**GPS and UAVSAR Evidence of Conjugate Faulting, Step Over, and Inflation Associated with the 2010 Magnitude 7.2 El Mayor-Cucapah Earthquake**

Andrea Donnellan, Jay Parker, Bruce Bills, Paul Rosen, Scott Hensley, Yang Zheng, Yunling Lou, Brian Hawkins

*Jet Propulsion Laboratory, California Institute of Technology*

John Rundle

*University of California Davis*

Marlon Pierce, Geoffrey Fox, Yu Ma, Jun Wang

*Indiana University*

Dennis McLeod, Rami Al-Ghanmi

*University of Southern California*

Tom Herring

*Massachusetts Institute of Technology*

Alessandro Grippo

*Santa Monica College*

Lisa Grant Ludwig

*University of California, Irvine*

**Abstract**

GPS and UAVSAR observations of the 2010 M 7.2 El Mayor – Cucupah earthquake indicate a pattern of substantial deformation and sympathetic fault slip associated with the rupture. A series of conjugate left-lateral faults slipped in associate with the earthquake and continued to slip into December 2010. A right-lateral step over developed to the northwest of the mainshock rupture, which connects the Laguna Salada and Elsinore faults. Slip on this step over occurred at a depth of 2-10 km and also continued postseismically. Further northeast the Superstition Hills fault slipped 2 cm at the surface during and the Imperial Fault slipped 4 cm. The pairs of data that make up the UAVSAR interferogram were collected in October 2009 and April 2011, so it is not possible to determine whether these right lateral slip events occurred during the event. The UAVSAR data show a regional elliptical fringe pattern across the Imperial Valley that is generally matched by a broad pattern of uplift observed in the GPS data. About 2 cm of uplift occurred in the Salton Trough surrounding the mainshock and an additional 7 mm of uplift occurred in the April – July 2010 timeframe in the southern part of the Imperial Valley. The GPS station closest to the rupture subsided during the earthquake, but began uplifting in March 2011. The uplift pattern and conjugate sets of faults may indicate leaky transform faulting in the Salton Trough.

**Introduction**

The 4 April 2010, M 7.2 El Mayor-Cucapah earthquake occurred in northern Baja, Mexico on a northwest-southeast trending right-lateral oblique normal fault (Hauksson et al, 2010). The fault ruptured the surface and extended just south of the border between Baja and California. The region was observed by continuous GPS and with UAVSAR beginning in October of 2009 and several times following the earthquake providing detailed co-seismic and postseismic images of surface deformation.

About 42 mm/yr of shear deformation occur across southern California between Palm Springs and the Mexican border (Meade and Hager, 2005, Fay and Humphreys, 2005). In this region the San Andreas fault is slipping at about 25 mm/yr, the San Jacinto Fault at 12 mm/yr, and the Elsinore fault at about 4 mm/yr (Keller at al., 1982; Weldon and Sieh, 1985; Rockwell et al., 1990; Petersen and Wesnousky, 1994; Humphreys and Weldon, 1994; Fay and Humphreys, 2005). This area to the north of the Gulf of California is a transition zone between the extensional tectonic regime of the East Pacific Rise and the transform tectonics of the strike-slip San Andreas fault system (Figure 1A). Both tectonic regimes are manifest in the Imperial Valley and Salton Trough by abundant seismicity along northwest-trending right-lateral strike-slip faults and northeast-trending left-lateral conjugate faults, with swarms of shallow earthquakes in the Brawley seismic zone southeast of the Salton Sea (Nicholson et al., 1986, Irwin, 1990). The Salton Trough is characterized by high heat flow, Quaternary volcanism, and hydrothermal activity associated with magma intrusion at shallow depth (Irwin, 1990; Hill et al., 1990).

The paleoseismic and historic records show the region is capable of producing large earthquakes, such as the southern San Andreas fault rupture in ~1700 A.D. (WGCEP, 2008), and sequences of earthquakes. The 1940 M­w7.0 El Centro and 1979 Mw6.5 Imperial Valley earthquakes ruptured overlapping sections of the Imperial fault (Toppozada et al., 2002) and the 1968 Mw6.6 Borrego Mountain earthquake triggered slip on the Superstition Hills fault (Nicholson et al., 1986). The northwest-trending Superstition Hills fault, a branch of the San Jacinto fault zone, subsequently ruptured in 1987 in a Mw 6.6 earthquake which was preceded a few hours by the Mw 6.2 Elmore Ranch earthquake on the conjugate northeast-trending Elmore Ranch fault (Hill et al., 1990). The southern Elsinore fault zone has not ruptured historically. The southern Coyote Mountains segment of the Elsinore fault zone is separated from the northern Laguna Salada fault zone, which ruptured in 1892, by a releasing step-over with several northeast-trending cross-faults (WGCEP, 2008)

The rapid deformation rates and high earthquake hazard make the Imperial Valley transition zone between the Gulf of California and the San Andreas fault system an excellent target for UAVSAR observations (Figure 2B). The region was identified in 2007 as having a higher likelihood of earthquakes (Holliday et al., 2007) based on methods derived from pattern informatics forecasting methodology developed by Rundle and Tiampo (Rundle et al, 2002; Tiampo et al, 2002; Rundle et al, 2003). As a result observations were collected over the region to both better understand the crustal deformation in the region and to establish a baseline measurement in the event an earthquake were to occur there.

**Pattern Informatics and Forecasting**

A method of earthquake forecasting called RIPI (Holliday et al., 2006a; Holliday et al., 2007) was developed that was based on finding locations in a seismically active region in which changes in seismic activity are largest. The basic idea is that precursors are changes from the background, so locations of large change in seismic activity of either quiescence or activation would be the most likely candidates for future large events. The Relative Intensity Pattern Informatics (RIPI) method identifies hotspots within California that are at a higher likelihood of having an earthquake of M5 or greater. The approach divides the seismogenic region to be studied into a grid of square boxes or pixels whose size is related to the magnitude of the earthquakes to be forecast. The rates of seismicity in each box are studied to quantify anomalous behavior. Seismicity precursors represent changes, which can be either a local increase or decrease of seismic activity, so the method identifies the locations in which these changes are most significant during a predefined change interval. The subsequent forecast interval is a five-year time window during which the forecast is valid. The box size is selected to be consistent with the correlation length associated with accelerated seismic activity (Bowman et al. 1998), and the minimum earthquake magnitude considered is the lower limit of sensitivity and completeness of the network in the region under consideration. Earthquake precursory signals have not been seen in heavily instrumented areas such as Parkfield (Borcherdt et al., 2006), suggesting that broader anomalies develop instead. The anomalous seismicity identified in the hotspot maps might represent these broader anomalies (Holliday et al., 2007).

The actively deforming Salton Trough, which includes northern Baja, the Salton Trough, and areas west of the Salton Trough, was identified as a location of increased earthquake probabilities or hotspots using pattern informatics forecasting methodology (Holliday et al, 2007). The effectiveness of the Pattern Informatics method was tested in a truly prospective test from January 1, 2006 - December 31, 2010. It was found to have considerable skill at locating the future earthquakes M>4.95 that occurred during the test period (Lee et al, 2011).

The increased earthquake probability, large earthquakes in the past, and the active deformation on several faults in the region made the Salton Trough a good target for observing with UAVSAR. Because the faults in the region are primarily northwest-southeast striking right-lateral faults we designed the UAVSAR experiment, reported here, with flight swaths perpendicular to the faults in order to observe maximal range changes indicative of displacements along the faults.

**UAVSAR and GPS Observation of the El Mayor/Cucapah Earthquake**

The NASA/JPL UAVSAR is an airborne L-band fully polarimetric radar housed in a pod that is mounted to the belly of a Gulfstream III aircraft. It employs an electronically scanned antenna with beam steering based on inertial navigation unit (INU) data to facilitate repeat pass radar interferometric observations. The aircraft employs a precision autopilot that allows the plane to fly a specified trajectory within a 5 m tube. The instrument observes approximately 22 km wide swaths that are typically up to about 100 km long with longer lines in excess of 300 km possible. Radar interferometric images (or interferograms) are generated from repeat passes flown over a desired site. UAVSAR requires additional processing compared to spaceborne data because the aircraft trajectories are very irregular compared to satellite trajectories and combined GPS/INU measurements have 2-3 cm position accuracy that is an order of magnitude less accurate than what is needed for geodetically useful observations. To overcome this difficulty, offset measurements between single look complex (SLC) images from the two passes are used to solve for the residual baseline, velocity and attitude angles. Motion data is corrected and the imagery reprocessed [Hensley, 2007]. Products generated by the UAVSAR processor include both slant range multi-looked interferograms and unwrapped phase products, with 36 looks and approximately 6-7 m postings, as well as the corresponding geocoded data products in geographic coordinates based on the SRTM 30 m DEM.

UAVSAR data were first collected for the Salton Trough experiment along the border on October 20, 2009 (Table 1). The El Mayor-Cucapah earthquake ruptured northward in Baja, Mexico to the border between the US and Mexico, while the UAVSAR observations were collected in the US to the border of Mexico. As a result, UAVSAR observes the northern terminus of the rupture and associated crustal deformation response north of the rupture. Repeat pass data were collected on April 12 and 13, 2010 about one week after the M 7.2 El Mayor-Cucapah earthquake, on July 1 of 2010 and December 1, 2010 (Figure 1), making it possible to construct interferograms for the mainshock, and near term postseismic deformation. Data were also collected in April 2009, and September 2010, but are not used in this study. In the first case the observations were further north across the Imperial Valley and are too far north to show co or postseismic motions. For the latter case the RPI product is noisy suggesting too many error sources to make a useful product.

GPS data are also continuously collected for the region and were used in part to constrain some characteristics of the phase unwrapped repeat pass interferometry products, but also highlight a pattern of uplift in the Imperial Valley. Up to 2 cm of uplift occurred spanning the earthquake, persist at a lower level to the July 1, 2010 time period in the southern part of the Salton Trough and show uplift starting in spring of 2011 near the mainshock rupture and Mexican border.

The southernmost interferogram (Line 26501) shows two lobes of deformation marking the north end of the rupture near the Mexican border. The data were examined in a variety of ways to understand the robustness of the solution. The east lobe and localized discontinuities or offsets are reflective of ground motion, however error sources may be obscuring the deformation in the western part of the interferogram. The earthquake caused large offsets of the ground in the region of this line, which could contaminate the aircraft residual motion estimates. In the residual motion estimation procedure a correction to the relative motion between the two passes is estimated. 2D pixel offsets between the two images via amplitude correlation of tiles is computed. A model relates the image offsets to a residual baseline slope. The slope is integrated in time to give the relative motion error. The error is assumed to have zero mean and as a result half of the error is added to each flown track. The data are then reprocessed with the updated motion for the final products. When the deformation signal is large compared to a pixel, there is a possibility of corrupting the offset measurement and thus the estimated motion. The western lobe has widely different characteristics for different solutions, while the eastern lobe and other features persist for various solutions.

Left lateral offsets of the fringes can be seen including along a well-defined discontinuity conjugate to the mainshock rupture, which correspond with the location of the Yuha Fault. The Yuha fault is one of a series of northeast-trending cross-faults (Nicholson et al., 1986) between major strands of the southern Elsinore and Laguna Salada fault zones. In addition to the Yuha fault a number of northwest and northeast striking offsets that are conjugate to each other can be noted in the interferogram. The eastern lobe shows more data outages due to temporal decorrelation in the Imperial Valley from active cultivation of agricultural fields. This lobe of deformation shows disturbance on its eastern margin, which may be due to leveling or settling of the Imperial Valley from liquefaction. Soil moisture effects, which are not unlikely given the liquefaction of the area, can be a contributing source of error to the results. Northwest striking Linear offsets in the interferogram can be observed on both the Imperial fault (line 26501 ellipsoid in Figure 1B) and on the Superstition Hills fault (line 26505 in figure 2A).

Further east a large elliptical fringe pattern tens of kilometers across can be seen in both line 26501 and the next line north (26505). The elliptical pattern (Figure 1A) could be attributed to atmosphere, residual, aircraft motion, or crustal motion. 1–2 cm of uplift is observed at the GPS stations for the same time period as that spanned by the coseismic interferogram (October 20/21, 2009 – April 12/13, 2010), and about 7 mm of uplift are observed in the GPS stations for the same time period as the postseismic interferograms (April 12/13, 2010 – July 1, 2010). Uncertainties in the line-of-sight measurement of the UAVSAR instrument coupled with the sparseness of the GPS network did not permit the decomposition the UAVSAR observations into horizontal and vertical deformation.

We compared the UAVSAR line of site measurements to GPS results calculated for the same time frame as the UAVSAR data (Figures 3 and 4). We converted the GPS north, east, and up vectors to line of site for the given azimuth and elevation for that location. UAVSAR pixels were averaged over a 1x1 km box. The results show that for local scales the correlation between the UAVSAR and GPS results is good and that the UAVSAR results can be deemed reliable. Ramps in the solution and other effects make it difficult to draw more regional conclusions from the UAVSAR solutions. GPS results can be used to validate and presumably improve the UAVSAR results over time. Unfortunately there are no GPS stations located in the western lobe of the interferogram to provide constraints on the results there.

An evaluation of 3D GPS displacements determined for the period October 21, 2009 – April 13, 2010 to the Wei et al (2011) GPS solution determined just spanning the earthquake indicates an uplift that is slightly larger for the six month GPS solution, compared to the coseismic only GPS solution suggesting a regional uplift pattern that persists beyond the earthquake. A similar pattern of uplift is observed in the postseismic GPS solution but is more confined to the southern Imperial Valley. If the uplift were observed only for the event then it is possible that liquefaction caused local uplift of the GPS monuments (Sasaki and Tamura, 2004).

Webb and Kedar (written communication) calculated time dependent strain for southern California and the results show substantial dilatation across the Imperial Valley in the region between the Salton Sea and the Mexican border, which grows more pronounced before the El Mayor-Cucapah earthquake. A ring of compression surrounds the Imperial Valley during this time period. More dilation is observed co-seismically with compression at the edges, suggesting a regional dome of uplift associated with the earthquake similar to the elliptical pattern observed in the interferograms. Holocene eruptions at the south end of the Salton Sea as recent at 16,000 years ago and hydrothermal activity suggest that magma in the region is at a shallow depth (Goldstein and Flexser, 1984). Other studies indicate a magma chamber at 5 km depth with magma that can be as shallow as 1.5 km (Robinson et al, 1976). Robinson et al (1976) suggest that this region is a leaky transform fault.

The co-seismic interferogram on line 26501 includes the timespan April 12–13, 2010, whereas line 26505 does not. A two lobed pattern of deformation is observed in the April 12–13, 2010 timeframe (Figure 2B, suggesting that rapid postseismic motions occurred in the weeks following the event. This two lobed pattern continues for the April 13 – July 1, 2010 timeframe (Figure 2C) and is suggested in the July 1 – December 1, 2010 interferogram (Figure 2D). Two conjugate zones of shear are observed during this longer postseismic time period.

We plotted the line of site range changes for these three time periods on four transects. The first two transects (Lines A and B) are oriented perpendicular to the strike of the mainshock rupture with line A being further north and further away from the northern extent of the rupture. Line B spans the interferogram along and just north of the Yuha fault. Line C runs parallel to and just north of the extension of the mainshock rupture and crosses the Yuha fault. Line D crosses perpendicular to the fringes on the eastern side of the Imperial Valley.

We converted GPS deformation measurements into line-of-sight motions commensurate with the UAVSAR observation geometry of the interferograms. The elevation between the ground and the instrument varies from about 20° at the far edge of the swath to about 65° at the near edge of the swath for UAVSAR. We used an elevation angle that matched or was most appropriate to the closest UAVSAR observation (pixel) and an azimuth of -5°, which is perpendicular to the flight path heading of the aircraft. As a result, GPS projections can vary according to the swath on which they were projected. The locations of the GPS stations do not lie on the cross section line for the most part so we then projected the locations of the GPS stations onto nearby lines (Figures 3–6). Some of the GPS stations lie somewhat distant from the lines, but still provide a general validation of the on the observed InSAR products. There can be an overall unknown phase constant that must be constrained with knowledge of areas known not to be undergoing deformation or with in situ measurement. We corrected the range change to match the GPS range change estimates for stations on or very near the lines.

The coseismic observations indicate about 4 cm of coseismic change near the rupture (Figure 2A). The interferogram shows a fabric of conjugate northeast and northwest striking surface ruptures (Figure 7A). In our convention positive range change is toward the aircraft. The GPS stations roughly indicate the same sense of motion as the UAVSAR data. Line B, which is closer to the rupture shows about 10 cm of motion peak to peak. The region between stations P494 and P496 shows a noisy but much flatter profile of motion. It is likely that liquefaction caused leveling at the western edge of the Imperial Valley on approximately a 10 km scale. The postseismic Lines A and B for the period April 13 – July 1, 2010 suggests the development of a fault stepover indicating continued activity at the northern end of the rupture. 3 cm of right slip are observed on the northwest step over in the time period April 13 – July 1, 2010 and about 5 cm of range change are observed at the northern extension of the mainshock rupture. A ramp in the data is likely due to unmodeled errors.

Line C shows a range change difference of over 30 cm from the north edge of line 26501 through the northeast lobe of the interferogram and offsets on the Yuha fault and a fault to the south coseismically and postseismically (Figure 4). Line CC shows a 60 cm gradient across the main or eastern lobe of the interferogram (Figure 5), which is due to a large slip gradient near the north end of the rupture.

Further east the coseismic and UAVSAR data show much greater variations along profile line D (Figure 6). Water in the region along with liquefaction most likely disturbed the area, but can also result in soil moisture changes and an additional source of error in the UAVSAR solutions. The GPS results show small postseismic motions and the excursion seen in the UAVSAR postseismic observations are most likely due to unmodeled errors.

**Co- and Post-seismic Fault Slip**

The combined GPS and UAVSAR data, which include one week of postseismic motion, can be inverted for a single fault (Table 2). Wei et al (2011) fit spaceborne radar data that observe the rupture and GPS data to a similar 120 km rupture, but use seismicity to constrain the model to two long faults offset by a normal fault, and a fault segment at the north end of the rupture. We do not model these characteristics south of the U.S. – Mexico border. The north end of the rupture in the inversion is about 3 km north of the mapped rupture suggesting some combination of deeper slip that did not rupture the surface in this region or northward migration of slip during the immediate postseismic period.

The interferogram of the El Mayor-Cucapah earthquake shows linear northeast striking patterns that cross and offset the fringes (Figure 7). The most prominent of these is on the Yuha fault, which is a northeast striking strike-slip fault just north of the border between California and Baja. There is a smaller secondary fault further south indicated in the interferogram that we do not model here. The northeast striking lineations can be fit by a single fault at depth that is subparallel to, but south of the Yuha fault. The results suggest superficial slip on the Yuha and secondary fault in the unconsolidated surface sediment reflecting slip on a single fault at depth.

A map view of the interferogram in the region of the mainshock suggests that a step over occurs, and modeling suggests that the El Mayor-Cucupah rupture is bounded on the north by the left lateral northeast striking Yuha fault (Figure 9). These faults continued to slip to December 1, 2010 (Figures 7B–D). On June 15, 2010 a M 5.7 aftershock occurred just northwest of the northern terminus of the rupture.

Inversions for slip on the northeast linear structure that steps west of the mainshock rupture yield a moment magnitude ranging from 5.5 – 5.8 (Table 3). We carried out inversions for one, two, and three fault segments for the observed postseismic interferogram. The 2/dof of the best-fit model of 0.47 includes slip on the two offset northwest striking faults separated by the left lateral Yuha fault. The 2/dof for a single fault is 1.54 or three times worse than the three fault segment model. While we can’t model this event in detail, the UAVSAR data point to locations of the structures, their step overs, and conjugate structures with the Yuha fault being the primary conjugate structure. We fixed the location, strike, and length of the fault surfaces based on those identified in the UAVSAR image. We constrained the dip of the NE striking faults to the mechanisms determined from seismic waveforms. Cumulatively the moment release from the earthquake to July 1, 2010 is equivalent to M 6.0.

While the model can not provide exact details of postseismic rupture characteristics numerous model runs indicate that the mainshock rupture terminates at the Yuha fault. Afterslip on the mainshock is required by the models. Left slip occurs on the conjugate Yuha fault. Deeper slip occurs associated with the June 15, 2010 Coyote Creek aftershock. The modeling prefers a steeply dipping fault that dips slightly eastward and slips at a depth of 2-10 km. We explored the relocated earthquakes of Hauksson et al (2011) and found that the earthquakes from 2­–8 km in that region fall on a line that follows the UAVSAR step over. A cross section by depth through that line suggests a slight eastward dip.

Coseismic creep is observed on the Superstition and Imperial faults (Figure 10). Using the assumption that all of the slip is horizontal and parallel to the respective fault 2 cm of horizontal right-lateral slip occurred on the Superstition Hills fault and 4 cm of right lateral strike slip motion occurred on the Imperial fault. These results show that locally UAVSAR can produce very detailed results of surface deformation.

**Observed Uplift in the Imperial Valley**

The UAVSAR observations suggest a ring of deformation in the Imperial Valley. However, the horizontal motions overwhelm the results in the repeat pass interferogram, making it difficult to infer any pattern of vertical motions. GPS results for the region indicate about 2 cm of uplift in the Imperial Valley associated with the earthquake and subsidence near and west of the rupture. Additional uplift of about 7 mm in the southernmost half of the Imperial Valley up to July 1, 2010 following the earthquake (Figure 2).

Over the longer term since the earthquake the stations closest to the northeast end of the rupture show the most uplift. Station P494 subsides following the earthquake and then rises about 30 mm in the April 1, 2011 – July 28, 2011 time frame (Figure 11). Station P496 shows a continuous uplift of about 20 mm in the time frame from the earthquake on April 10, 2010 to July 28, 2011. Water or magma injection could explain the Imperial Valley pattern of uplift. The southeastward motion of the eastern side of the fault rupture would cause a pull apart in the Imperial Valley, consistent with the dilation that is calculated from the GPS time series data (Kedar et al, written communication).

We compare the Yellowstone caldera to the Salton Trough to explain the vertical motions. At a very simplistic level, the Yellowstone caldera region and the Salton trough have several interesting features in common: both experience frequent large earthquakes, both have very high heat flow, and associated geysers and/or mud volcanoes. There have been several episodes of inflation and deflation of the Yellowstone caldera floor in the period of time covered by annual leveling surveys starting in 1976. Many of the episodes of vertical motion were associated in time with earthquake swarms and changes in activity of geysers and mud pots (Dzurizin, 2007). There have been several large historic earthquakes in the region with the largest being the M 7.5 Hebgen Lake event on August 18, 1959.

The long term (105 to 106 year) source of both high heat flow and elevated topography is “episodic intrusion of new basaltic magma from the mantle into the crust beneath the caldera”(VD, p 254). There is good evidence for a partly molten rhyolitic magma at depth (Christiansen, 2001; Smith and Braile, 1994).

A leveling survey of the Yellowstone caldera was conducted in 1923, and then from 1976 onward, the survey has been repeated on a yearly basis. Starting in 1990, these leveling surveys have been supplemented by GPS measurements, which also see horizontal motion. Starting in 1992 InSAR measurements have also been obtained. These surveys show several episodes of inflation and subsidence of the caldera floor (Dzurisn and Yamashita, 1987; Dzurisin et al., 1990). The caldera rim has remained relatively stable, but the center has shown 90 cm of uplift, from 1923 to 1985, followed by 20 cm of subsidence between 1985 and 1995, followed by uplift since 1995. The rate of uplift increased dramatically in 2004 (Chang et al., 2007), and has continued until the present, though not at the 5-7 cm/yr rate seen between 2004 and 2006 (Chang et al., 2010). The likely mechanisms for short term vertical motion include both movement of magma (Christiansen, 2001; Smith and Braile, 1994) and pressurization of the deep hydrothermal system (Fournier, 1989, Dzurisin et al.,1990).

Fournier and Pitt (1985) proposed that the Yellowstone hydrothermal system has a deep zone in which pore fluid pressure is near lithostatic, and a shallow zone in which pore pressure is hydrostatic. The two zones are presumed to be separated by an impermeable, self-sealing layer created by mineral deposition and plastic flow at a depth near 5 km. In this model, uplift can be explained by water released upon crystallization of rhyolitic magma. The net volume increase would yield surface uplift (Fournier, 1989; Dzurisin et al., 1990). If the self-sealed layer within the deep hydrothermal system were ruptured during an earthquake swarm, the resulting depressurization and fluid loss would lead to surface subsidence.

It is tempting to draw parallels between behavior seen in Yellowstone and that in the Salton Trough. There are obvious similarities, including high heat flow, recent volcanic activity, and occasional large earthquakes. Rudolph and Manga (2010) observed an increase in gas flux from mud volcanoes near to the location of the 4 April 2010 El Mayor-Cucapah earthquake, and argued that it was due to a transient increase in subsurface permeability.

In addition to the 5 small rhyolite domes, which were extruded onto the Quaternary sediments at the south end of the Salton Sea (Robinson et al., 1976), it has recently been found that there are thick (150-300 m) rhyolite layers at 1.6 to 2.7 km depth in the same area (Schmitt and Hulen., 2008). They appear to have been emplaced roughly 400 kyr ago. Assuming that the sedimentation rate roughly equals the subsidence rate (Lachenbruch et al.,1985), this implies a mean subsidence rate of 4-6 mm/yr, which is close to the estimate from repeat leveling (Larsen and Reilinger, 1991). However, trenching across the Brawley fault zone (Meltzner et al., 2006) has shown that the recent sedimentation rate (1970-2004) was at least twice as fast as the average over the preceding millennium.

**Conclusions**

The El Mayor – Cucupah earthquake triggered slip on several right-lateral and conjugate left-lateral faults in the Salton Trough (Figure 12). The stepover observed in the UAVSAR data connects the Laguna Salada and Elsinore faults. The broad pattern of uplift suggests a regional intrusion of water or possibly magma. The region of uplifting crust localizes southward over the year following the earthquake. The observed pattern of co-seismic and post-seismic deformation induced by the 2010 El Mayor-Cucapah earthquake is consistent with the transitional tectonic regime, and the historic record of earthquake sequences in which major events have occurred on northwest-trending strike-slip faults, and with minor slip on conjugate cross-faults. The history of triggered slip and sequences of earthquakes suggests the potential for triggering an earthquake on the southern Elsinore fault zone, which has not ruptured in several centuries.

**Acknowledgements**

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA. We thank Michael Heflin and Geoffrey Blewitt for useful discussion and additional analysis of GPS data.

**References**

Goldstein, N.E., S. Flexser, Melt Zones Beneath Five Volcanic Complexes in California: An Assessment of Shallow Magma Occurrence, Lawrence Berkeley Laboratory Report LBL-18232, 1984.

E. Hauksson, W. Yang, and P. Shearer, "Waveform Relocated Earthquake Catalog for Southern California (1981 to 2011)," 2011 SCEC Annual Meeting Abstract, Palm Springs, 2011.

Hauksson, E., J. Stock, K. Hutton, W. Yang, A. Vidal-Villegas, H. Kanamori, The 2010 Mw 7.2 El Mayor-Cucapah Earthquake Sequence, Baja California, Mexico and Southernmost California, USA: Active Seismotectonics along the Mexican Pacific Margin, Pure and Applied Geophyscis, DOI 10.1007/s00024-010-029-7, 2010.

Hearn, L., Y. Fialko, Can compliant fault zones be used to measure absolute stresses in the upper crust?, J. Geophys. Res., 114, B04403, doi:10.1029/2008JB005901, 2009.

Hill, D. P., Eaton, J. P. and Jones, L. M., Seismicity, 1980-86, in "The San Andreas Fault System, California",  *USGS Prof. Paper* 1515, (1990).

Holliday, J.R., C.C. Chien, K.F. Tiampo, J.B. Rundle, D.L. Turcotte, and A. Donnellan, A RELM Earthquake Forecast Based on Pattern Informatics, Seismological Research Letters, 78:1, 87–93, 2007.

Irwin, W. P., Geology and Plate-Tectonic Development, in "The San Andreas Fault System, California",  *USGS Prof. Paper* 1515, (1990).

Lee, Y-T, D.L. Turcotte, J.R. Holliday, J.B. Rundle, C-C. Chen, K.F Tiampo, Results of the RELM test of earthquake predictions in California, submitted to Proc. Nat. Acad. Sci. (2011).

Nicholson, C., Seeber, L., Williams, P. and Sykes, L. R., Seismic evidence for conjugate slip and block rotation within the San Andreas fault system, southern California, *Tectonics*, v. 5, no. 4, p. 629-648 (1986).Robinson, P.T., Elders, W.A., and Muffler, L.J.P., 1976. Quaternary volcanism in the Salton Sea geothermal field , Imperial Valley, California. Geol. SOC. Am. Bull., V . 87, pp. 347-360.

Rundle, J.B., K.F. Tiampo, W. Klein and J.S.S. Martins, Self-organization in leaky threshold systems: The influence of near mean field dynamics and its implications for earthquakes, neurobiology and forecasting, *Proc. Nat. Acad. Sci*. USA, **99**, Supplement 1, 2514-2521, (2002)

Rundle, JB, DL Turcotte, C Sammis, W Klein and R. Shcherbakov, Statistical physics approach to understanding the multiscale dynamics of earthquake fault systems (invited), *Rev. Geophys. Space Phys*., **41**(4),  DOI  10.1029/2003RG000135 (2003).

Sasaki, T. and K. Tamura, Prediction of Liquefaction-Induced Uplift Displacement of Underground Structures, 36th Joint Meeting Panel on Wind and Seismic Effects, Gaithersburg, Maryland, 17-22 May, 2004.

Tiampo, KF, JB Rundle, S. McGinnis, S. Gross and W. Klein, Mean field threshold systems and phase dynamics:  An application to earthquake fault systems, *Europhys. Lett.*, **60**, 481-487, (2002).

Toppozada, T. R., Branum, D. M., Reichle, M. S., and Hallstrom, C. L., San Andreas Fault Zone, California: M>5.5 Earthquake history, *Bull. Seism. Soc. Amer.,* v. 92, no. 7, pp 2555-2601 (2002).

Wei, S, E. Fielding, S. Leprince, A. Sladen, J-P. Avouac, D. Helmberger, E.Hauksson, R. Chu, M. Simons, K. Hudnut, T. Herring, and R. Briggs, Superficial simplicity of the 2010 El Mayor-Cucapah earthquake of Baja California, Mexico, Nature Geoscience, DOI:10.1038/NGEO1213, 2011.

Working Group of California Earthquake Probability, *The Uniform California Earthquake Rupture Forecast, v2* (USGS Open File Report 2007-1437, 2007; http://pubs.usgs.gov/of/2007/1437/).

**Figure Captions**

**Figure 1.** Top Panel: Regional context of the UAVSAR study in the Salton Trough. The Pacific North American plate boundary is shown by the solid line, with general sense of motion marked by gray arrows. Seismicity is plotted for the time of the UAVSAR study, which is from October 20, 2009 – December 1, 2010. Area of study, GPS uplift and coseismic UAVSAR repeat pass interferometry images are also shown. Bottom Panel: region of study showing general Pacific-North American plate motion marked as darker gray arrows. Heavy dashed lines mark slip of the mainshock rupture and faults with observed creep. Arrows indicate general sense of motion. Red circles indicate GPS uplift and blue circles subsidence observed by GPS station.. Largest circle shows about 2 cm of uplift. Light dotted lines indicate sections along which UAVSAR line of sight (LOS) changes are plotted in subsequent figures. Northern swath is line 26505 and southern swath is line 26501.

**Figure 2.** L-band UAVSAR repeat pass interferometry (RPI) products. Each cycle through the color wheel indicates 12 cm of displacement along the radar line of sight. Dotted lines indicate sections along which UAVSAR line of sight (LOS) changes are plotted in subsequent figures. Lines A and B are roughly perpendicular to the mainshock fault motion, line C is perpendicular to the Yuha fault, CC passes through the maximum observed displacements, and Line D through the Imperial Valley. A) Coseismic unwrapped interferogram and vertical coseismic GPS observations for the time period October 2009 – April 2010. Timeframe for the northern swath, which is line 26505, is October 20, 2009 – April 12, 2010. The southern swath is line 26501 and the time frame for first and second passes is October 21, 2009 – April 13, 2010. Red circles indicate uplift and blue circles indicate subsidence. Largest observed uplift is 2 cm and largest subsidence is -1.3 cm. B) Unwrapped interferogram for postseismic observations for the period April 12-13, 2010. C) Postseismic inteferogram for the time period April 13 – July 1, 2010. Linear offsets are marked by dotted ellipses. D) Postseismic interferogram for the time period July 1, 2010 – December 1, 2010.

**Figure 3.** UAVSAR line of site measurements versus GPS line of site component from 3D GPS solutions for the same time period. UAVSAR pixels are averaged over a 1x1 km box. GPS north, east, and up, are converted to line of site for the elevation and azimuth at each GPS point. Dotted line in each plot shows a correlation of 1. A) An offset of 10.02 cm is removed from UAVSAR by averaging differences between the GPS and UAVSAR line of site estimates. IID2 and P500 are removed from the first fit and fit separately. The offset between the two fits is 7 cm. B) An offset of 4.6 cm is added to the UAVSAR. Only P497 and P77 are in the first fit. The difference between GPS solutions is less than 2 cm while the variance in UAVSAR at those points is 7 cm. C) An offset of 1.2 cm is added to the UAVSAR. P500 is deleted from the first fit and the average. P500 is 8 cm different than the corresponding GPS observation. D) An offset of 15.12 cm is added to the UAVSAR. P492 is not included in the average or first correlation fit.

**Figure 4.** Graphical illustration of fits from figure 3 ranging from good correlation with the GPS of less than 1 cm (green) to poor fits (red and purple). Panels correspond to plots in Figure 3.

**Figure 5.** Cross sections for Lines A and B. Line of site range changes are plotted along the lines for coseismic and postseismic observations. GPS data are projected onto the line of site for the appropriate elevation angle for that point in the image and are plotted twice if located in two swaths. The GPS data were used to correct the range change ambiguity in this and subsequent plots.

**Figure 6.** Line of site range change in cm is plotted along the section perpendicular to the Yuha fault found at 5 km in the section. GPS data are projected onto the line of site for the appropriate elevation angle for that point in the image. Slip on two left lateral structures that are conjugate to the mainshock rupture, near 5 and 8 km in the section.

**Figure 7.** Line of site range change in cm is plotted along a north south section through the largest displacements found in the coseismic repeat pass interferometry. GPS data are projected onto the line of site for the appropriate elevation angle for that point in the image.

**Figure 8.**  Line of site range changes are plotted along the lines for coseismic and postseismic observations for a cross section through the Imperial Valley plotted north to south showing deformation pattern on that region.

**Figure 9.** Detail of the north end of the rupture for A) the coseismic interval of October 21, 2009 – April 13, 2010, B) April 12 – 13, 2010, C) April 13, 2010 – July 1, 2010, and D) July 1, 2010 – December 1, 2010. Offsets associated with the mainshock and the M 5.7 June 15, 2010 aftershock and conjugate slip on the Yuha fault persist in the images.

**Figure 10.** Coseismic creep on the Superstition Hills and Imperial faults can be seen in the coseismic interferograms for line 26505 and in the agricultural area in 26501 (south line). Detailed cross sections are plotted for each fault indicating 1 cm of line of site changes on the Superstition Hills fault and 2.3 cm of line of site changes on the Imperial fault. This corresponds to 2.0 creep on the Superstition Hills fault and 4.3 cm of creep on the Imperial fault if the slip is horizontal and parallel to the slip lineation.

**Figure 11.** Vertical time series for stations in the southern Imperial Valley spanning the north end of the rupture. Station plots are organized roughly geographically. Horizontal axis is time and vertical axis is vertical position in mm. Solid vertical line marks the time of the earthquake. Dashed lines mark the beginning of the coseismic interferograms and the end of the postseismic interferograms respectively.

**Figure 12.** Mapped faults in the Salton trough (solid labeled lines) and areas of slip identified by UAVSAR.

**Tables**

|  |  |  |
| --- | --- | --- |
| **Repeat Pass Interferometry Product**  **Description** | **Pass 1**  **Pass 2** | **Aircraft Heading** |
| SanAnd\_26505\_09083-006\_10027-005\_0174d\_s01\_L090\_02  Coseismic Imperial Valley | 2009/10/20  2010/04/12 | -95.35 |
| SanAnd\_26501\_09083-010\_10028-000\_0174d\_s01\_L090\_02  Coseismic along Mexican border | 2009/10/20  2010/04/13 | -95.33 |
| SanAnd\_26501\_10027-001\_10028-000\_0001d\_s01\_L090\_01  Immediate postseismic along border | 2010/04/12  2010/04/13 | -95.34 |
| SanAnd\_26501\_10028-000\_10057-100\_0079d\_s01\_L090\_01  Postseismic along border | 2010/04/13  2010/07/01 | -95.38 |
| SanAnd\_26501\_10057-100\_10084-000\_0153d\_s01\_L090\_01  Later postseismic along border | 2010/07/01  2010/12/01 | -95.38 |

Table 1. Repeat Pass Interferometry product identifiers, dates of passes, and aircraft heading, with a description of characteristics and location of the line.

|  |  |  |  |
| --- | --- | --- | --- |
| **Model** | **Single Fault** | **Two Faults** | |
|  |  | **Rupture** | **Yuha Fault** |
| **Latitude** | 32.641234 | 32.632167 | 32.729903 |
| **Longitude** | -115.752267 | -115.748914 | -115.740246 |
| **Strike** | 134.1 | 134.1 | 46 |
| **Dip** | -63.29 | -63 | -90 |
| **Length (km)** | 120 | 120 | 8 |
| **Depth (km)** | 0 | 0 | 0 |
| **Width (km)** | 11.1 | 11.2 | 0.5 |
| **Strike slip (cm)** | 131 | 145 | -8 |
| **Dip slip (cm)** | 94 | 87 | 0 |
| **Tensile slip (cm)** | 0.1 | 0 | 0 |
| **Moment (dyne/cm2)** | 6.4x1026 | 6.8x1026 | 9.5x1022 |
| **Mw** | 7.2 | 7.2 | 4.6 |
| **Cumulative Mw** | 7.2 | 7.2 | |
| **2/dof** | 3.5 | 3.5 | |

Table 2. Combined GPS and UAVSAR inversions for fault slip for a single fault model and for a primary fault and secondary conjugate fault. Fault latitude and longitude correspond to the NW end main rupture fault. The latitude and longidude of the Yuha fault corresponds to the SW corner of the fault. The depth of the fault corresponds to the top edge and a negative dip is downward to the NE for the mainshock rupture and vertical for the Yuha fault. In the final inversion reported in the table for the single fault model the depth, width, and all slip parameters were left free. For the two fault model the location, strike-slip, and dip-slip of the rupture were left free and the width and slip on the Yuha fault were left free. Other parameters were left free in earlier runs to minimize the residuals.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Model** | **Single Fault** | **Two Faults** | | **Three Faults** | | |
|  | **Aftershock** | **Aftershock** | **Yuha Fault** | **Aftershock** | **Rupture** | **Yuha Fault** |
| **Latitude** | 32.763021 | | 32.645506 | 32.763021 | 32.667297 | |
| **Longitude** | -116.000034 | | -115.822435 | -116.000034 | -115.805105 | |
| **Strike** | 128 | 128 | 36 | 128 | 128 | 36 |
| **Dip** | -83 | -83 | -90 | -83 | -83 | -90 |
| **Length (km)** | 18 | 20 | 9 | 18 | 25 | 6 |
| **Depth (km)** | 2 | 2 | 1 | 2 | 2 | .4 |
| **Width (km)** | 10 | 10 | 9 | 10 | 10 | 9 |
| **Strike slip (cm)** | 4 | 6.5 | -4.2 | 9.6 | 6.4 | -7.6 |
| **Dip slip (cm)** | 1 | 1 | 0 | 1 | 0 | 0 |
| **Tensile slip (cm)** | 0 | 0 | 0 | 0 | 0 | 0 |
| **Moment (dyne/cm2)** | 2.2X1024 | 3.9x1024 | 1x1024 | 5.2x1024 | 4.8x1024 | 1.2x1024 |
| **Mw** | 5.5 | 5.7 | 5.3 | 5.8 | 5.8 | 5.4 |
| **Cumulative Mw** | 5.5 | 5.8 | | 6.0 | | |
| **2/dof** | 1.54 | 1.2 | | 0.47 | | |

Table 3. UAVSAR inversions for postseismic motions. Fault latitude and longitude correspond to the NW ends of the afterhock and main rupture fault. The latitude and longidude of the Yuha fault corresponds to the SW corner of the fault. The depth of the fault corresponds to the top edge and a negative dip is downward to the NE for the aftershock and mainshock rupture and vertical for the Yuha fault. Strike slip is the only free parameter in the final inversion reported in the table, though other parameters were left free in earlier runs to minimize the residuals.

**Figures**

**Copyright Material**

**Supporting Nonprint Material**