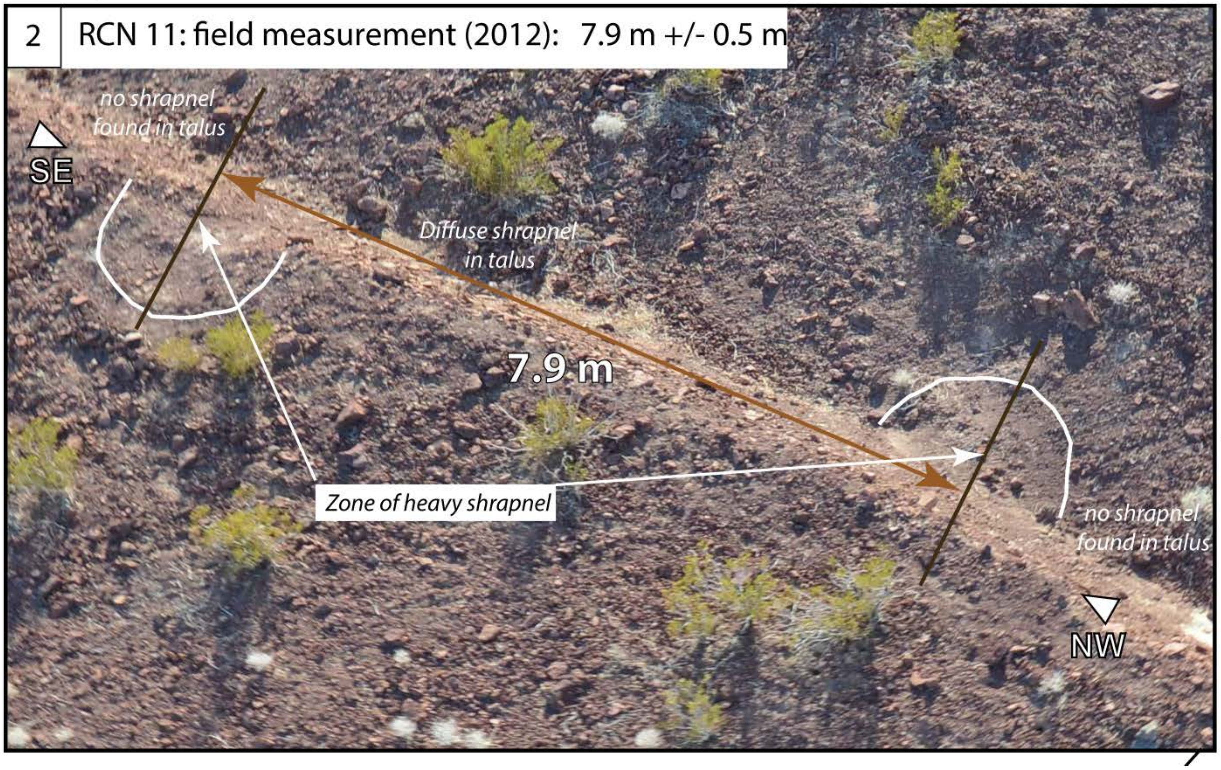

Figure 2. Aerial photo of RCN11 location where bomb crater is offset by the fault. Overlain linework details the fault displacement we report (7.9 m +/- 0.5 m). Assigned uncertainty is due primarily to width of bomb crater halves. Because of the subtle topographic profile of the offset feature, it is not resolvable in any of the LiDAR data collected to date. In the field, distinct shrapnel pieces found in both crater halves and scattered in talus between the crater halves but not outside the crater halves significantly increased our confidence in this offset. Photo was taken by Hudnut during helicopter overflight during the 2012 field campaign, as permitted by USMC MCAGCC.

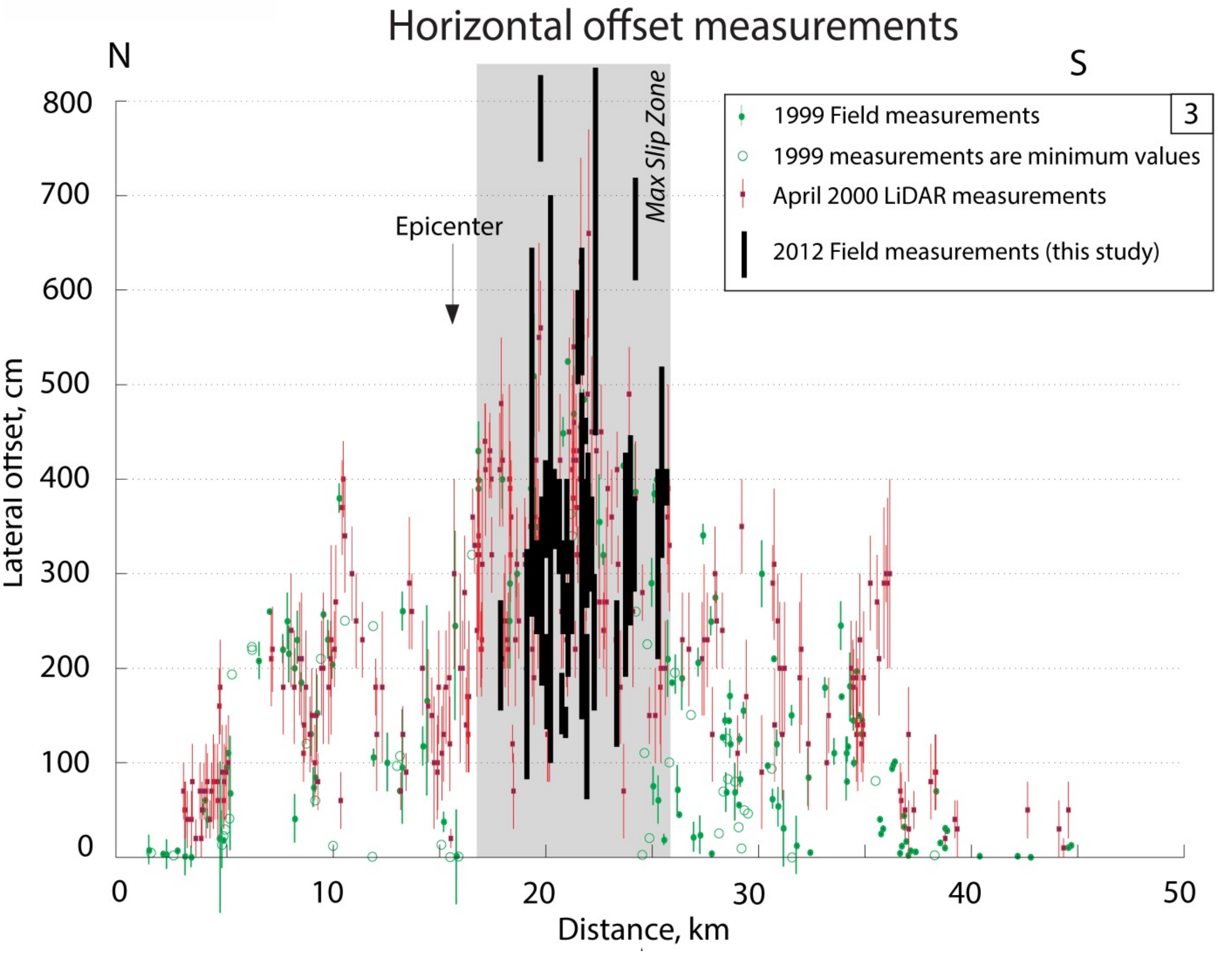

Figure 3. Field measurements made by our team on top of reported yield measurement from the direct aftermath of the earthquake (e.g. Treiman et al, 2002) and computer based measurements made using DEM's derived from the April 2000 LiDAR scan (Chen et al, in review, Hudnut et al, 2002). Highlighted in gray is the maximum slip zone (~ >4 m r.l. offset) where we focused our efforts during the 2012 field campaign. Note the significant increase in the maximum dextral slip reported here (RCN 11 site shown in Figure 2, plus other sites such as ARMORY, HSZ 6), which concur with further increase maximum offset beyond reported maximum offset of Chen et al, in review. Figure was produced by Frank Sousa by modifying a base figure from Chen et al., in review.