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# DYNAMIC TRIGGERING IN THE COSO GEOTHERMAL FIELD, 2004-2013

by

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## Abstract

We take advantage of EarthScope's USArray Transportable Array (TA), regional seismic networks to investigate 154 $M \geq 7$ earthquakes over a ten-year period (2004- 2013), in search of remotely triggered seismicity within the continental United States. We conduct an automated search to detect high frequency signals (which may indicate triggering of small local earthquakes) using a time window of 5 hours before and after each mainshock. The automated detection applies a short-term average (STA) to long-term-average (LTA) algorithms, to create a catalogue of detections. Using the catalog we search for an increase in detection rates after each main-shock. Sharp increases in detection rates may indicate triggered seismicity that is either instantaneous or delayed.

Here, we use both STA/LTA detection methods and local earthquake catalogs to investigate remote triggering in the Coso Geothermal Field (CGF); geothermal sites have long been suggested as areas susceptible to remote triggering of seismicity. Of 154 remote mainshocks ($M$) $\geq 7$ studied, we find 34 mainshocks (22%) likely triggered local seismicity in the CGF region as a result of an imposing transfer of dynamic stress from the remote mainshock events. We assume there is a triggered response in the CGF based on the increase in the magnitude and frequency (rate) from pre-mainshock to post-mainshock auto-detection rates and cataloged seismicity. We observe both instantaneous (16 events) and delayed (18 events) triggering of local seismicity within ± 5 hours of the mainshock. We suggest remote triggering in the CGF region is enhanced by the orientation (back-azimuth) of the passing seismic waves. We find several events align favorably with the local stress field and/or orientation of NNE-SSW trending faults in the CGF triggered region. We find triggering and non-triggering mainshocks (in terms of generated peak dynamic stresses and mainshock parameters) display similar

patterns. From this we surmise triggering in the CGF region to be strongly dependent on the state of regional stresses. We suggest that triggering is more likely to occur when critically stressed fault exists, this fault can respond to the passage of dynamic stresses in a manner triggering failure of the fault.

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# Introduction

Earthquakes occur on a frequent basis worldwide, yet linkages among events has remained an outstanding question. Large magnitude ($M$) ≥ 7 events lead to devastating regional effects such as: ground shaking, subsidence, liquefaction, ground displacement and secondary effects such as tsunamis, flooding and fire. These events pose a direct danger to human life and infrastructure. These large earthquakes generate seismic wave energy that propagates through the Earth and can disturb the local stress field thousands of km away from the main-shock, and trigger seismicity.

Previous studies demonstrate that the passage of seismic waves originating from large Magnitude ($M$) ≥ 7 earthquakes, can trigger seismicity (i.e. small earthquakes and tremor) at remote distances [e.g., *Velasco et al*., 2008; *Guilhem et al*., 2010; *Chao et al*., 2012]. The disturbance leading to these triggered seismic events is typically interpreted as the product of propagating dynamic stresses produced by seismic waves. [*Hill et al*., 1993; *Brodsky et al*., 2000; *Kilb et al*., 2000; *Gomberg et al*., 2001, 2004; *West et al*., 2005, *Parsons et al*., 2012]. Large earthquakes produce surface waves that travel within the Earths crust as elastic disturbances that distort and modify stress on fault planes that lie in their paths [*Parsons et al*., 2012].

It is currently hypothesized that the main disturbance contributing to triggered seismic events is the passing of large amplitude surface waves of M ≥ 7 earthquakes [*Velasco et al*., 2008; *Peng et al*., 2009; *Peng et al*., 2011]. Important factors that control the potential of triggering an earthquake include the amplitude of the passing surface waves and the back azimuth angles of the surface waves (both Love and Rayleigh waves) [*Chao et al*., 2013]. Surface waves exhibit properties such as dispersion, geometric spreading and unique radiation patterns. Different periods of surface waves travel at different velocities and are therefore not

sharp arrivals as the wave energy is dispersed. Triggered seismic events can either occur instantaneously during the passage of seismic waves of mainshock or may be delayed [*Gonzalez-Huizar et al*., 2012].

How one earthquake leads to another can impact our understanding and definition of seismic hazards in the continental United States. To address this we take advantage of resources such as the Incorporated Research Institutes for Seismology (IRIS) Data Management Center (DMC), we obtained seismograms using the Standing Order of Data (SOD) interface from USArray's transportable array (TA) stations and regional seismic networks within the continental United States for a ten-year period (2004-2013). This investigation focuses on analyzing a time window of 5 hours before and 5 hours after 154 ($M$) ≥ 7 earthquakes, to detect high frequency signals that may indicate triggering of earthquakes within the continental United States. We search for instantaneous and delayed triggered seismic events, statistically significant changes in detection rates, and associations with existing catalogues. We find one region in particular, the Coso Geothermal Field, is susceptible to significant dynamic instantaneous and delayed triggering.

## Background

Earthquakes can be triggered by changes in static stress or dynamic stress [Velasco et al., 2008]. Triggering by static stresses only affect areas in the near- field (a few fault lengths away) of a main-shock rupture [Hill and Prejean, 2014]. Regions where static stresses are very small that show an increase in seismicity rates, after the associated main-shock, are assumed to be dynamically triggered. Dynamic stresses travel along the wavetrain of a main-shock and can influence the stress state and trigger earthquakes in the near field [*Kilb et al*., 2000] and regions thousands of km away from the main-shock [*Velasco et al*., 2008; *Brodsky et al*., 2000; *Tibi et al*., 2003]. Figure 1 depicts dynamic stress changes, primarily caused by surface waves that are assumed to be responsible in triggering distant aftershock.

Surface waves generate strain and previous studies of dynamic triggering have correlated individual surface wave components, Love and Rayleigh, with triggered seismicity [*Hill*, 2008; *Gonzalez-Huizar and Velasco*, 2011]. Triggered seismic events can either occur instantaneously during the passage of the seismic wavetrain of a main-shock or after a delayed period of time. The physical process involved in the dynamic triggering of earthquakes is still unclear, although several theories have been proposed. Hypotheses for triggering include induced fluid pressure changes [Brodsky and Prejean, 2005], deformation by seismic waves [Parsons, 2005], and coulomb stress changes (local discrete deformation) [*Kilb et al*., 2002; *Hill*, 2008]. It is likely that a combination of these processes take part in the remote triggering of earthquakes.

Dynamic triggering has been widely observed following the 1992 M=7.3 Landers, CA earthquake [*Hill et al*., 1993]. For example, the 2002 Denali earthquake [*Gomberg et al*., 2004; *Husen et al*., 2004; *Husker and Brodsky*, 2004; *Moran et al*., 2004; *Pankow et al*., 2004; *Prejean et al*., 2004], and the 2011 Tohoku earthquake [*Chao et al*., 2012; *Gonzalez-Huizar et al*., 2012].

*Gomberg et al.*, 2001 observed increased rates of seismicity in several localities in California following both the 1992 M=7.3 Landers and 1999 M=7.1 Hectors Mine earthquake, as well as a delayed increase in rates of seismicity (delayed triggering) in Long Valley, a volcanic region in California.

Observations of recent increases in seismicity in the midwestern United States may be related to deep wastewater injection sites [*van der Elts et al.*, 2013]. Fluid injection sites are susceptible to triggering by small changes in stress induced by the passage of seismic waves of distant large earthquakes. Most triggered injection sites have a long delay between the beginning of fluid injection and the start of seismicity, suggesting fluid injection can push a fault system into a critical state [*van der Elts et al.*, 2013]. Three sites: Prague, Oklahoma; Snyder, Texas; and Trinidad, Colorado hosted triggered events after large magnitude distant earthquakes: the Maule, Chile February 27 2010 M=8.8; Tohoku-oki March 11 2011 M=9.1; and Sumatra April 12 2012 M=8.6 [*van der Elts et al.*, 2013].

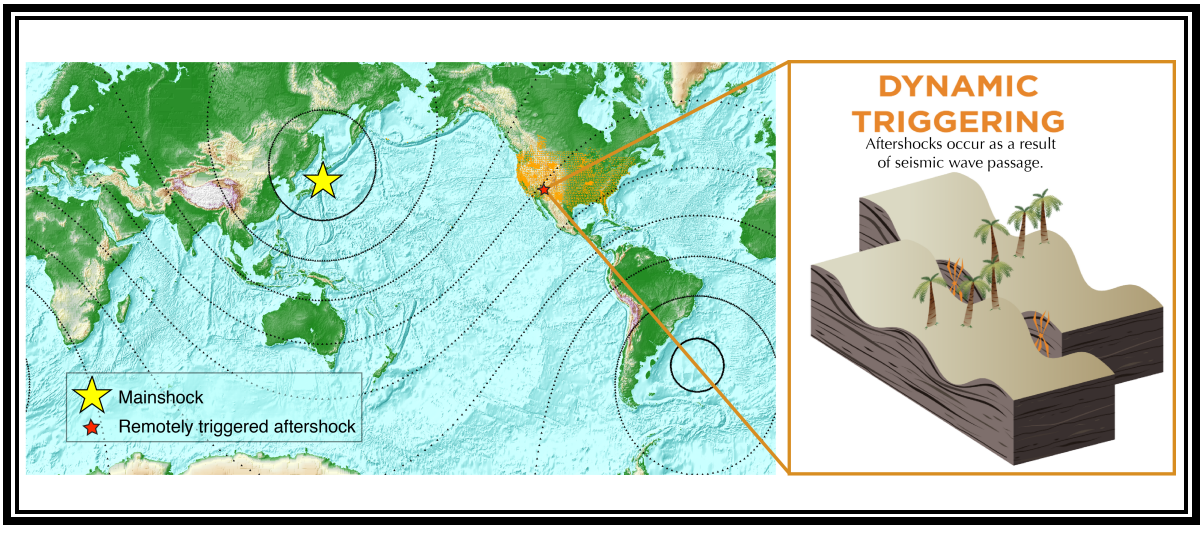



Figure 1: Illustration of the process of Dynamic Triggering of remote aftershocks. Taken from Velasco et al. (2015).

## Data and Data Analysis

We have obtained broadband 3-component data for the +450 stations in the USArray TA network and available regional seismic networks within the continental United States. The seismograms were obtained from Incorporated Research Institutes for Seismology (IRIS) Data Management Center (DMC) using the Standing Order of Data (SOD) interface for a ten-year period (2004-2013). This investigation focuses on analyzing a time window of 5 hours before and after 154 M ≥ 7 earthquakes (2004-2013) (Figure 2). We search for dynamically triggered earthquakes, aiming to identify significant increases in the rate of seismicity in the continental United States following the mainshock earthquake. To prepare data for analysis, we use the Antelope software package provided by Boulder Real Time Technologies, Inc (BRTT). We create an Antelope database for all seismogram data acquired by SOD, and perform automated detections on waveforms, as described below.

We conduct an automated search to identify and detect high frequency signals on 3-component station data. Our detection algorithms implement a time domain short-term average (STA) to long-term-average (LTA) ratio to identify signals above the noise level and create a catalog of detections (which may or may not indicate an earthquake). We use four STA/LTA algorithms (e.g., 1s/10s; 4 s/40 s; 8 s/80 s; 16 s/160s) [*Velasco et. al*, 2015], seeking to identify un-cataloged, locally recorded small earthquakes on a single station within continuous seismic data.

We first acquire seismogram data from ±5 hours of each main-shock event, generate and an Antelope database, high pass filter (5 Hz) the seismograms, and apply the automated STA/LTA algorithm for signal detections at each station recorded on three components. To remove any spurious detections we assume that a detection is real only if it was recorded on a

minimum of two channels (Figure 3). We statistically analyze results by comparing the seismicity rate 5-hours before and 5-hours after the main-shock event to identify an increase in seismicity rates (Figure 4) and to assess the potential for instantaneous and delayed triggering. Our preferred STA/LTA method of 4s/40s (STA/LTA) in combination with a requirement that assumes all real detections must be recorded on at least 2 channels at a single station effectively identifies small-triggered earthquakes [*Velasco et. al*, 2015].

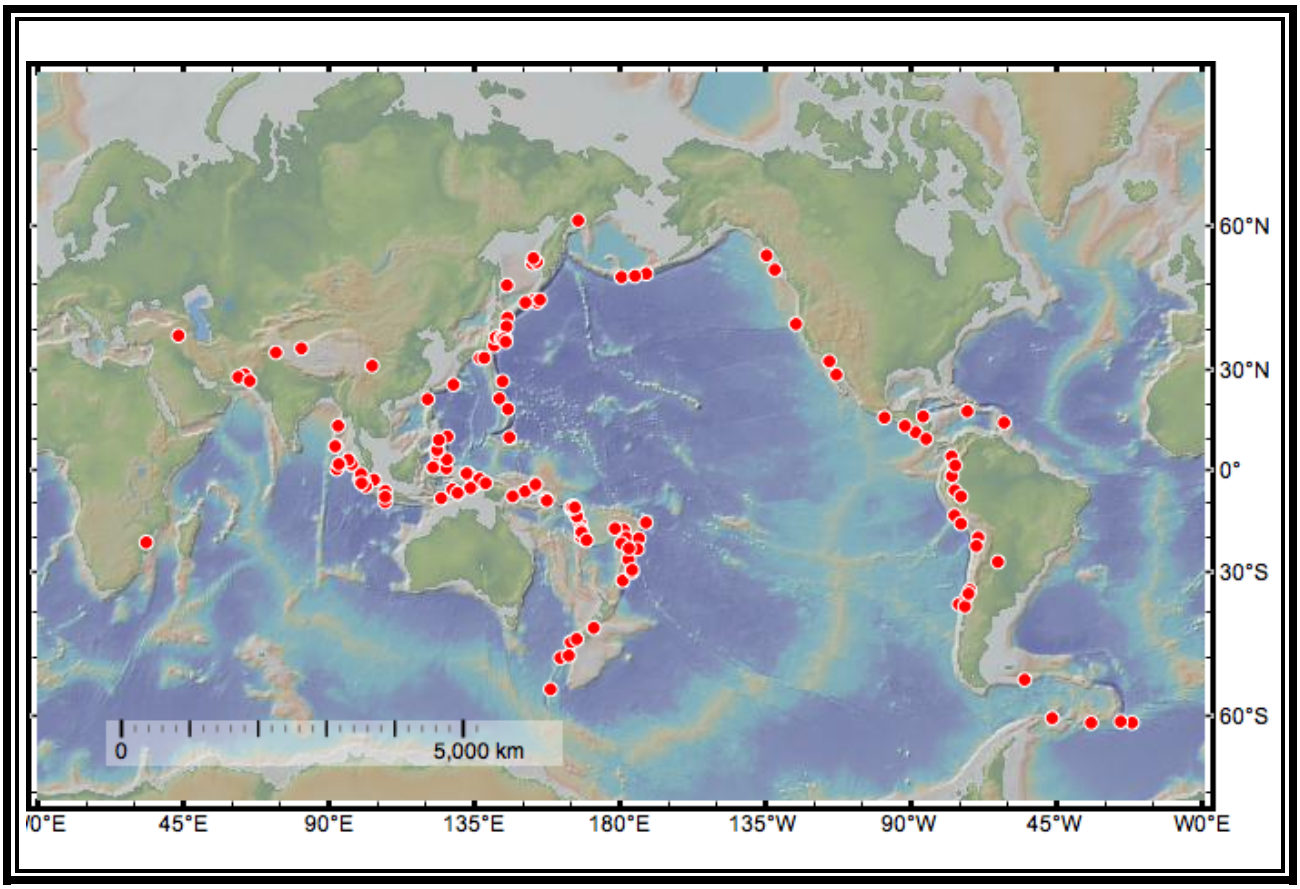
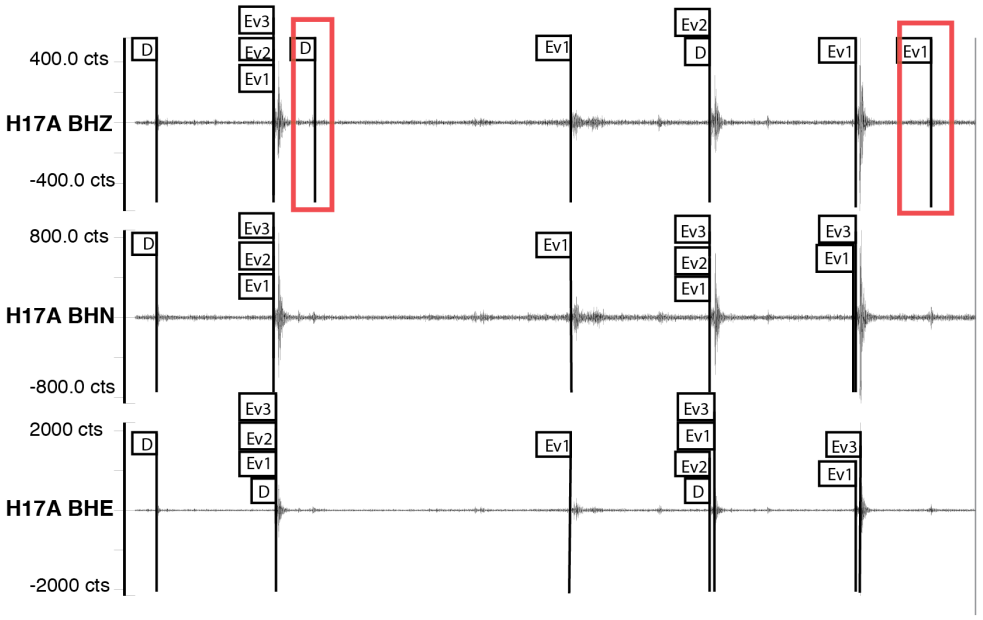


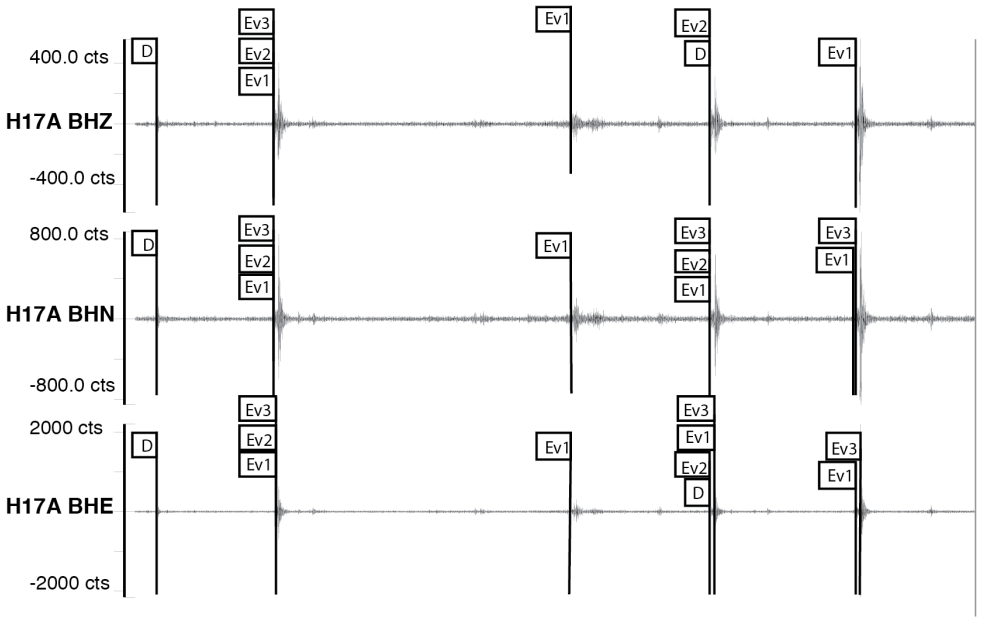

Figure 2: World map. Mercator projection, red circles indicated the locations of 154 M ≥ 7 mainshock earthquakes (2004-2013) in our study. We apply an automated detection algorithm to ± 5 hours of the mainshock origin times, to find dynamically triggered seismicity in the continental United States.

A) Seperate detections on each component




Filter: 5 HP, Amp: Auto

B) Detections required to exist on two-components




Filter: 5 HP, Amp: Auto

Figure 3: Seismogram from Yellowstone swarm December 29, 2008, recorded at station H17A. Vertical Black lines indicate STA/LTA algorithm detections with flags corresponding to ratios D=1 s/10 s; Ev1= 4 s/40 s; Ev2= 8 s/80 s; Ev3=16 s/160 s. (A) Initial detections derived from processing each channel individually (BHZ, BHN, BHE for vertical, horizontal North-South and horizontal east-west, respectively). (B) Detections that remain after removal of detections that were identified on only one component (i.e., we require a detection recorded on a minimum of two channels). In this example the first D-detected event is a false positive, Ev2 does not detect the last earthquake in the waveform and there is one event (mid-trace) that is only successfully detected by Ev1. Taken from Velasco et al. (2015).

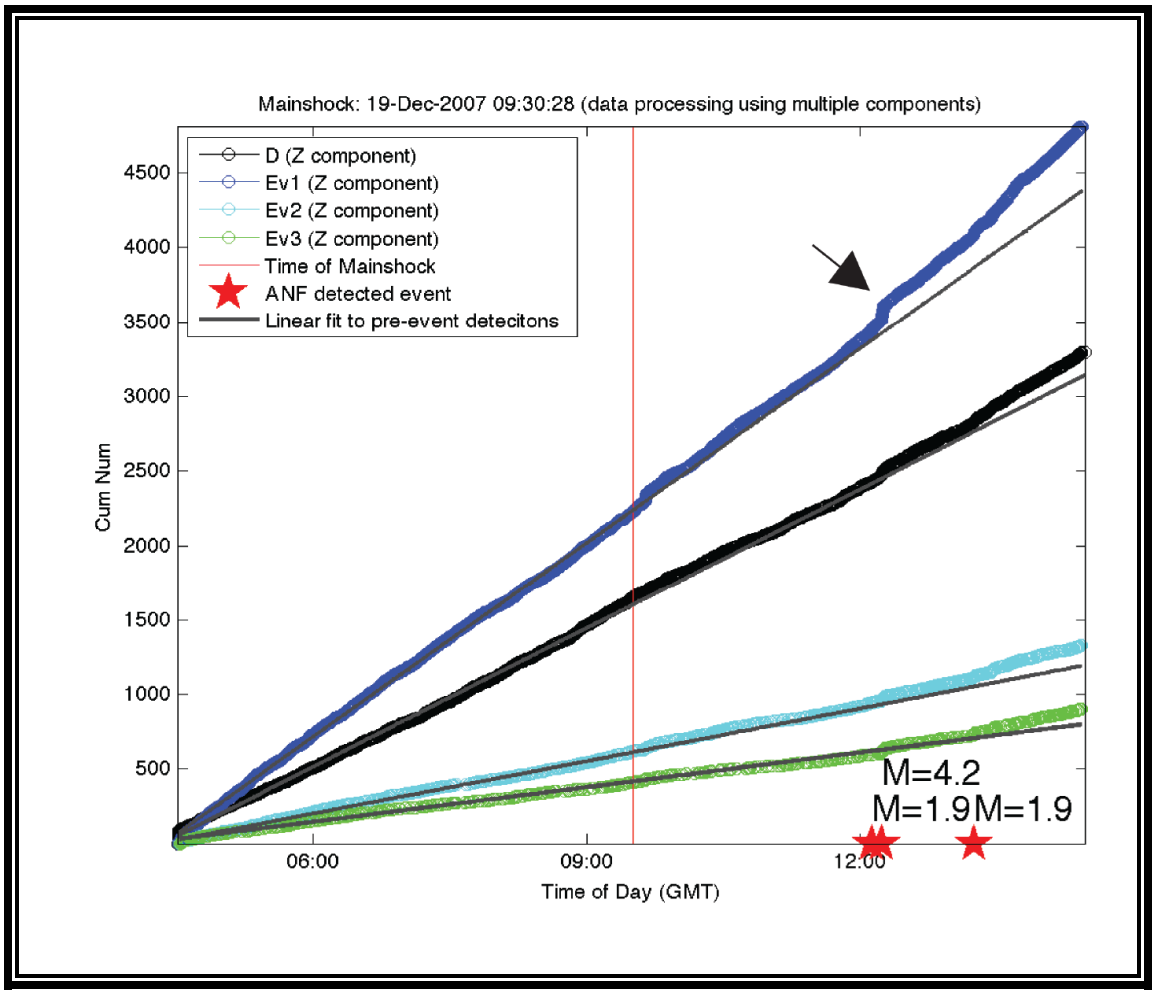



Figure 4: Cumulative number of detections plotted against time of day for the December 19, 2007 South Fiji Islands magnitude 7.8 earthquake. Automated time domain detections (D black; EV1 blue; Ev2 cyan; Ev3 green) corresponding to detection algorithms D= 1 s/10 s; Ev1= 4 s/40 s; Ev2= 8 s/80 s; Ev3= 16 s/160 s. Seismic stations within the continental United States, December 19, 2007 are used. Red stars correspond to events in then Array Network Facility (ANF) catalog, where the earthquake magnitude is listed above each star. Black arrow indicates a kink in detection where Ev1 (4 s /40 s) detections successfully at identify a real earthquake that corresponds to the ANF catalogue.

## Applying STA/LTA detectors to 154 Mainshocks

We apply four STA/LTA detectors (Velasco et al., 2015) to ±5 hours from the mainshock origin time for 154 M ≥ 7 earthquakes (2004-2013) (Figure 2) recorded by USArray. We assign the mainshock origin to time zero, stack the results from all 154 earthquakes at all stations, and count the number of detections at each station. We then color code detections by day and night, defining night as between 9PM-5AM local time and daytime 5AM-9PM local time. We find that for 76 events there appears to be a strong increase in the number of detections following the mainhshock, 49 events have a strong decrease in the number of detections following the mainshock, and 29 showed no change in detection rate following the mainshock (Figure 4). A decrease is counter to what we expected. If anything, we expected either no change in the number of detections (i.e., lack of remote triggering) or a slight increase in the number of detections (i.e., potentially elevated seismicity caused by remotely triggered small earthquakes). As noted in Velasco et al. (2015), an increase or decrease in the dectection rates (for the four STA/LTA detectors) may reflect anthropogenic noise. An increase may relate to the onset of daytime hours and a decreased rate of detections at the onset of nighttime hours. We find detection rates can indicate triggering in several cases when seismicity is prominent (Figure 4), although when waveforms are lacking seismic signals the STA/LTA detectors are prone to flag anthropogenic noise (Velasco et al., 2015). We discuss a successful identification of locally triggered seismicity using the Ev1 detection algorithm below.

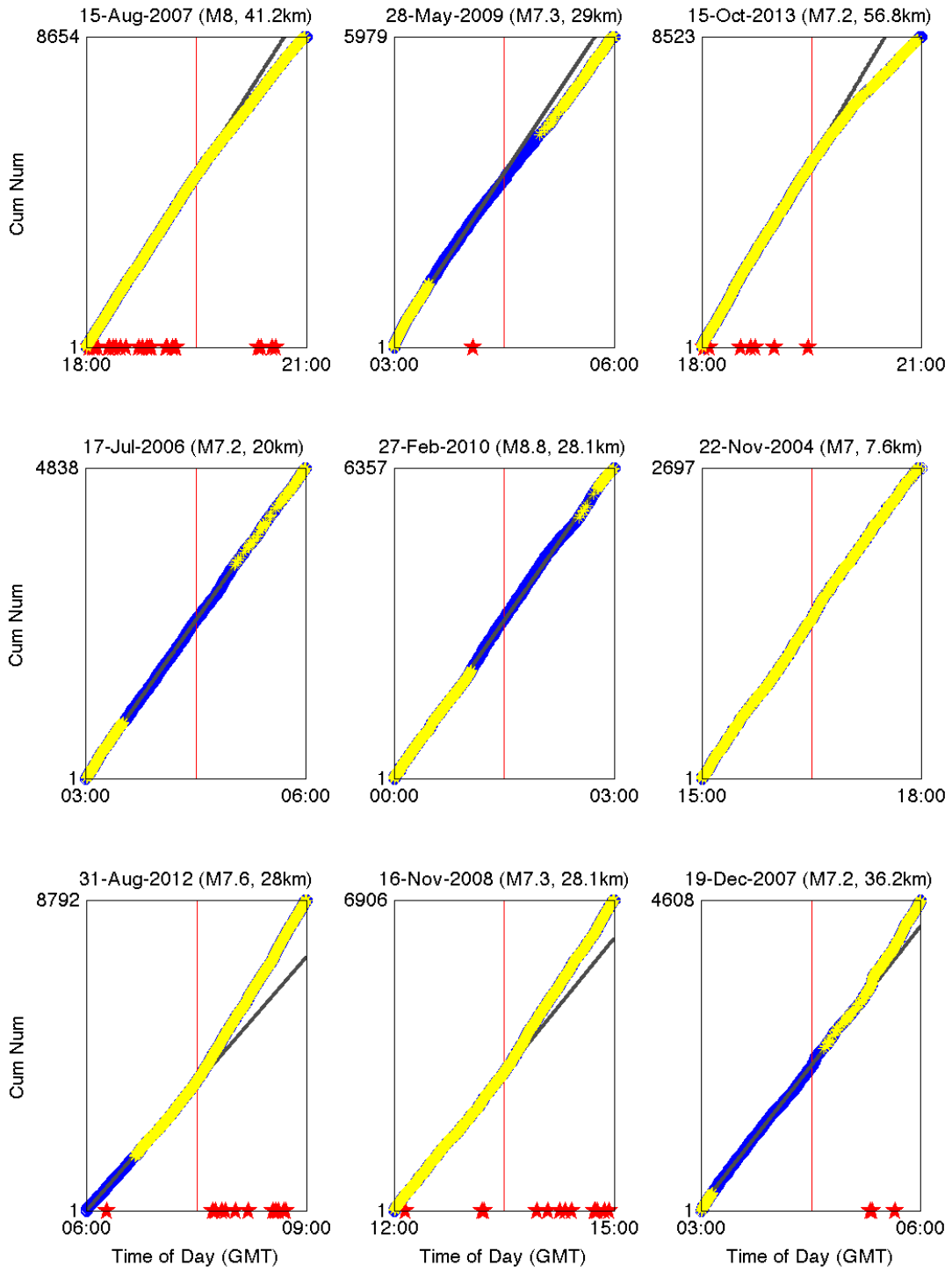

15-Aug-2007 (M8, 41.2km)
8654
1
18:00
21:00
28-May-2009 (M7.3, 29km)
5979
1
03:00
06:00
15-Oct-2013 (M7.2, 56.8km)
8523
1
18:00
21:00
Cum Num
17-Jul-2006 (M7.2, 20km)
4838
1
03:00
06:00
27-Feb-2010 (M8.8, 28.1km)
6357
1
00:00
03:00
22-Nov-2004 (M7, 7.6km)
2697
1
15:00
18:00
Cum Num
31-Aug-2012 (M7.6, 28km)
8792
1
06:00
09:00
16-Nov-2008 (M7.3, 28.1km)
6906
1
12:00
15:00
19-Dec-2007 (M7.2, 36.2km)
4608
1
03:00
06:00
Cum Num
Time of Day (GMT)
Time of Day (GMT)
Time of Day (GMT)

Figure 4: Examination of the stacked cumulative number of Ev1 detections as a function of time. We evaluate data within ±5 hours of the mainshock origin time, which is set to time zero. A linear fit to the pre-mainshock detections (grey line). The events can be categorized as: (top row) showing a decrease in the number of detections following the mainshock; (middle row) showing no change in the number of detections or (bottom row) showing a increase in the number of detections. The detections colored in yellow indicate a daytime detection.

## Identification of Locally Triggered Seismicity, Applying the Ev1 detection method to the Feb. 27, 2010 Offshore Bio-Bio (M=8.8) Chile earthquake

We apply the Ev1 detector to ±5 hours of USArray data with respect to the Feb. 27, 2010 Offshore Bio-Bio (M=8.8) Chile earthquake. This mainshock event occurred at 06:34:14 UTC, which at the centroid of the USArray network in Denver, Colorado, was 11:34:14 PM MST. The fact that these data were collected during nighttime hours at the recording site is optimal, as nighttime hours have much less anthropogenic noise (Astiz et al., 2014; Velasco et al., 2015). For this 2010 mainshock event, the Ev1 detector net a total of 6166 detections, of which 2971 (48%) occurred within the 5 hours following the mainshock. This result indicates no strong change in earthquake rate for these stacked data. However, if we repeat this exercise using data from each individual station separately, we find evidence of a rate increase following the mainshock. At station R11A, a high signal-to-noise station, we find evidence of three regional earthquakes during the mainshock coda (Figure 5). The first of these occurred at the time of the mainshock's S-wave passage and the largest of the three events occurred at the time of the Love wave, while the other, and smallest event, occurred between the mainshock's *S*-wave and Love-wave arrivals (Figure 5). The *Lg*- minus *P*-wave arrival times for all three small quakes (~38 sec) indicates these events are several hundred km from station R11A.

One location that is consistent with the 330 km distance from station R11A is Coso Junction, CA (longitude=-115.6°; Lattitude=38.35°). Based on the Southern California Seismic Network catalog, we determined the Coso region (33.5 ≤ Latitude ≤36.5; -119 ≤ Longitude ≤ -117) has a magnitude of completeness threshold of about magnitude one. Limiting the catalog to only events at or about magnitude one, we find that within a week-prior and a week-after the passage of seismic waves from the Chile mainshock the our Coso, CA, region catalog contains

23 ($1 \leq M_L \leq 2.8$) and 66 events ($1 \leq M_L \leq 3.8$), respectively (Table 1). Specifically we find an increase in seimic activity near Coso began after the passage of the *S*-wave (Figure 5) [*Peng et al*., 2010a]. This increase in seismic activity suggests these events may constitute remote aftershocks from the M8.8 Chile earthquake triggered in the Coso Geothermal field, where in this case the onset of triggering began with the S-wave.

As a second test, to investigate if this increase in seismic activity in the Coso region is out of the norm, we examine the 1373 earthquakes in the region that occurred in the year 2010, which are at or above the magnitude of completeness level ($M_L \geq 1$). On average this equates to about 4 earthquakes a day (1 every 6 hours), or about 28 earthquakes a week. This expected 28 events per-week value is on-par with the 23 events observed in the week prior to the Chile mainshock, but the 66 events in the week following the mainshock are a factor of three higher.

We know that the Coso region is subject to bursts of seismic activity, so we conduct a third test that uses the time separation between consecutive events. For the full catalog of 1373 events in the year 2010 catalog, the median time between consecutive events is 2.88 hours. Whereas for the 66 events in the week after the mainshock the median time between consecutive events is 1.08 hour, a factor of almost three smaller. Taken together these three tests suggest that the increase in seimsic events in the week following the passage of the seismic waves from the Chile M8.8 mainshock is elevated in comparison with the typical background seismicity for the year 2010 near Coso Junction, CA by examining both the Southern California Seismic Network (SCSN) earthquake catalog and continuous waveform recordings. Finding the Ev1 method successfully Identifies dynamically triggered seismicity corresponding to the Coso Geothermal Field, we focus our study specifically on Coso region to investigate the behavior of the site over 2004-2013.

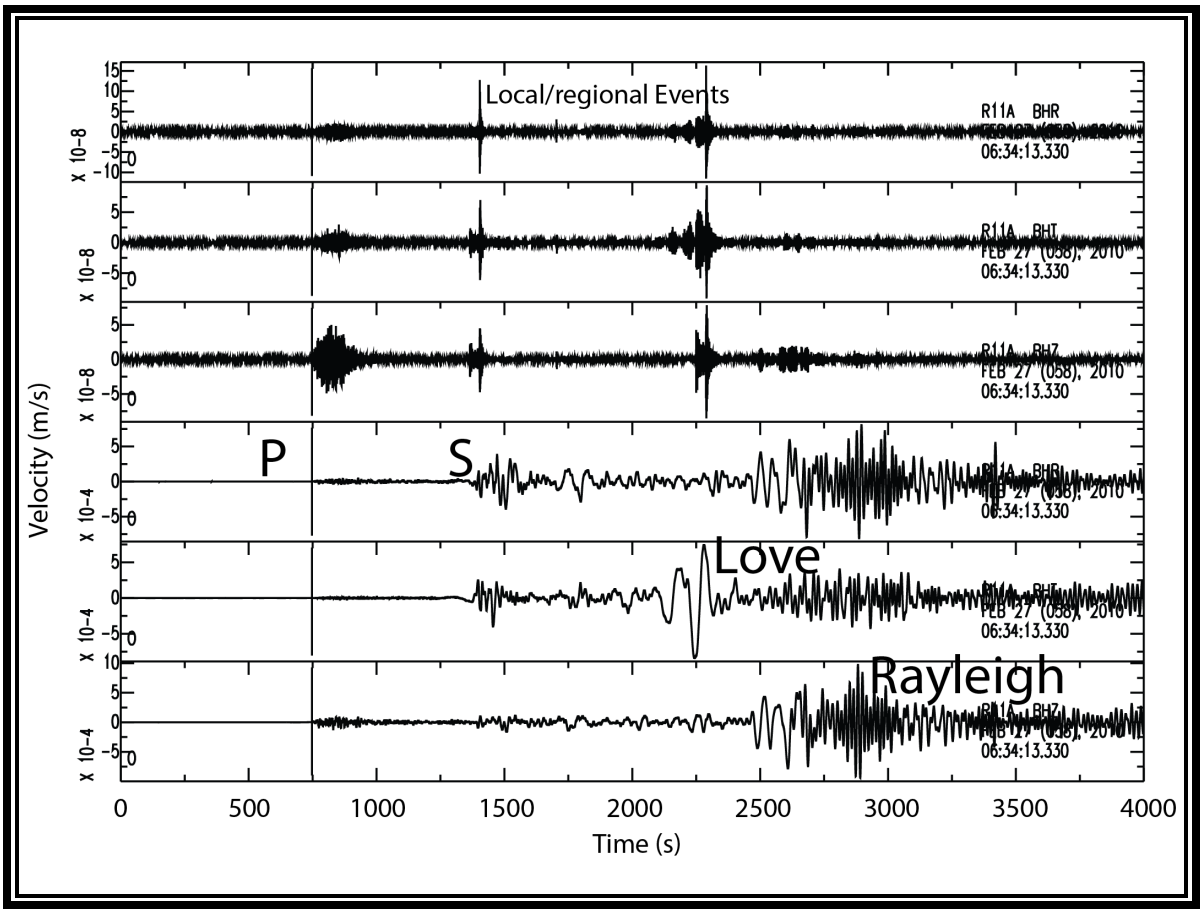



Figure 5: Seismic waveforms from the 27 February 2010 06:34:14 M=8.8 Offshore Bio Bio, Chile earthquake recorded at USArray TA station R11A. Top three waveforms are High pass at 5Hz, which removes the surface wave signal and reveals three regional events in the mainshock coda wave that arrive at the time of the S-wave (first event) the Love-wave (third and largest event) and at a time in between the S- and Love wave (second and smallest event). Bottom three waveforms display the raw waveform data. Taken from Velasco et al. (2015).

Table 1: Events near Coso Junction, CA (33.5 ≤ Latitude ≤36.5; -119 ≤ Longitude ≤ -117), which occurred within ±1 week of the 27 February 2010 Chile earthquake (thicker line demarks the transition from before the mainshock to after the mainshock). These earthquakes range in magnitude from the completeness threshold of magnitude 1.0 up to a magnitude 3.8 event. Of these, there are only 5 events at or above magnitude 2 (none of which are above magnitude 3) in the week prior, to the mainshock whereas 23 events at or above magnitude 2 (6 of which are above magnitude 3) in the week after the mainshock.

| ID | Magnitude | Date | Time | Latitude | Longitude | Depth (km) |
|---|---|---|---|---|---|---|
| 10546173 | 1.51 | 2010/02/22 | 21:42:37 | 35.9380 | -117.6400 | 3.90 |
| 10546189 | 2.50 | 2010/02/22 | 21:55:31 | 35.7530 | -118.9990 | 21.30 |
| 10546285 | 1.73 | 2010/02/23 | 03:49:36 | 35.9240 | -117.2750 | 6.80 |
| 10546757 | 2.33 | 2010/02/24 | 00:30:19 | 36.0640 | -117.8670 | 4.50 |
| 10546885 | 1.03 | 2010/02/24 | 04:15:30 | 35.9550 | -117.6530 | 3.10 |
| 10547061 | 1.28 | 2010/02/24 | 11:40:08 | 36.1150 | -117.6590 | 5.40 |
| 10547109 | 1.13 | 2010/02/24 | 14:57:48 | 36.0570 | -117.8820 | 5.90 |
| 10547221 | 1.10 | 2010/02/24 | 22:09:42 | 36.0550 | -117.8510 | 5.10 |
| 10547261 | 1.11 | 2010/02/25 | 00:34:27 | 36.0690 | -117.8590 | 0.70 |
| 10547309 | 1.53 | 2010/02/25 | 03:18:06 | 36.1060 | -117.7160 | 2.40 |
| 10547365 | 1.03 | 2010/02/25 | 09:53:12 | 35.9750 | -117.6480 | 3.30 |
| 14594612 | 1.42 | 2010/02/26 | 02:55:32 | 35.9310 | -117.2870 | 4.90 |
| 14594620 | 1.45 | 2010/02/26 | 03:43:09 | 36.0390 | -117.8370 | 0.00 |
| 14594628 | 1.40 | 2010/02/26 | 04:43:32 | 36.0680 | -117.8440 | 2.70 |
| 14594692 | 1.18 | 2010/02/26 | 10:11:47 | 36.0630 | -117.8730 | 1.80 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 14594708 | 2.64 | 2010/02/26 | 12:46:43 | 36.0630 | -117.8710 | 2.80 |
| 14594716 | 1.63 | 2010/02/26 | 13:03:22 | 36.0630 | -117.8770 | 2.70 |
| 14594724 | 2.69 | 2010/02/26 | 13:22:53 | 36.0730 | -117.8800 | 2.90 |
| 14594860 | 2.79 | 2010/02/26 | 20:12:05 | 36.0640 | -117.8720 | 2.80 |
| 28253759 | 1.06 | 2010/02/27 | 01:25:05 | 35.9310 | -117.2640 | 6.40 |
| 14594900 | 1.78 | 2010/02/27 | 01:25:17 | 35.9320 | -117.2590 | 6.20 |
| 14594924 | 1.14 | 2010/02/27 | 02:45:31 | 36.0650 | -117.8670 | 4.60 |
| 14594956 | 1.79 | 2010/02/27 | 04:52:16 | 36.0700 | -117.8710 | 4.40 |
| **LINE** | **LINE** | **LINE** | **LINE** | **LINE** | **LINE** | **LINE** |
| 14594996 | 2.91 | 2010/02/27 | 06:56:03 | 36.0730 | -117.8780 | 2.50 |
| 14595004 | 2.10 | 2010/02/27 | 07:01:03 | 36.0710 | -117.8820 | 1.50 |
| 14595012 | 3.45 | 2010/02/27 | 07:10:48 | 36.0620 | -117.8880 | 0.60 |
| 14595020 | 2.26 | 2010/02/27 | 07:21:55 | 36.0690 | -117.8880 | 2.00 |
| 14595076 | 1.52 | 2010/02/27 | 09:34:55 | 36.0670 | -117.8830 | 1.30 |
| 14595140 | 1.35 | 2010/02/27 | 11:59:15 | 36.0670 | -117.8810 | 3.70 |
| 14595156 | 1.56 | 2010/02/27 | 13:54:16 | 36.0710 | -117.8690 | 4.60 |
| 14595164 | 3.11 | 2010/02/27 | 13:56:39 | 36.0660 | -117.8830 | 2.00 |
| 14595172 | 3.30 | 2010/02/27 | 15:01:36 | 36.0610 | -117.8770 | 2.60 |
| 14595180 | 1.26 | 2010/02/27 | 15:19:22 | 36.0690 | -117.8630 | 4.50 |
| 14595196 | 1.29 | 2010/02/27 | 15:57:26 | 36.0640 | -117.8700 | 3.90 |
| 14595236 | 1.13 | 2010/02/27 | 18:59:31 | 36.0760 | -117.8700 | 4.00 |
| 14595244 | 1.47 | 2010/02/27 | 19:08:07 | 36.0590 | -117.8820 | 2.50 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 14595276 | 1.47 | 2010/02/27 | 19:56:40 | 36.0620 | -117.8760 | 2.70 |
| 14595284 | 1.09 | 2010/02/27 | 20:12:48 | 36.0560 | -117.9070 | 5.70 |
| 14595292 | 2.80 | 2010/02/27 | 20:23:54 | 36.0630 | -117.8890 | 0.10 |
| 14595316 | 1.82 | 2010/02/27 | 23:25:46 | 36.0610 | -117.8760 | 2.60 |
| 14595380 | 1.76 | 2010/02/28 | 02:26:15 | 36.0690 | -117.8650 | 4.30 |
| 14595452 | 3.43 | 2010/02/28 | 06:30:17 | 36.0600 | -117.8820 | 0.90 |
| 28213759 | 2.60 | 2010/02/28 | 06:30:41 | 36.0600 | -117.8780 | 1.10 |
| 14595460 | 1.76 | 2010/02/28 | 06:38:04 | 36.0710 | -117.8710 | 4.10 |
| 14595468 | 3.13 | 2010/02/28 | 06:56:29 | 36.0610 | -117.8790 | 2.70 |
| 14595476 | 2.58 | 2010/02/28 | 07:08:48 | 36.0620 | -117.8790 | 2.40 |
| 14595556 | 1.48 | 2010/02/28 | 14:22:33 | 36.0680 | -117.8600 | 4.80 |
| 14595580 | 1.49 | 2010/02/28 | 15:59:36 | 36.0660 | -117.8730 | 4.10 |
| 14595628 | 1.26 | 2010/02/28 | 22:30:28 | 36.0600 | -117.8740 | 2.90 |
| 14595676 | 1.54 | 2010/03/01 | 00:23:23 | 35.8050 | -118.5370 | 5.50 |
| 14595684 | 1.13 | 2010/03/01 | 01:04:20 | 36.0390 | -117.8190 | 1.30 |
| 14595708 | 1.67 | 2010/03/01 | 02:20:37 | 36.0640 | -117.8700 | 3.00 |
| 14595756 | 1.27 | 2010/03/01 | 04:46:10 | 36.0630 | -117.8720 | 2.80 |
| 14595764 | 1.46 | 2010/03/01 | 05:03:24 | 36.1000 | -117.7980 | 7.90 |
| 14595820 | 3.76 | 2010/03/01 | 09:06:03 | 36.0700 | -117.8790 | 0.90 |
| 14595828 | 2.10 | 2010/03/01 | 09:16:04 | 36.0690 | -117.8710 | 2.20 |
| 14595844 | 1.93 | 2010/03/01 | 09:24:06 | 36.0660 | -117.8680 | 2.70 |
| 14595852 | 1.21 | 2010/03/01 | 09:29:57 | 36.0650 | -117.8670 | 4.30 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 14595868 | 2.75 | 2010/03/01 | 10:32:08 | 36.0640 | -117.8700 | 2.20 |
| 14595876 | 2.61 | 2010/03/01 | 10:39:40 | 36.0650 | -117.8760 | 2.50 |
| 10144402 | 2.75 | 2010/03/01 | 10:40:00 | 36.0650 | -117.8820 | 1.90 |
| 14595884 | 1.20 | 2010/03/01 | 10:46:49 | 36.0700 | -117.8850 | 2.20 |
| 14595892 | 2.31 | 2010/03/01 | 10:50:57 | 36.0690 | -117.8750 | 0.60 |
| 14595916 | 2.11 | 2010/03/01 | 12:36:38 | 36.0690 | -117.8810 | 2.40 |
| 14595964 | 1.15 | 2010/03/01 | 16:29:00 | 35.9510 | -117.6290 | 4.40 |
| 10144566 | 1.44 | 2010/03/01 | 16:29:16 | 36.0920 | -117.8660 | 0.00 |
| 14596172 | 1.00 | 2010/03/02 | 05:31:10 | 36.0530 | -117.8720 | 5.20 |
| 14596196 | 1.47 | 2010/03/02 | 06:57:33 | 36.0660 | -117.8690 | 3.50 |
| 14596204 | 3.47 | 2010/03/02 | 07:22:54 | 36.0650 | -117.8730 | 2.50 |
| 10144482 | 2.20 | 2010/03/02 | 07:23:28 | 36.0630 | -117.8600 | 3.40 |
| 14596212 | 1.86 | 2010/03/02 | 07:26:16 | 36.0660 | -117.8810 | 2.10 |
| 14596228 | 1.39 | 2010/03/02 | 07:48:53 | 36.0610 | -117.8730 | 2.40 |
| 14596252 | 1.06 | 2010/03/02 | 08:20:27 | 36.0600 | -117.8660 | 5.00 |
| 14596260 | 1.21 | 2010/03/02 | 08:30:22 | 36.0580 | -117.8700 | 4.70 |
| 14596308 | 1.73 | 2010/03/02 | 14:39:00 | 36.0640 | -117.8730 | 3.00 |
| 14596340 | 1.06 | 2010/03/02 | 17:58:25 | 36.0620 | -117.8660 | 4.90 |
| 14596388 | 1.61 | 2010/03/02 | 20:42:46 | 35.9830 | -117.3250 | 6.10 |
| 14596420 | 1.01 | 2010/03/03 | 01:15:57 | 36.0650 | -117.8780 | 0.70 |
| 14596508 | 1.22 | 2010/03/03 | 07:07:41 | 36.0590 | -117.8800 | 2.50 |
| 14596564 | 1.68 | 2010/03/03 | 12:08:36 | 36.3220 | -117.9200 | 8.30 |

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|---|---|---|---|---|---|---|
| 14596796 | 1.24 | 2010/03/04 | 04:32:03 | 35.6380 | -118.3930 | 8.80 |
| 14596924 | 1.08 | 2010/03/04 | 18:32:23 | 36.0720 | -117.8530 | 4.20 |
| 14596972 | 1.49 | 2010/03/04 | 23:45:46 | 35.6830 | -118.2000 | 11.20 |
| 14596988 | 1.08 | 2010/03/05 | 02:35:58 | 36.0700 | -117.8740 | 4.50 |
| 14597012 | 2.94 | 2010/03/05 | 03:46:25 | 36.1380 | -117.8390 | 1.10 |
| 14597044 | 1.19 | 2010/03/05 | 08:39:02 | 36.1400 | -117.8430 | 5.60 |
| 14597060 | 1.07 | 2010/03/05 | 09:04:43 | 36.0550 | -117.8440 | 4.90 |
| 14597092 | 2.09 | 2010/03/05 | 11:43:22 | 35.7120 | -117.6330 | 12.90 |
| 14597372 | 1.09 | 2010/03/06 | 05:31:35 | 36.0940 | -117.8440 | 1.60 |

# The Coso Geothermal Field a Regional Case Study

## COSO GEOTHERMAL FIELD: GEOLOGY

The Coso Geothermal Field (CGF) is located to east of the Sierra Nevada between Owens Valley and the Garlock fault in southern California within the present-day Basin and Range province (Figure 6). The CGF, situated above a shallow heat source (presumed to be a partially molten magma body) and is one of the most seismically active regions in the continental United States. The CGF is a highly-fractured, trans-tensional region [*Davatzes and Hickman*, 2006] affected by to both strike-slip and normal faulting. Faults within the CGF can be divided into two groups: 1) WNW striking dextral strike slip faults and minor NE trending faults sinistral strike-slip [*Duffield et al*., 1980; *Roquemore*, 1984] that are relatively inactive by [*Davatzes and Hickman*, 2006] and 2) N to NNE striking normal faults that dip both west and east (Figure 7). According to Davatzes and Hickman (2006) the most prominent of these fault systems in the CGF is the Coso Wash normal fault which coincides with the eastern margin of the geothermal field. The Coso Wash fault is composed of several *en-echelon* NNE- SSW trending segments variably connected by NW- trending faults [*Davatzes and Hickman*, 2006]. Based on previous studies of geomorphic expression, offset hydrothermal deposits and basalt flow Davatzes and Hickman (2006) interpret these faults to be actively slipping.

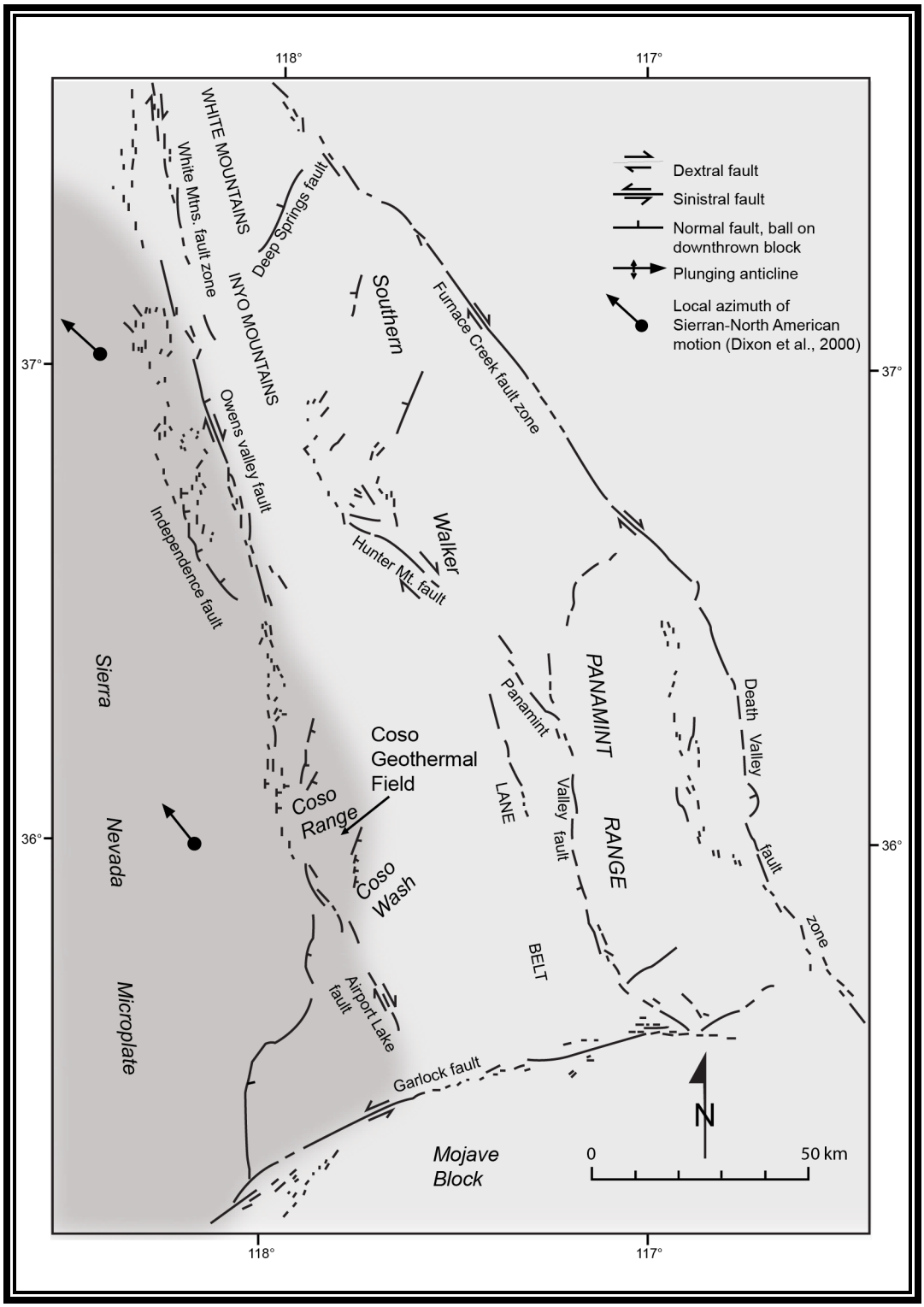



Figure 6: Regional location map of the Coso Range and the southern Walker Lane belt. Dark shading indicates the extent of the rigid Sierra Nevada microplate. Note that there is a right-releasing jog along the eastern margin of the Sierran microplate at the latitude of the Coso Range. Figure redrafted and modified from Unruh et al. (2008).

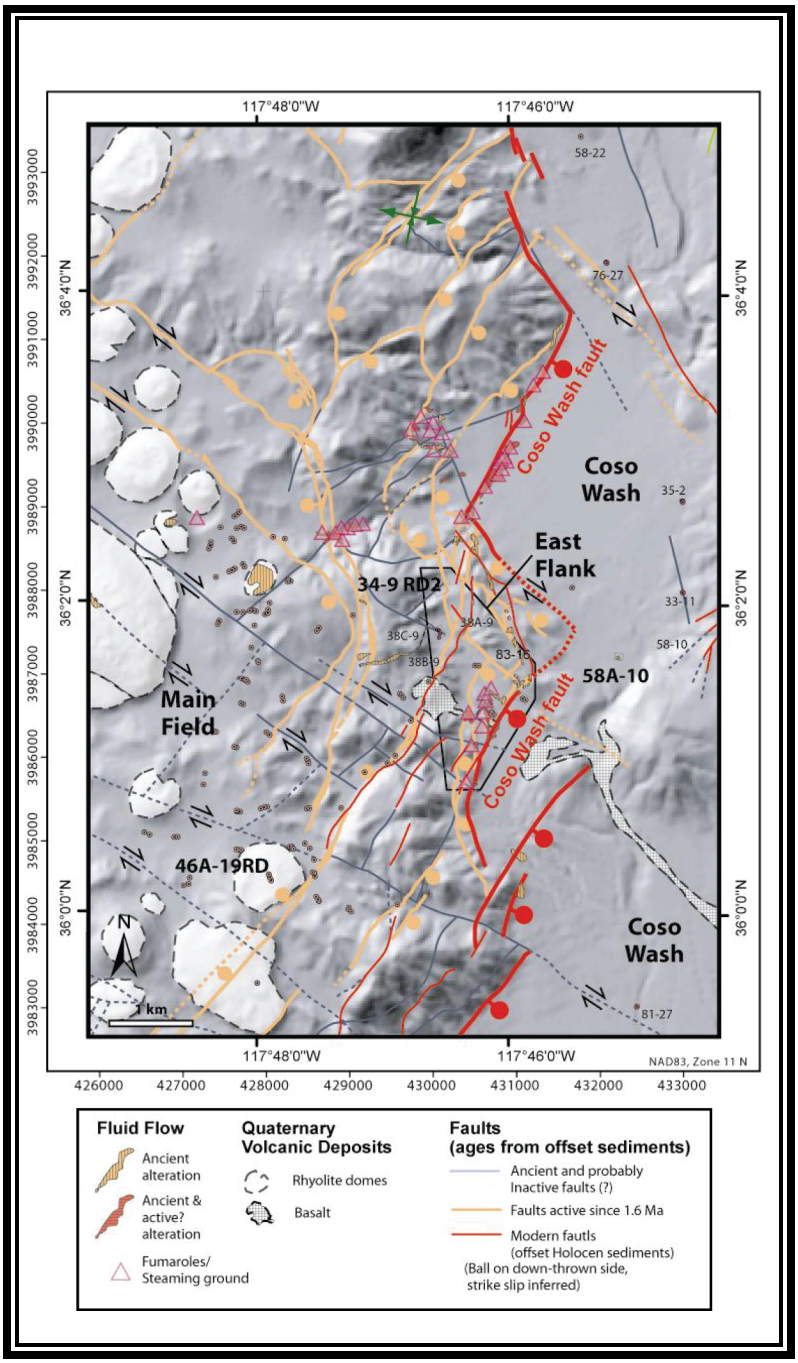



Figure 7: Tectonic map of the east flank of the Coso geothermal field over shaded relief image of topography. Figure modified from Davatzes and Hickman (2006)

## COSO GEOTHERMAL FIELD: DATA AND METHODS

Dynamic stresses from large mainshocks tend to preferentially trigger remote earthquakes in geothermal areas. Given this, the CGF presents an ideal study site to observe the interaction of dynamic stresses produced by M ≥ 7 earthquakes and the local stress field. Remotely triggered seismicity in the CGF has been clearly documented [e.g., *Hill et al*., 1993; *Prejean et al*., 2004; *Peng* 2010a; *Aiken and Peng*, 2014]. The Southern California Seismic Network (SCSN) [*Hutton et al*., 2010] maintains an extensive catalog, to which we can compare our database of detections.

We investigate triggering at CGF and the surrounding region, implementing a combination visual inspection, detection catalog (applying the Ev1 STA/LTA algorithm), and the SCSN catalog. We identify instantaneous triggered seismicity within the wavetrain of the mainshock earthquake and or delayed triggered seismicity within 5 hours of the initial mainshock. We first generate individual databases for all 154 mainshock events from our main Antelope database. We include all available waveform data for TA and CI network stations within a 400 km radius of the CGF (Figure 8), we then apply the a 4s/40s (Ev1) STA/LTA detection algorithm [Velasco et. al, 2015] to ± 5 hours of all 154 events from 2004-2013. We compile catalog data for ±5 hours for each of the 154 mainshock event. We also request local earthquakes in a box defined as 35.5°N–36.5°N, 119°W–117°W with a minimum magnitude of $M_L = 0$. Catalog data from the Southern California Seismic Network (SCSN, network code CI) were accessed from the Southern California Earthquake Data Center (last accessed Feb. 2015, http://scedc.caltech.edu). We then visually inspect waveform data using detections and catalogue data as a guide to identify locally triggered events.

We compute the mainshock generated peak dynamic stress (PDS) at six seismic stations (TA-HELL, TA-R11A, CI-MPM, CI-CWC, CI-SLA, CI-CLC) following the method in Pankow et al. [2004], where peak vector velocities are computed using three-component broadband data

and multiplied by shear modulus/ Love wave group velocity (μ = 33000 MPa, U = 3.5 km/s). We then average the PDS between these stations for each mainshock (Table 2). We then examine the average PDS values as a function of mainshock: magnitude, distance, depth, and back-azimuth for each triggering and non-triggering mainshock.

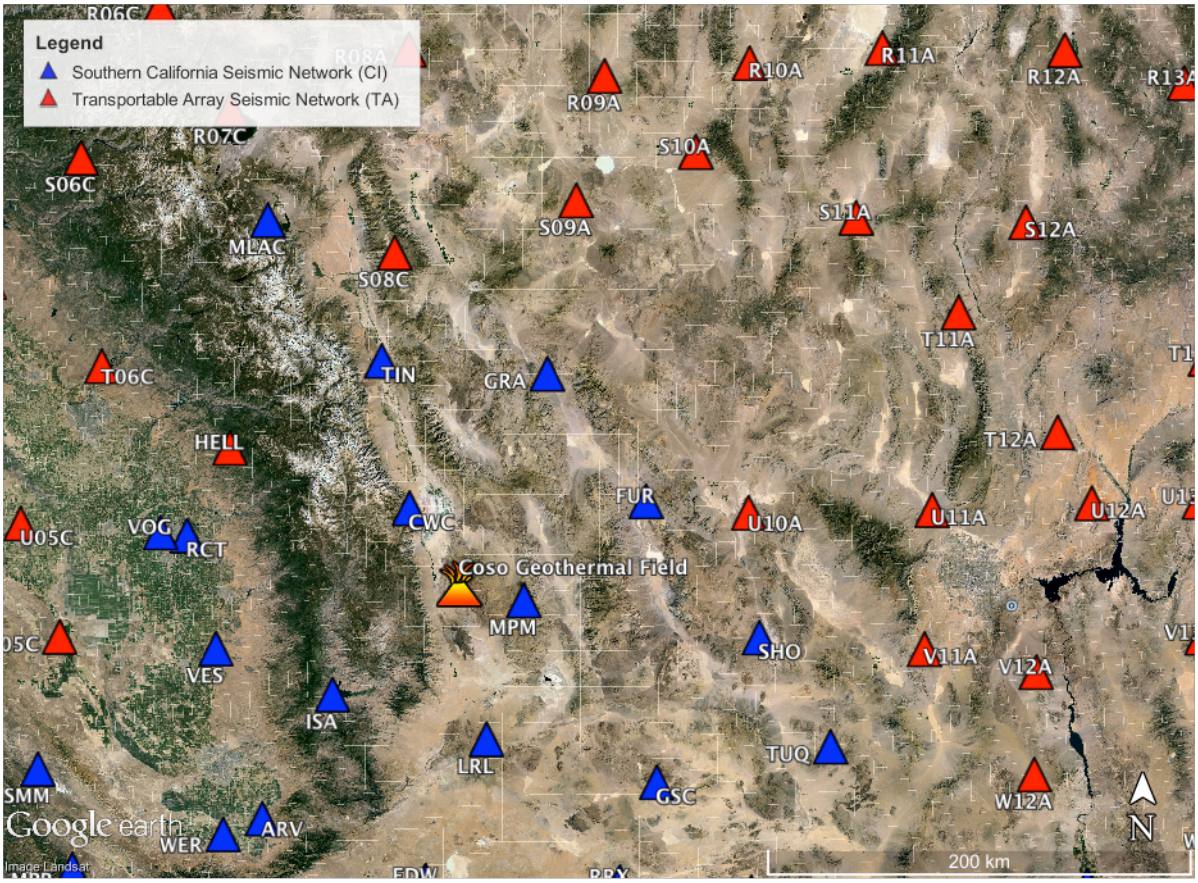


Figure 8: Google Earth satellite image of the Coso Geothermal Field and surrounding region. Red triangles indicate USArray Transportable Array (TA) station locations, blue triangles represent Southern California Seismic Network (SCSN, network code-CI) station locations. The centroid of the Coso Geothermal Field is indicated by the orange-yellow volcano shaped symbol.

Table 2: Mainshock parameters, including distance and back-azimuth, which are calculated with respect to SCSN CI-Network Code station MPM (36.06 N, -117.49 E). We compute the average mainshock generated peak dynamic stress (PDS) at six seismic stations (TA-HELL, TA-R11A, CI-MPM, CI-CWC, CI-SLA, CI-CLC). PDS values are averaged between each of the six stations. Rows Highlighted in Green indicate the mainshock triggered local seismicity in the Coso Geothermal Field or surrounding region.

| Date | Time (UTC) | Lat | Lon | Mag | Depth (Km) | Distance (Km) to CI.MPM | Azimuth (Deg) CI.MPM | Back-Azimuth (Deg) to CI.MPM | Peak Dynamic Stress (PDS) |
|---|---|---|---|---|---|---|---|---|---|
| 02/07/2004 | 02:42:34 | -4.03 | 135.09 | 7.3 | 15 | 11953.2 | 265.805 | 91.2549 | 0.000951909 |
| 07/15/2004 | 04:27:13 | -17.7 | -178.77 | 7 | 560 | 6984.07 | 250.127 | 80.5988 | 0.000522767 |
| 07/25/2004 | 14:35:17 | -2.49 | 103.97 | 7.3 | 581.9 | 15415.7 | 266.267 | 92.7966 | 0.000674331 |
| 09/05/2004 | 14:57:17 | 33.21 | 137.07 | 7.4 | 10 | 11488.3 | 303.906 | 81.2741 | 0.000725826 |
| 09/05/2004 | 10:07:07 | 33.07 | 136.73 | 7 | 18.7 | 11454.5 | 304.004 | 81.437 | 0.000598295 |
| 11/11/2004 | 21:26:42 | -8.15 | 124.74 | 7.4 | 23.1 | 13076.8 | 260.867 | 94.2415 | 0.001028384 |
| 11/15/2004 | 09:06:55 | 4.74 | -77.47 | 7.2 | 15 | 4480.49 | 82.7011 | 264.417 | 0.001352797 |
| 11/22/2004 | 20:26:23 | -46.5 | 164.83 | 7 | 7.6 | 9075.34 | 223.026 | 81.0269 | 0.000775071 |
| 11/26/2004 | 02:25:00 | -3.65 | 135.41 | 7 | 5.1 | 11918.6 | 266.207 | 91.1146 | 0.000730408 |
| 11/28/2004 | 18:32:12 | 42.9 | 145.21 | 7 | 42.8 | 10615.3 | 312.941 | 85.0335 | 0.001738581 |
| 12/23/2004 | 14:59:00 | -49.71 | 161.58 | 8 | 10 | 9365 | 220.124 | 83.0775 | 0.006890485 |
| 12/26/2004 | 00:58:52 | 3.41 | 95.9 | 9.1 | 26.1 | 16303.9 | 276.139 | 84.8775 | 0.028128087 |
| 02/05/2005 | 12:23:18 | 5.29 | 123.44 | 7 | 540.4 | 13240.1 | 276.007 | 87.0853 | 0.000225805 |
| 03/02/2005 | 10:42:09 | -6.57 | 129.88 | 7.1 | 197.6 | 12520.9 | 262.934 | 92.7129 | 0.000420858 |
| 03/28/2005 | 16:09:35 | 2.1 | 97.11 | 8.1 | 30 | 16179.9 | 273.67 | 86.9796 | 0.007146753 |
| 06/13/2005 | 22:44:32 | -19.92 | -69.22 | 7.8 | 111.9 | 5702.12 | 115.75 | 286.809 | 0.005804851 |
| 06/15/2005 | 02:50:55 | 41.45 | -125.58 | 7.1 | 18 | 4664.88 | 350.885 | 167.835 | 0.069235226 |
| 07/24/2005 | 15:42:05 | 7.91 | 92.15 | 7.1 | 17.5 | 16634.4 | 285.593 | 76.4892 | 0.001298649 |
| 08/16/2005 | 02:46:26 | 38.2 | 142.11 | 7 | 37.8 | 10929.1 | 308.475 | 83.5507 | 0.000770446 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 09/09/2005 | 07:26:42 | -4.56 | 153.48 | 7.4 | 93.8 | 9911.27 | 265.47 | 89.9235 | 0.11648992 |
| 09/26/2005 | 01:55:37 | -5.74 | -76.48 | 7.5 | 129.1 | 4601.29 | 98.6519 | 276.518 | 0.002978745 |
| 10/08/2005 | 03:50:35 | 34.52 | 73.64 | 7.3 | 7.9 | 16042.6 | 344.224 | 19.2248 | 0.002866493 |
| 01/02/2006 | 06:10:48 | -61.01 | -21.65 | 7.1 | 10 | 10335 | 150.973 | 264.897 | 0.001089995 |
| 01/02/2006 | 22:13:40 | -19.97 | -178.11 | 7.1 | 584.1 | 6959.68 | 247.5 | 79.1791 | 0.000437189 |
| 01/27/2006 | 16:58:54 | -5.45 | 128.19 | 7.5 | 403.6 | 12713.4 | 264.063 | 92.4417 | 0.001039623 |
| 02/22/2006 | 22:19:09 | -21.31 | 33.55 | 7 | 16.4 | 16104.8 | 128.667 | 236.862 | 0.00155586 |
| 04/20/2006 | 23:25:02 | 61.04 | 167.1 | 7.3 | 26.6 | 9234.93 | 331.668 | 102.81 | 0.004552836 |
| 05/03/2006 | 15:26:39 | -20.16 | -174.14 | 7.9 | 53.5 | 6557.25 | 246.416 | 77.294 | 0.006180815 |
| 05/16/2006 | 10:39:23 | -31.84 | -179.15 | 7.4 | 156 | 7366.15 | 234.976 | 74.191 | 0.002812005 |
| 07/17/2006 | 08:19:26 | -9.32 | 107.42 | 7.2 | 20 | 14955.5 | 256.998 | 99.1687 | 0.000779884 |
| 08/20/2006 | 03:41:45 | -61.02 | -34.29 | 7 | 0.5 | 9650.76 | 151.028 | 275.947 | 0.00085041 |
| 11/15/2006 | 11:14:14 | 46.68 | 153.21 | 8.3 | 12.2 | 9965.23 | 316.49 | 90.5069 | 0.007581712 |
| 12/26/2006 | 12:26:21 | 21.86 | 120.54 | 7 | 6.6 | 13298.7 | 295.162 | 76.9896 | 0.00048633 |
| 01/13/2007 | 04:23:23 | 46.23 | 154.5 | 8.1 | 22.5 | 9865.11 | 316.055 | 91.432 | 0.019001692 |
| 01/21/2007 | 11:27:44 | 1.08 | 126.36 | 7.5 | 23.5 | 12929.4 | 271.195 | 89.4733 | 0.00157559 |
| 03/25/2007 | 00:40:03 | -20.57 | 169.35 | 7.1 | 36.2 | 8265.53 | 248.721 | 83.9654 | 0.00092128 |
| 04/01/2007 | 20:39:56 | -8.45 | 157.03 | 8.1 | 9.5 | 9521.15 | 261.58 | 89.339 | 0.007198832 |
| 08/01/2007 | 17:08:55 | -15.67 | 167.7 | 7.2 | 149.5 | 8391.42 | 253.895 | 85.8321 | 0.000998905 |
| 08/08/2007 | 17:05:06 | -5.89 | 107.45 | 7.4 | 295.8 | 15001.8 | 261.746 | 95.8329 | 0.001542557 |
| 08/15/2007 | 23:40:58 | -13.38 | -76.56 | 8 | 41.2 | 4749.95 | 109.832 | 284.852 | 0.0128186 |
| 09/02/2007 | 01:05:19 | -11.59 | 165.82 | 7.2 | 37.5 | 8567.59 | 258.177 | 87.2965 | 0.003150703 |
| 09/12/2007 | 11:10:26 | -4.46 | 101.4 | 8.5 | 35.5 | 15774.7 | 265.798 | 93.3001 | 0.006445037 |
| 09/12/2007 | 23:49:04 | -2.62 | 100.73 | 7.9 | 36 | 15684.9 | 262.965 | 95.4705 | 0.005177511 |
| 09/13/2007 | 03:35:28 | -2.16 | 99.57 | 7.1 | 20 | 15906.3 | 266.443 | 92.8382 | 0.00614856 |
| 09/28/2007 | 13:38:57 | 22.01 | 142.71 | 7.5 | 253.5 | 11030.6 | 292.169 | 86.3171 | 0.00604742 |
| 09/30/2007 | 05:23:34 | -49.25 | 164.19 | 7.4 | 10 | 10753.4 | 280.542 | 88.7749 | 0.0018636 |
| 09/30/2007 | 02:08:31 | 10.54 | 145.8 | 7 | 18.5 | 9170.26 | 220.348 | 81.1252 | 0.0018636 |
| 10/31/2007 | 03:30:18 | 18.96 | 145.38 | 7.2 | 221.9 | 10769.9 | 288.978 | 87.6863 | 0.00580915 |
| 11/14/2007 | 15:40:49 | -22.32 | -69.78 | 7.7 | 33.6 | 5728.36 | 118.866 | 288.957 | 0.003780075 |
| 11/29/2007 | 19:00:19 | 14.99 | -61.22 | 7.4 | 147.3 | 6405.9 | 72.2653 | 260.262 | 0.001223833 |
| 12/09/2007 | 07:28:20 | -26.1 | -177.36 | 7.8 | 149.8 | 7032.07 | 240.637 | 75.7515 | 0.004642827 |
| 12/19/2007 | 09:30:28 | 51.4 | -179.54 | 7.2 | 36.2 | 8118.15 | 324.628 | 112.468 | 0.001939075 |
| 02/20/2008 | 08:08:31 | 2.76 | 95.96 | 7.3 | 31.4 | 16303 | 274.965 | 85.8588 | 0.001144171 |
| 02/25/2008 | 08:36:33 | -2.49 | 99.92 | 7.2 | 29.8 | 15865.5 | 265.933 | 93.2295 | 0.00096269 |
| 03/20/2008 | 22:32:58 | 35.55 | 81.51 | 7.1 | 10 | 15634.5 | 335.362 | 30.7457 | 0.001119035 |
| 04/09/2008 | 12:46:12 | -20.04 | 168.91 | 7.3 | 31.4 | 8305.25 | 249.309 | 84.2751 | 0.001356333 |
| 04/12/2008 | 00:30:12 | -55.59 | 158.54 | 7.1 | 10 | 9638.27 | 214.441 | 85.0308 | 0.001012874 |
| 05/12/2008 | 06:27:59 | 31.06 | 103.37 | 7.9 | 7.6 | 14523.8 | 312.442 | 59.3093 | 0.009771979 |
| 07/05/2008 | 02:12:06 | 53.95 | 152.86 | 7.7 | 646.1 | 9995.84 | 323.767 | 90.2815 | 0.003856144 |
| 11/16/2008 | 17:02:32 | 1.35 | 122.16 | 7.3 | 28.1 | 13396.5 | 271.554 | 89.2149 | 0.00067138 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 11/24/2008 | 09:03:00 | 54.22 | 154.29 | 7.3 | 505.3 | 9902.51 | 324.05 | 91.4401 | 0.00086155 |
| 01/03/2009 | 22:33:42 | -0.71 | 133.31 | 7.2 | 34.4 | 12235.2 | 269.44 | 90.1907 | 0.001580922 |
| 01/03/2009 | 19:43:55 | -0.53 | 132.6 | 7.4 | 31.1 | 12156.1 | 269.253 | 90.2456 | 0.00236238 |
| 01/15/2009 | 17:49:38 | 46.83 | 155.25 | 7.3 | 31.1 | 9809.49 | 316.671 | 91.992 | 0.002960232 |
| 02/11/2009 | 17:34:51 | 3.78 | 126.5 | 7.1 | 24.2 | 12907.7 | 274.177 | 88.1697 | 0.000878606 |
| 03/19/2009 | 18:17:40 | -23.16 | -174.59 | 7.6 | 30.9 | 6679.92 | 243.157 | 75.8029 | 0.001979349 |
| 05/28/2009 | 08:24:48 | 16.81 | -86.24 | 7.3 | 29 | 3899.6 | 59.9519 | 244.654 | 0.016658235 |
| 07/15/2009 | 09:22:31 | -45.83 | 166.64 | 7.8 | 20.9 | 8924.84 | 223.483 | 79.7981 | 0.001907862 |
| 08/09/2009 | 10:55:56 | 33.15 | 138.06 | 7.1 | 302.2 | 11364 | 303.821 | 82.0159 | 0.000925952 |
| 08/10/2009 | 19:55:39 | 14.05 | 92.87 | 7.5 | 30.7 | 16349.1 | 296.189 | 67.6154 | 0.001251789 |
| 09/02/2009 | 07:55:01 | -7.73 | 107.41 | 7 | 57.8 | 14982.3 | 259.186 | 97.6374 | 0.000889204 |
| 09/29/2009 | 17:48:11 | -15.51 | -171.94 | 8.1 | 18.5 | 6223.9 | 251.284 | 79.2478 | 0.026917685 |
| 09/30/2009 | 10:16:10 | -0.71 | 99.97 | 7.6 | 90.2 | 15867 | 268.841 | 90.9204 | 0.001625302 |
| 10/07/2009 | 23:13:49 | -13.08 | 166.46 | 7.4 | 32.9 | 8501.96 | 256.662 | 86.8032 | 0.006547865 |
| 10/07/2009 | 22:18:53 | -12.47 | 166.37 | 7.8 | 59 | 8512.63 | 257.251 | 86.97 | 0.006547865 |
| 10/07/2009 | 22:03:14 | -13.04 | 166.5 | 7.6 | 33.7 | 8506.54 | 256.624 | 86.8031 | 0.006547865 |
| 11/09/2009 | 10:44:54 | -17.27 | 178.45 | 7.3 | 591.3 | 7268.69 | 251.047 | 81.8326 | 0.000519495 |
| 01/03/2010 | 22:36:29 | -8.88 | 157.42 | 7.1 | 29.8 | 9478.81 | 261.147 | 89.2454 | 0.000981646 |
| 01/12/2010 | 21:53:10 | 18.38 | -72.59 | 7 | 15 | 5312.98 | 64.9403 | 252.54 | 0.013277649 |
| 02/26/2010 | 20:31:26 | 25.98 | 128.51 | 7 | 24.2 | 12409.6 | 297.917 | 79.0217 | 0.001555469 |
| 02/27/2010 | 06:34:13 | -36.15 | -72.93 | 8.8 | 28.1 | 6027.12 | 138.915 | 303.895 | 0.02660814 |
| 02/27/2010 | 08:01:23 | -37.84 | -75.21 | 7.4 | 35 | 6098.33 | 135.964 | 300.813 | 0.026608272 |
| 03/11/2010 | 14:55:29 | -34.29 | -71.8 | 7 | 24.4 | 6085.21 | 133.428 | 298.699 | 0.0008014 |
| 04/04/2010 | 22:40:43 | 32.28 | -115.26 | 7.2 | 5.2 | 3581.78 | 3.547 | 184.188 | 0.275735931 |
| 04/06/2010 | 22:15:02 | 2.36 | 97.11 | 7.8 | 33.4 | 16178.3 | 274.124 | 86.6067 | 0.001852559 |
| 05/09/2010 | 05:59:42 | 3.73 | 96.03 | 7.3 | 42.3 | 16286.2 | 276.688 | 84.4278 | 0.000496037 |
| 05/27/2010 | 17:14:46 | -13.67 | 166.67 | 7.2 | 34.7 | 8487.58 | 256.009 | 86.6096 | 0.000796068 |
| 06/12/2010 | 19:26:50 | 7.85 | 91.95 | 7.5 | 31.4 | 16657.4 | 285.57 | 76.4818 | 0.00190963 |
| 06/16/2010 | 03:16:29 | -2.2 | 136.59 | 7 | 22.1 | 11789.8 | 267.728 | 90.6232 | 0.000768485 |
| 07/18/2010 | 13:35:00 | -6.04 | 150.66 | 7.3 | 43.1 | 10223.7 | 263.997 | 90.1935 | 0.001965414 |
| 07/23/2010 | 23:15:09 | 6.74 | 123.33 | 7.5 | 633.7 | 13225.5 | 277.612 | 86.3155 | 0.002063532 |
| 07/23/2010 | 22:51:13 | 6.42 | 123.58 | 7.7 | 584.7 | 13217.6 | 277.278 | 86.4867 | 0.002064046 |
| 07/23/2010 | 22:08:11 | 6.71 | 123.49 | 7.3 | 610.2 | 13243 | 277.658 | 86.2748 | 0.002063702 |
| 08/10/2010 | 05:23:46 | -17.53 | 168.04 | 7.3 | 33.5 | 8371.25 | 251.962 | 85.2448 | 0.001476788 |
| 08/12/2010 | 11:54:15 | -1.28 | -77.37 | 7.1 | 206.5 | 4467.91 | 91.9727 | 271.508 | 0.000868994 |
| 09/03/2010 | 16:35:46 | -43.36 | 171.9 | 7 | 4 | 8458.95 | 225.161 | 76.4622 | 0.000291494 |
| 09/29/2010 | 17:11:24 | -4.99 | 133.78 | 7 | 20.5 | 12095.8 | 264.768 | 91.6782 | 0.000120228 |
| 10/25/2010 | 14:42:22 | -3.52 | 100.1 | 7.8 | 20 | 15837.8 | 264.28 | 94.5298 | 0.000620282 |
| 12/21/2010 | 17:19:40 | 26.9 | 143.7 | 7.4 | 14 | 10894 | 297.019 | 86.0098 | 0.002584838 |
| 12/25/2010 | 13:16:37 | -19.7 | 167.95 | 7.3 | 16 | 8401.75 | 249.747 | 84.7126 | 0.002476037 |
| 01/01/2011 | 09:56:58 | -26.8 | -63.14 | 7 | 576.8 | 6523.82 | 121.695 | 287.832 | 0.000439329 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 01/02/2011 | 20:20:17 | -38.36 | -73.33 | 7.1 | 24 | 6196.93 | 138.454 | 302.475 | 0.000517332 |
| 01/18/2011 | 20:23:23 | 28.78 | 63.95 | 7.2 | 68 | 16848.2 | 357.365 | 3.00227 | 0.000773355 |
| 03/09/2011 | 02:45:20 | 38.44 | 142.84 | 7.3 | 32 | 10862.7 | 308.652 | 83.9771 | 0.073477319 |
| 03/11/2011 | 06:25:50 | 38.06 | 144.59 | 7.6 | 18.6 | 10905.2 | 308.552 | 83.7002 | 0.031109647 |
| 03/11/2011 | 06:15:40 | 36.28 | 141.11 | 7.9 | 42.6 | 11041.9 | 306.642 | 83.2248 | 0.031109699 |
| 03/11/2011 | 05:46:24 | 38.3 | 142.37 | 9 | 29 | 10714 | 308.14 | 85.1178 | 0.031109689 |
| 04/07/2011 | 14:32:43 | 38.28 | 141.59 | 7.1 | 42 | 10973.4 | 308.603 | 83.2115 | 0.00086303 |
| 06/24/2011 | 03:09:39 | 52.05 | -171.84 | 7.3 | 52 | 7670.51 | 327.462 | 119.428 | 0.004170384 |
| 07/06/2011 | 19:03:18 | -29.54 | -176.34 | 7.6 | 17 | 7036.27 | 236.666 | 73.4861 | 0.009762159 |
| 07/10/2011 | 00:57:10 | 38.03 | 143.26 | 7 | 23 | 10830.7 | 308.207 | 84.2936 | 0.001320038 |
| 08/20/2011 | 18:19:23 | -18.31 | 168.22 | 7.1 | 28 | 8368.61 | 251.093 | 84.9919 | 0.001540841 |
| 08/20/2011 | 16:55:02 | -18.37 | 168.14 | 7.2 | 32 | 8359.6 | 251.148 | 84.9808 | 0.001540841 |
| 08/24/2011 | 17:46:11 | -7.64 | -74.53 | 7 | 147 | 4841.9 | 101.063 | 278.073 | 0.000798595 |
| 09/03/2011 | 22:55:40 | -20.67 | 169.72 | 7 | 185.1 | 8228.35 | 248.58 | 83.7971 | 0.00054425 |
| 09/15/2011 | 19:31:04 | -21.61 | -179.53 | 7.3 | 644.6 | 7139.3 | 245.988 | 79.0016 | 0.000458186 |
| 10/21/2011 | 17:57:16 | -28.99 | -176.24 | 7.4 | 33 | 7009.71 | 237.228 | 73.6918 | 0.00507078 |
| 10/23/2011 | 10:41:22 | 38.72 | 43.51 | 7.3 | 16 | 15328.8 | 22.2368 | 331.068 | 0.001696676 |
| 12/14/2011 | 05:04:59 | -7.56 | 146.8 | 7.1 | 140.9 | 10649.1 | 262.453 | 90.7489 | 0.0007128 |
| 01/10/2012 | 18:36:59 | 2.43 | 93.21 | 7.2 | 19 | 16610.7 | 274.72 | 85.9426 | 0.00061983 |
| 03/14/2012 | 09:08:35 | 40.89 | 144.94 | 7 | 12 | 10657 | 310.948 | 85.0464 | 0.000925183 |
| 03/20/2012 | 18:02:47 | 16.49 | -98.23 | 7.4 | 20 | 2792.23 | 48.2839 | 231.083 | 0.055302541 |
| 03/25/2012 | 22:37:06 | -35.2 | -72.22 | 7.1 | 40.7 | 6100.83 | 134.605 | 299.618 | 0.001358723 |
| 04/11/2012 | 10:43:10 | 0.8 | 92.46 | 8.2 | 25.1 | 16702.6 | 271.591 | 88.6211 | 0.025105815 |
| 04/11/2012 | 08:38:36 | 2.33 | 93.06 | 8.6 | 20 | 16628.1 | 274.546 | 86.0857 | 0.025186717 |
| 04/12/2012 | 07:15:48 | 28.7 | -113.1 | 7 | 13 | 3211.1 | 8.01021 | 189.127 | 0.029198688 |
| 08/14/2012 | 02:59:38 | 49.8 | 145.06 | 7.7 | 583.2 | 10555.4 | 319.85 | 84.3115 | 0.003854235 |
| 08/27/2012 | 04:37:19 | 12.14 | -88.59 | 7.4 | 28 | 3463.53 | 66.1479 | 249.266 | 0.015814505 |
| 08/31/2012 | 12:47:33 | 10.81 | 126.64 | 7.6 | 28 | 12844.7 | 281.903 | 84.8364 | 0.005002687 |
| 09/05/2012 | 14:42:07 | 10.09 | -85.32 | 7.6 | 35 | 3732.98 | 71.6345 | 254.532 | 0.015341917 |
| 09/30/2012 | 16:31:35 | 1.93 | -76.36 | 7.2 | 170 | 4582.57 | 87.0868 | 267.806 | 0.001337575 |
| 10/28/2012 | 03:04:08 | 52.79 | -132.1 | 7.8 | 14 | 6012.16 | 349.085 | 161.834 | 0.021059563 |
| 11/07/2012 | 16:35:46 | 13.99 | -91.9 | 7.3 | 24 | 3216.62 | 60.1884 | 243.36 | 0.018488655 |
| 12/07/2012 | 08:18:23 | 37.89 | 143.95 | 7.3 | 31 | 10771.8 | 308.015 | 84.7398 | 0.003197728 |
| 12/10/2012 | 16:53:08 | -6.53 | 129.83 | 7.1 | 155 | 12526.6 | 262.975 | 92.7031 | 0.000361869 |
| 01/05/2013 | 08:58:19 | 55.39 | -134.65 | 7.5 | 10 | 6341.2 | 348.415 | 159.393 | 0.021417886 |
| 02/06/2013 | 01:54:14 | -10.5 | 165.59 | 7 | 8.8 | 8641.19 | 259.012 | 87.6173 | 0.005368167 |
| 02/06/2013 | 01:23:19 | -11.18 | 164.88 | 7.1 | 10 | 8668.07 | 258.636 | 87.5809 | 0.005368167 |
| 02/06/2013 | 01:12:25 | -10.8 | 165.11 | 7.9 | 24 | 8587.32 | 259.297 | 87.5914 | 0.005368157 |
| 02/08/2013 | 15:26:38 | -10.93 | 166.02 | 7.1 | 21 | 8542.4 | 258.84 | 87.4086 | 0.001304938 |
| 04/06/2013 | 04:42:35 | -3.52 | 138.48 | 7 | 66 | 11577.8 | 266.396 | 90.8732 | 0.000526982 |
| 04/16/2013 | 10:44:20 | 28.03 | 62 | 7.7 | 80 | 16934.6 | 0.96620 | 358.907 | 0.004550144 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 04/19/2013 | 03:05:52 | 46.22 | 150.79 | 7.2 | 110 | 10151.8 | 316.041 | 88.7613 | 0.001402128 |
| 05/23/2013 | 17:19:04 | -23.01 | -177.23 | 7.4 | 173.7 | 6939.21 | 243.97 | 77.2243 | 0.00204213 |
| 05/24/2013 | 05:44:48 | 54.89 | 153.22 | 8.4 | 598.1 | 9973.2 | 324.711 | 90.5787 | 0.015103699 |
| 07/07/2013 | 18:35:30 | -3.92 | 153.92 | 7.3 | 386.3 | 9862.31 | 266.105 | 89.9043 | 0.001018847 |
| 07/15/2013 | 14:03:39 | -60.83 | -25.17 | 7.3 | 11 | 10145.2 | 150.686 | 267.978 | 0.0005596 |
| 08/30/2013 | 16:25:02 | 51.61 | -175.36 | 7 | 33.5 | 7862.76 | 325.961 | 116.149 | 0.00192539 |
| 09/24/2013 | 11:29:48 | 27 | 65.51 | 7.7 | 20 | 17032 | 354.098 | 6.61772 | 0.004836334 |
| 09/25/2013 | 16:42:43 | -15.85 | -74.56 | 7 | 45.8 | 5030.97 | 112.493 | 286.267 | 0.001221542 |
| 10/15/2013 | 00:12:37 | 9.77 | 124.02 | 7.2 | 56.8 | 13141 | 281.012 | 84.7718 | 0.00192539 |
| 10/25/2013 | 17:10:16 | 37.19 | 144.66 | 7.3 | 10 | 10715.9 | 307.265 | 85.2557 | 0.004836334 |
| 11/17/2013 | 09:04:55 | -60.3 | -46.36 | 7.8 | 10 | 8987.02 | 151.482 | 286.511 | 0.002431775 |
| 11/25/2013 | 06:27:33 | -53.88 | -54.88 | 7 | 10 | 8259.26 | 146.884 | 292.664 | 0.001221542 |

**COSO GEOTHERMAL FIELD: TRIGGERING MAINSHOCKS**

We examined local triggering in the Coso Geothermal Field, from 154 remote mainshocks (M≥7). For each mainshock, we compare post-mainshock seismicity with pre-mainshock background levels. Of the original 154 mainshocks in our study, we eliminate 120 of the mainshocks where the local post-mainshock seismicity rate is constant or decreases relative to the pre-mainshock rates. The remaining 34 mainshocks have moment magnitudes ranging from 7.0 to 8.8 and depths of 10 to 598.1 km. We hypothesize that these 34 mainshocks (22% of those examined) triggered local seismicity in the 5 hours following the mainshock. The our auto-detection and the SCSN catalog indicate that 16 mainshocks instantaneously (within the wavetrain of the mainshock) triggered local seismicity; 18 mainshocks triggered seismicity that was delayed by within ~1-5 hours of the mainshock (Table 3). An investigation of the potential seismic triggering phases is compiled in Table 3. A majority of instantaneously triggered earthquakes identified are in phase with the passing of surface waves, without a time delay. Of note, we find a magnitude 6.9 mainshock earthquake on July, 18 2010 at 13:04:11 UTC, in the New Britain Region, Papua New Guinea instantanously triggered seismicity in the CGF in phase with the arrival of the mainshocks *S*-wave and Rayliegh waves. We included this event although it was below our $M \geq 7$ magnitude cut off, and note that it occurred ~30 minutes prior to a magnitude 7.3 mainshock. Both mainshocks originated from the same region (New Britain Region, Papua New Guinea) and appear to have instantaneosly triggered seismicity in the CGF. We include the $M = 6.9$ mainshock in Table 3, however it is excluded from further analysis.

Of the 16 cases of assumed instantanous triggering 8 (50%) of the triggered events displayed no activity in the CGF or its vicinity within 5 hours prior to the mainshock rupture. Of the 18 delayed triggered events 3 (17%) of the triggered events displayed no prior activity within 5 hours prior to passage of the mainshock coda. The cases of assumed triggered seismicity that

display pre-mainshock activity account for 68% of our total triggered catalog, and we find activity in the 5-hours post-mainshock display a rapid increase in the frequency and magnitude of seismicity in the study area. This suggests the propagating dynamic stresses of the seismic waves generated from the mainshock excited the system, therefore increasing seismic activity. We identify 147 local events ranging in magnitude ($M_L$) 0.02-3.45 (Figure 9) triggered within 5 hours following 34 ($M_W \geq 7.0$ ). Of the 147 local events we find 17 events that had not been previously cataloged.

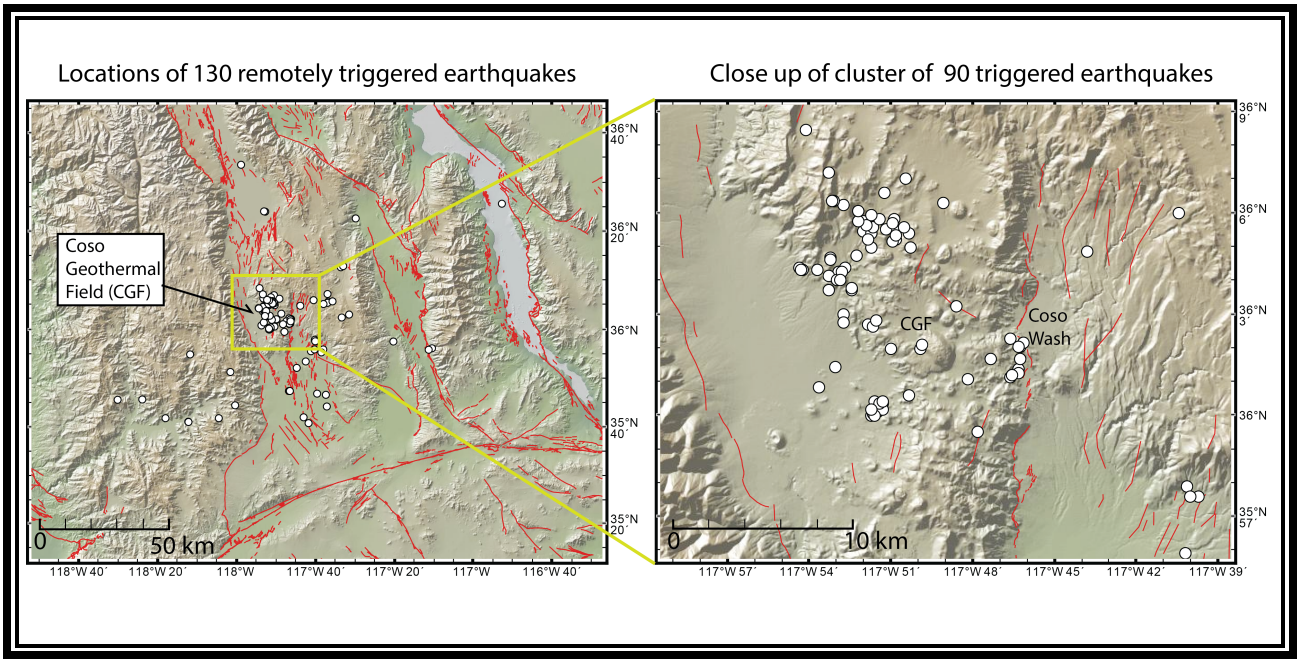



Figure 9: Map of locally triggered seismicity in the Coso geothermal field and surrounding study area. On the left white circles indicate locations of 130 remotely triggered local seismicity, cataloged and located by the Southern California Earthquake Center, events range in magnitude ($M_L$) 0.02-3.45, red lines indicate quaternary faults. On the right we zoom into a cluster of seismicity in the Coso Geothermal Field. The white circles indicate locations of 90 remotely triggered local seismicity, cataloged and located by the Southern California Earthquake Center, events range in magnitude ($M_L$) 0.02-3.45, red lines indicate quaternary faults.

Table 3: Mainshock parameters of our set of 34 M ≥ 7 "Triggering Mainshocks", including one additional triggering mainshock of M=6.9. We compute distance and back-azimuth, with respect to SCSN CI-Network Code station MPM (36.06 N, -117.49 E) located 30 km from the center of the Coso Geothermal Field (36.03N, -117.82E). We calculate the average mainshock generated peak dynamic stress (PDS) at six seismic stations (TA-HELL, TA-R11A, CI-MPM, CI-CWC, CI-SLA, CI-CLC). PDS values are an average of the PDS from all six stations. The table also includes information about if the locally triggered seismicity is assumed to be consistent with triggering that is instantaneous or delay. We indicate which phases of the mainshocks wavetrain is the assumed triggering factor (P=P-Wave, S=S-Wave, L=Love Wave, R=Rayleigh Wave, C=coda of the mainshock). We also indicate weather the Coso Geothermal field or anywhere in our Coso study area (35.5°N–36.5°N, 119°W–117°W) exhibited seismicity in the 5-hours prior to the passage of the mainshock earthquake (Y=Yes, there was seismicity cataloged prior to the mainshock earthquake; N=No, there was not seismicity cataloged prior to the mainshock earthquake).

| Date | Time (UTC) | Mag | Depth (km) | Distance (Km) to CI.MPM | Back-azimuth (Deg) to CI.MPM | Avg PDS (Mpa) | Instant or Delay? | Trig Phase | Prior Seismicity ? |
|---|---|---|---|---|---|---|---|---|---|
| 07/24/2005 | 15:42:05 | 7.1 | 17.5 | 16634.4 | 76.4892 | 0.001298649 | Instant | S | Y |
| 09/26/2005 | 1:55:37 | 7.5 | 129.1 | 4601.29 | 276.518 | 0.002978745 | Delay | -- | Y |
| 01/02/2006 | 6:10:48 | 7.1 | 10 | 10335 | 264.897 | 0.001089995 | Instant | L | N |
| 05/03/2006 | 15:26:39 | 7.9 | 53.5 | 6557.25 | 77.294 | 0.006180815 | Delay | -- | Y |
| 07/17/2006 | 8:19:26 | 7.2 | 20 | 14955.5 | 99.1687 | 0.000779884 | Instant | C,R | N |
| 09/12/2007 | 11:10:26 | 8.5 | 35.5 | 15774.7 | 93.3001 | 0.006445037 | Instant | C,R | N |
| 09/13/2007 | 3:35:28 | 7.1 | 20 | 15906.3 | 92.8382 | 0.00614856 | Delay | -- | N |
| 04/12/2008 | 0:30:12 | 7.1 | 10 | 9638.27 | 85.0308 | 0.001012874 | Instant | C,R | N |
| 02/11/2009 | 17:34:51 | 7.1 | 24.2 | 12907.7 | 88.1697 | 0.000878606 | Instant | R | Y |
| 08/09/2009 | 10:55:56 | 7.1 | 302.2 | 11364 | 82.0159 | 0.000925952 | Instant | S | N |
| 09/29/2009 | 17:48:11 | 8.1 | 18.5 | 6223.9 | 79.2478 | 0.026917685 | Delay | -- | N |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 01/03/2010 | 22:36:29 | 7.1 | 29.8 | 9478.81 | 89.2454 | 0.000981646 | Instant | R | Y |
| 01/12/2010 | 21:53:10 | 7 | 15 | 5312.98 | 252.54 | 0.013277649 | Delay | -- | Y |
| 02/27/2010 | 6:34:13 | 8.8 | 28.1 | 6027.12 | 303.895 | 0.02660814 | Instant | S,L | Y |
| 04/06/2010 | 22:15:02 | 7.8 | 33.4 | 16178.3 | 86.6067 | 0.001852559 | Instant | R | N |
| 05/09/2010 | 5:59:42 | 7.3 | 42.3 | 16286.2 | 84.4278 | 0.000496037 | Delay | -- | Y |
| 07/18/2010 | 13:04:11 | 6.9 | 42 | -- | -- | -- | Instant | S,R | |
| 07/18/2010 | 13:35:00 | 7.3 | 43.1 | 10223.7 | 90.1935 | 0.001965414 | Instant | L | Y |
| 12/21/2010 | 17:19:40 | 7.4 | 14 | 10894 | 86.0098 | 0.002584838 | Delay | -- | Y |
| 06/24/2011 | 3:09:39 | 7.3 | 52 | 7670.51 | 119.428 | 0.004170384 | Delay | -- | Y |
| 07/06/2011 | 19:03:18 | 7.6 | 17 | 7036.27 | 73.4861 | 0.009762159 | Delay | -- | Y |
| 08/20/2011 | 18:19:23 | 7.1 | 28 | 8368.61 | 84.9919 | 0.001540841 | Delay | -- | Y |
| 08/24/2011 | 17:46:11 | 7 | 147 | 4841.9 | 278.073 | 0.000798595 | Instant | R | N |
| 10/21/2011 | 17:57:16 | 7.4 | 33 | 7009.71 | 73.6918 | 0.00507078 | Delay | -- | Y |
| 03/20/2012 | 18:02:47 | 7.4 | 20 | 2792.23 | 231.083 | 0.055302541 | Delay | -- | Y |
| 08/31/2012 | 12:47:33 | 7.6 | 28 | 12844.7 | 84.8364 | 0.005002687 | Delay | -- | N |
| 11/07/2012 | 16:35:46 | 7.3 | 24 | 3216.62 | 243.36 | 0.018488655 | Delay | -- | Y |
| 12/07/2012 | 8:18:23 | 7.3 | 31 | 10771.8 | 84.7398 | 0.003197728 | Instant | S,R | N |
| 12/10/2012 | 16:53:08 | 7.1 | 155 | 12526.6 | 92.7031 | 0.000361869 | Instant | R | Y |
| 04/06/2013 | 4:42:35 | 7 | 66 | 11577.8 | 90.8732 | 0.000526982 | Instant | S,R | Y |
| 04/16/2013 | 10:44:20 | 7.7 | 80 | 16934.6 | 358.907 | 0.004550144 | Delay | -- | Y |
| 05/23/2013 | 17:19:04 | 7.4 | 173.7 | 6939.21 | 77.2243 | 0.00204213 | Delay | -- | Y |
| 05/24/2013 | 5:44:48 | 8.4 | 598.1 | 9973.2 | 90.5787 | 0.015103699 | Delay | -- | Y |
| 07/15/2013 | 14:03:39 | 7.3 | 11 | 10145.2 | 267.978 | 0.0005596 | Instant | R | Y |
| 11/17/2013 | 9:04:55 | 7.8 | 10 | 8987.02 | 286.511 | 0.002431775 | Delay | -- | Y |

## COSO GEOTHERMAL FIELD: MAINSHOCK PARAMETERS

The locations and mechanisms of the 154 mainshock events we study vary throughout the highly seismogenic regions of the world (Figure 10). Several are concentrated near the western edge of the Pacific Plate, a naturally more seismically active area. Notably, the majority of triggering mainshocks exhibit a thrust mechanism (Figure 10), although based on the similarities between the locations and mechanisms of triggering and non-triggering mainshocks, we do not assign any region as a preferential trigger locality specific to the CGF region.

We find the average mainshock PDS values, for both non-triggering mainshocks and triggering mainshocks (Figure 11) range between values of ($10^{-3}$–$10^{-1}$ MPa). As expected, there is a general trend of larger PDS values corresponding to larger magnitudes, although we find several Mw 7-7.5 mainshocks that deviate from this trend, producing PDS values as high as 0.17 MPa, a value more consistent with a magnitude 9 mainshock. The highest value PDS values we computed was ~0.3 MPa for non-triggering events and ~0.06MPa for triggering events. The lowest PDS we computed for a triggering event is ~0.0005MPa a small value implying relatively weak triggering, which is consistent with the finding of Aiken and Peng (2014) who indicate geothermal sites in California are susceptible to a triggering threshold of <0.001 MPa.

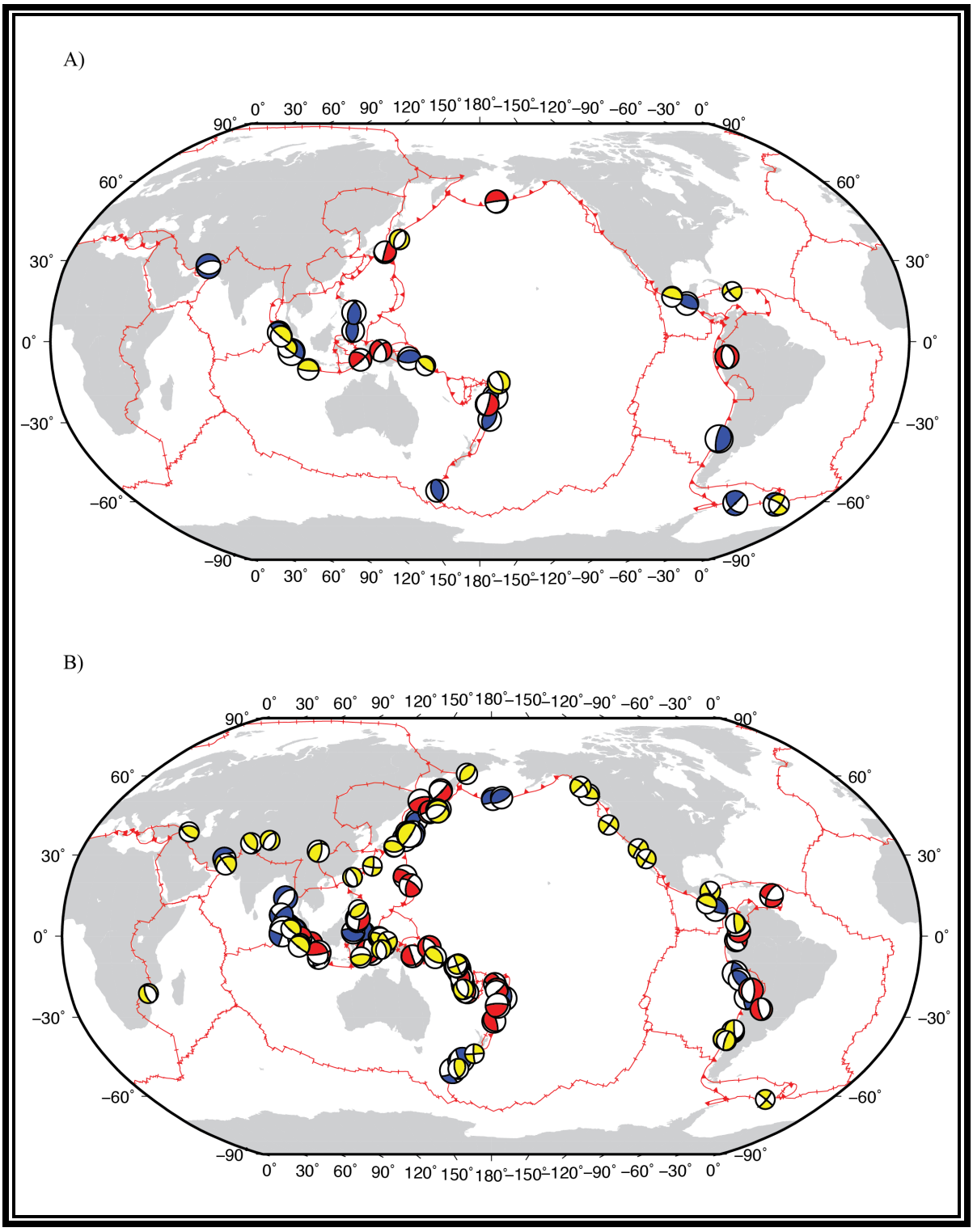

A)
B)
0° 30° 60° 90° 120° 150° 180° –150° –120° –90° –60° –30° 0°
90°
60°
30°
0°
–30°
–60°
–90°

Figure 10: World map of 154 mainshocks in our study and beach-balls to indicate their mechanisms, color coded by depth. Shallow source (0-20km) depth mainshocks are indicated by yellow mechanisms; mainshocks with a source depth between (21-70km) are indicated by blue mechanisms, mainshocks with a source depth of (71km-600km) are indicated by red mechanisms. A) World map indicating locations and mechanisms of 34 triggering mainshocks, these events triggered remote seismicity in the Coso Geothermal Field and surrounds region. B) World map indicating locations and mechanisms of 120 non-triggering mainshocks.

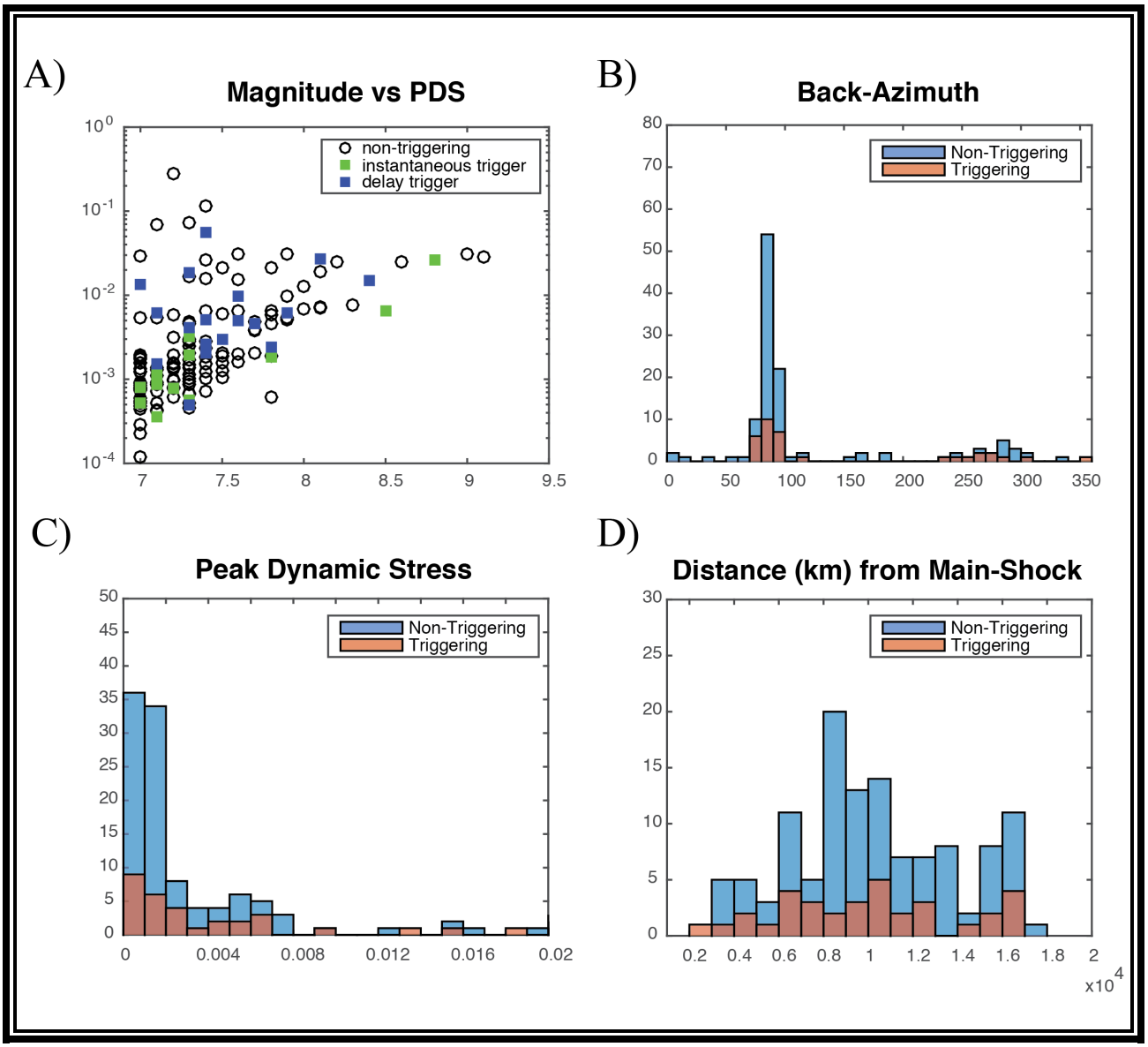



Figure 11: A) Scatter plot of Peak Dynamic Stress (PDS) (Y-axis) against Mainshock Magnitude) (X-Axis), black circles indicate 120 non-triggering mainshocks, green squares represent 16 mainshocks that instantaneously triggered local seismicity in the Coso geothermal field, blue squares represent 18 mainshocks that induced a delayed triggering of local seismicity in the Coso Geothermal field. B) Histogram of stacked mainshock back-azimuths plotted in 10 degree bins, orange indicated triggering mainshocks, blue indicates non-triggering mainshocks. C) Histogram of stacked mainshock generated PDS plotted in 0.001 MPa bins, orange indicated triggering mainshocks, blue indicates non-triggering mainshocks. D) Histogram of stacked distances from Mainshock to CI-network station MPM plotted in 1000 km bins, orange indicated triggering mainshocks, blue indicates non-triggering mainshocks.

## Discussion

In this study of 154 mainshock events, we observe mainshocks upwards of 10,000 km away capable of triggering remote seismicity in the CGF. This is consistent with prior documentation of triggering in the far-field [e.g., *Hill and Prejean*, 2014 and references therein]. We find 147 locally triggered earthquakes following 34 of the 154 mainshocks studied, indicating that dynamic earthquake triggering in the region of the CGF is quite common. Of our 147 local triggered earthquakes 33 are triggered within the wavetrain of the mainshock, 5 of these correspond to the arrival of the *S*-phase, 17 correspond to the passage of surface waves (Love and Rayleigh), 11 are triggered within the coda of the mainshock (Table 8.1). The majority of our local events occur within the first three hours after the passage of the surface waves. The time delay between the passage of dynamic stresses of the surface waves is not unexpected, several examples of delayed dynamic triggering have been previously documented [e.g., *Velasco et al*., 2008; *Jagla*, 2011; *Morton and Bilek*, 2014].

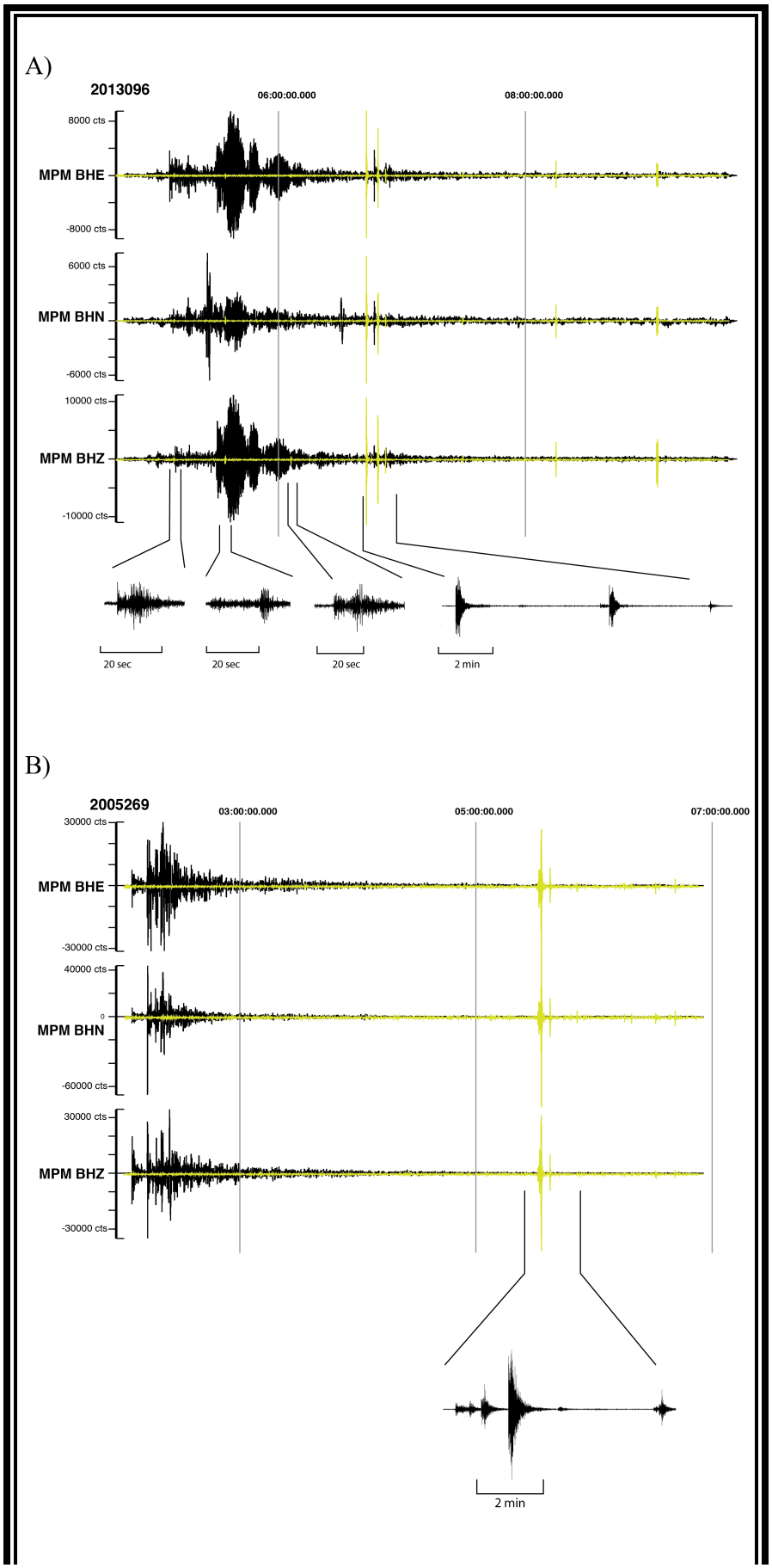
We suggest delayed triggering in these cases may be consistent with previous hypotheses [e.g., *Hill and Prejean*, 2014 and references therein] of which the excitation of crustal fluids, in this case fluids associated with the shallow heat source of the CGF, as the cause for the delay in the triggering of local seismicity. Delayed locally triggered seismicity (Figure 12) initiated by the onset of surface wave arrivals, suggest fluid diffusion as the processes responsible for the delay in the failure of these events [e.g., *Bodin and Gomberg*, 1994; *Brodsky*, 2006; *Syracuse et al*., 2010]. Recent documentation of dynamically triggered earthquakes indicate Rayleigh waves (which produce both longitudinal and transverse motion) can trigger events by inducing fluid excitation, or cause Coulomb failure. [*Rubinstein et al*. 2007, 2009; *Hill* 2008; *Miyazawa et al*. 2008; *Peng and Chao*, 2008; *Peng et al*., 2008, 2009, 2010a].

We identified 33 triggered earthquakes occurring in phase with either the early seismic arrivals or the passage of the surface waves without a time delay (Figure 12). These events may be induced by Coulomb failure [*Hill*, 2008; *Gonzalaz-Huizar and Velasco*, 2010]. We identified 3 cases of Love-wave and 14 cases of Rayleigh-wave instantaneous remote triggering of local earthquake in the CGF. Both Rayleigh and Love waves can cause the failure of a fault by the Coulomb failure criteria. [*Peng and Chao*, 2008; *Hill*, 2008; *Peng et al*. 2008, 2009, 2010a]. We examine back-azimuth angles of triggering mainshocks and find several events are consistent with fault orientations in the CGF region. Consistent back-azimuth angles indicate the orientation of seismic arrival phases, either parallel or perpendicular to the local stress field (Figure 13) (*Heidbach et al*., 2008). Back-azimuth angles are in agreement with the orientation of both active faults and borehole tensile fractures (trending N to NNE) documented by Davatzes and Hickman (2006). Our observations are consistent with those of Chao et al. (2013); the potential of remotely triggered seismicity is not solely dependent on the strain imposed by surface waves but their back-azimuth angles (orientations). As well previous documentation following the 1992 Landers and 2002 Denali Fault Earthquake mainshocks [*Anderson et al*., 1994; *Husker and Brodsky*, 2004; *Pankow et al*., 2004] indicate preferential triggering occurs in areas of high heat flow (i.e. geothermally active).

The general trends of mainshock parameters and PDS values show no clear indication of a triggering threshold for the CGF region, although we find the lowest PDS generated by a triggering mainshock is ~0.0005MPa. When comparing PDS as a function of mainshock parameters several triggering mainshocks follow similar trends as non-triggering mainshocks (Figure 11). Based on our data and findings, the initial pattern of triggering and non triggering mainshocks indicate, dynamic triggering is highly dependent on the state of the regional stress

field and dynamic stresses aligning favorably with the local stress field, not necessarily a specific threshold value of PDS generated. In future work we will determine if this initial finding is maintained after applying a series of statistical tests. If our results are confirmed, it will be consistent with the idea that a critically stressed fault can respond to the passage of dynamic stresses in a manner that invokes a clock-advance (premature failure of a fault), triggering failure of the fault [e.g., *Gomberg*, 2001; *Boese et al*., 2014]. The stress changes imposed by passing seismic waves can alter the stress state of a fault, by slightly reducing the frictional strength, or the contact surface of a fault. If the passage of seismic waves imposes enough strain, it can initiate the immediate failure of a fault. Although in several cases point to the likelihood this strain is not enough to immediately deform the system; in which case a time delayed processed may be initiated and eventually evolves into the failure of a fault [*Parsons*, 2005; *Gonzalez-Huizar and Velasco*, 2011].

The trends produced by comparison of PDS values and mainshock parameters may be a result of irregular sampling, or a lack of mainshock events to study originating from all possible orientations (the majority of $(M) \geq 7$ earthquakes occur in the same general regions). In addition, previous studies have found the occurrence of hundreds of dynamically triggered events following mainshock wave passage [e.g., *Hill et al*., 1993; *Husen et al*., 2004; *Prejean et al*., 2004], however since we limit the time window of our study to ±5 hours from the initial mainshock (with the exception of the Feb. 27, 2010 Offshore Bio-Bio (M=8.8) Chile earthquake), we may not observe this high number of locally triggered events.


A)
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08:00:00.000
8000 cts
MPM BHE
-8000 cts
6000 cts
MPM BHN
-6000 cts
10000 cts
MPM BHZ
-10000 cts
20 sec
20 sec
20 sec
2 min
B)
2005269
03:00:00.000
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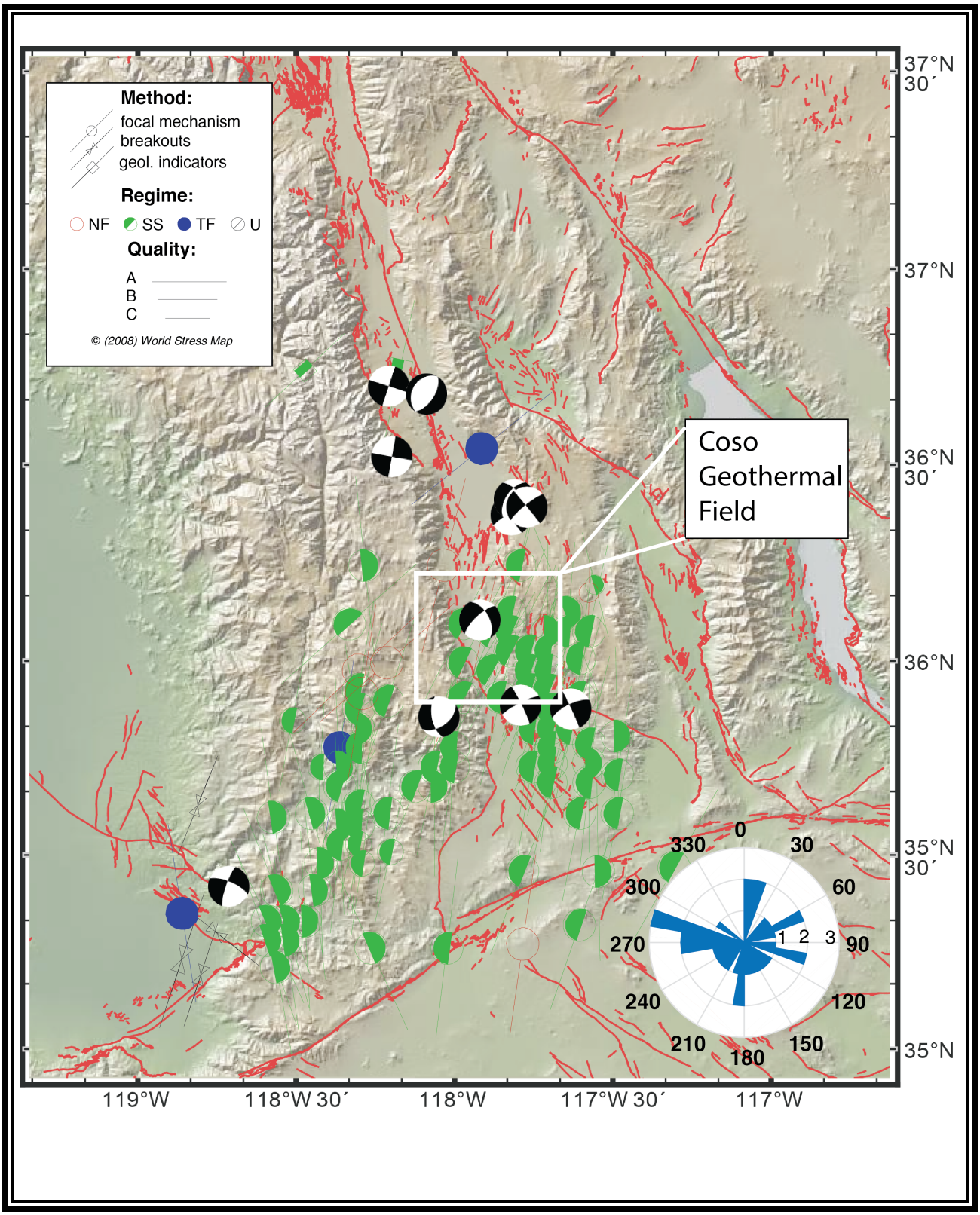
07:00:00.000
30000 cts
MPM BHE
-30000 cts
40000 cts
0
MPM BHN
-60000 cts
30000 cts
MPM BHZ
-30000 cts
2 min

Figure 12: Instantaneous and Delayed Triggered Seismicity, originating from the Coso Geothermal Field. Raw 3-component data colored black, yellow waveforms on top represent a 5Hz highpass of the raw data. We zoom into and display locally triggered earthquakes originating from the Coso Geothermal Field (CGF). A) 3-component waveform data from CI-network station MPM, capturing the 04/06/2013 04:42:35-UTC Mw=7.0 Irian Jaya, Indonesia earthquake and instantaneously triggered seismicity originating from the CGF study area. B) 3-component waveform data from CI-network station MPM, capturing the 09/26/2005 01:55:37-UTC Mw=7.5 Northern Peru earthquake and delayed triggered seismicity originating from the CGF study area.


Method:
focal mechanism
breakouts
geol. indicators
Regime:
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© (2008) World Stress Map
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Geothermal
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117°W 30´
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0
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120
150
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240
270
300
330
1 2 3

Figure 13: Map of southern California, we display focal mechanisms and stress data within our study area (35.5°N–36.5°N, 119°W–117°W). The blue rose plot indicates the back-azimuth angles of 34 triggering mainshocks; back-azimuth angles are stacked and plotted in bins of 10 degrees. Stress data retrieved from The World Stress Map database (via , last accessed 04/2015). Stress map data indicates the local in the stress field for our study area. The white box indicates the Coso Geothermal Field. Focal mechanisms (white and black beach balls) were retrieve from the Global Centroid Moment Tensor Project (http://www.globalcmt.org, last accessed 04/2015). We find remote triggering is enhanced by the orientation (back-azimuth) of the passing seismic waves. We find several events align favorably (parallel and perpendicular) with the local stress field and/or orientation of faults in the CGF triggered region.

## Conclusion

Of 154 mainshocks ($M$) ≥ 7 studied 34 mainshocks (22%) triggered local seismicity in the CGF region by imposing a transfer of dynamic stress. The CGF responded to the 34 mainshocks, displaying an increase in the magnitude and frequency (rate) from pre-mainshock to post-mainshock seismicity. We observe both instantaneous (16 events) and delayed (18 events) triggering of local seismicity from the ± 5 hours of the mainshock. We find remote triggering is enhanced by the orientation (back-azimuth) of the passing seismic waves. We find several events align favorably with the local stress field and/or orientation of faults in the CGF triggered region.

The CGF contains active fault systems and fluid processes which accounts for the high rate of background seismicity and this contributes to the CGF's susceptibility to dynamic triggering [Hill and Prejean, 2014]. Our findings support past research indicative of dynamic triggering typically occurring in areas of pre-exisiting seismicity [*Hill et al*., 1993; *Anderson et al*., 1994; *Husen et al*., 2004; *Husker and Brodsky*, 2004]. We infer triggered events found in the Coso region to be consistent with the "clock-advance" model [e.g., *Gomberg*, 2010, and references therein], the CGF displays a high susceptibility to remote triggering. We surmise, faults being triggered are already in a critical state and extremely close to failure, these triggered events are inevitable failures of the fault plane, activated prematurely due to the loading of imposed by dynamic stresses of the wavetrain of teleseismic events.

The majority of locations of locally triggered events reside either in the CGF or surrounding regional faults; consistent with previous observations indicating preferential triggering of geothermal areas and regions with pre-existing seismicity. We estimate PDS values ranging values ($10^{-3}$–$10^{-1}$ MPa), which is consistent with findings of Aiken and Peng (2014) indicating geothermal sites in California as susceptible to a triggering threshold of <0.001 MPa.

We contribute to a growing body of observations that demonstrate that local seismicity can be triggered by the passage of seismic waves of large ($M$) ≥ 7 earthquakes at remote distances upwards of 10,000 km away. To explain the triggering mechanisms in the case of instantaneous triggering in the CGF we propose direct failure of critically stressed faults by the Coulomb failure criteria [*Kilb et al*., 2002; *Hill*, 2008]. However, the majority of locally triggered events occur after the passage of mainshock surface waves. Mechanisms to explaining this delay include: a change in frictional contact along a fault [*Parsons*, 2005], pore fluid diffusion [*Brodsky and Prejean*, 2005], and arrival of multiple surfaces circling the Earth [*Peng et al*., 2011]. We propose a combination of these mechanisms incite a delay in the triggered response, although based on the properties of the CGF region, we surmise fluid diffusion to as the primary contributor in the development of the delay in triggered seismicity [e.g., *Brodsky*, 2006; *Bodin and Gomberg*, 1994; *Syracuse et al*., 2010].

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# Vita

Richard Alexander Alfaro-Diaz was born in San Juan, Puerto Rico. The son of Ricardo L. Alfaro and Linda Diaz-Howard, he graduated from Montwood High School in 2009 and enrolled at the University of Texas at El Paso (UTEP). While pursuing a Bachelor of Science degree in Geological Sciences, he conducted undergraduate research as a Keck Geology Consortium Project Fellow in 2013. He completed an Undergraduate Thesis on a study of the "Activation of a Secondary Oblique Slip Fault Following the Mw=7.6 Sept 5, 2012, Nicoya Costa Rica, Earthquake" the results of which were published as a Keck Short Contribution. He was a volunteer tutor for Ysleta High-school in the Ysleta Independent School District from 2009-2013. Mr. Alfaro was a Member of the Society of Collegiate Scholars from 2010-2015, and the treasurer for the UTEP-SACNAS chapter from 2013-2014. He received undergraduate scholarships and awards including the, W.P. Nash Scholarship, Africa Array Scholarship in 2013, a Keck Geology Consortium Fellowship in 2013, qualified for the Dean's list Spring/Fall 2010, Spring 2011, Spring/Fall 2012, Fall 2013 and received an undergraduate award for Research Excellence in 2013. He graduated with honors *cum laude* from UTEP in the fall of 2013. Mr. Alfaro then enrolled in the Masters of Geophysics program at UTEP in the spring of 2013. While a graduate student, he worked as a research assistant in 2014. He then received a National Science Foundation scholarship; from the program Student Mentoring to Achieve retention: Triads in Science (SMARTS) from 2014-2015. Through the SMARTS program he mentored an undergraduate student in the geology department to ensure engagement, and success in their undergraduate research. Mr. Alfaro received the Science, Technology, Engineering and Math education (STEM) GK-12 Graduate Fellowship from 2014-2015. As an NSF GK-12 fellow Mr. Alfaro participated as a "Scientist in Residence" at the Valle Verde Early College High

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