Accepted Manuscript

Analysis of the 2012 Ahar-Varzeghan (Iran) seismic sequence: Insights from statistical and stress transfer modeling

Pouye Yazdi, Miguel Angel Santoyo, Jorge M. Gaspar-Escribano

PII: S0921-8181(17)30368-5
DOI: https://doi.org/10.1016/j.gloplacha.2017.12.007
Reference: GLOBAL 2691
To appear in: Global and Planetary Change

Received date: 16 July 2017
Revised date: 17 October 2017
Accepted date: 6 December 2017

Please cite this article as: Pouye Yazdi, Miguel Angel Santoyo, Jorge M. Gaspar-Escribano, Analysis of the 2012 Ahar-Varzeghan (Iran) seismic sequence: Insights from statistical and stress transfer modeling. The address for the corresponding author was captured as affiliation for all authors. Please check if appropriate. Global(2017), https://doi.org/10.1016/j.gloplacha.2017.12.007

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.
Analysis of the 2012 Ahar-Varzeghan (Iran) Seismic Sequence: Insights from Statistical and Stress Transfer Modeling

Pouye Yazdi (1); Miguel Angel Santoyo (2); Jorge M. Gaspar-Escribano (3)

(1) Universidad Politécnica de Madrid (UPM), ETSI Topografía, Geodesia y Cartografía, C/Mercator 2, Campus Sur 28031 Madrid, Spain
pouye.yazdi@upm.es

(2) Universidad Nacional Autónoma de Mexico (UNAM), Institute of Geophysics in Campus Morelia 58190 Morelia, México
santoyo@geofisica.unam.mx

(3) Universidad Politécnica de Madrid (UPM), ETSI Topografía, Geodesia y Cartografía, C/Mercator 2, Campus Sur 28031 Madrid, Spain
jorge.gaspar@upm.es

Abstract
The 2012 Ahar-Varzeghan (Northwestern Iran) earthquake doublet and its following seismic sequence are analyzed in this paper. First, it is examined the time-varying statistical characteristics of seismic activity since the occurrence of the doublet (two large events with Mw=6.4 and 6.2) that initiated the sequence on 11 August 2012. A power law magnitude-frequency distribution (1.9 ≤ M ≤ 6.4) is obtained, with relatively low b-values for the complete series indicating the existence of relatively large magnitudes and high-stress level in the area. The Omori-Utsu model of the aftershock population decay with time shows a moderate decrease in activity rate. An epidemic-type aftershock sequence model that separates background seismicity from triggered aftershocks is then used to describe the temporal evolution of the seismicity during the period following the occurrence of the
doublet. Results for the entire series (above cutoff magnitude Mc = 1.9) indicate a relatively low productivity related to the earthquake-earthquake triggering. Indeed, the majority of these events seems to be generated by underlying transient or aseismic processes, which might be added to the tectonic loading stress. The proportion of aftershock events significantly increases when the analysis is limited to larger events (M ≥ 3.0) suggesting that the triggered large aftershocks entail a substantial portion of the energy released.

In order to analyze the spatial distribution of the sequence, new source models are proposed for the two main shocks. For the first shock, the coseismic slip distribution is constrained by the available data on surface ruptures. A Coulomb failure stress transfer model produced by the first event along optimally-oriented planes allows identifying the areas with positive stress loads where the rupture of the subsequent aftershocks may have occurred. The positive ΔCFS areas are compared for two depth intervals: 3-10 km and 15-22 km overlapping over 350 relocated hypocenters, giving arguments supporting the interpretation of ΔCFS as a main mechanism for aftershock triggering in deeper zones of the upper crust.

Keywords
Coulomb Stress, Statistical Seismology, Background Seismicity, Aftershocks, ETAS, Iran.

1 Introduction
Northwestern Iran is historically associated with destructive earthquakes mainly related to the North Tabriz Fault (NTF). This is a prominent tectonic structure that accommodates the deformation related to the shortening between the Arabian and Eurasian tectonic plates via right-lateral slip in Turkish-Iranian plateau and thrusting-slip in the Caucasus (Berberian, 1976; Copley and Jackson, 2006). The NTF stands at more than 50 km to the southeast of
Ahar and Varzeghan cities (Figure 1a), and expands along 150+ km in NW-SE direction. It predominantly presents a nearly vertical dip and right lateral strike-slip character (Berberian and Arshadi, 1976).

During the past two decades, the Iranian seismic network has surveyed this area, and no important seismic activity has occurred in the northern region of the NFT. GPS-derived velocities at the NTF indicate a mainly north-northeast tectonic movement. Close to Ahar city, the recent average slip has been measured to be about 11 mm/year (Djamour et al., 2011) and the modern stress field in this area is governed by a maximum horizontal compressive stress $\sigma_1$ in $128.5^\circ$ direction (Ghods et al., 2015). The recent relative quietness in this area was broken on 11 August 2012 with the occurrence of the earthquake sequence analyzed in the present work.

The sequence started with two destructive earthquakes of $\text{Mw}= 6.4$ and 6.2, located between cities Ahar and Varzeghan (Northwest Iran). Their epicenters are separated by a short distance of about 6 km with a short time lag of 11 minutes, constituting an earthquake doublet (hereafter referred to as the AV-doublet). The subsequent aftershock activity are developed with a high-rate with more than 2000 events ($M \geq 0.7$) during the first month. The seismic energy released induced significant ground motions that caused damage and losses in an extensive area (Razzaghi and Ghafory-Ashtiany, 2012).

Different authors have studied the seismic source model obtaining different moment tensor solutions for the two main shocks. Donner et al. (2015) estimate from surface wave inversions a seismic moment of $5.04 \times 10^{18}$ N.m (Mw=6.4) and conclude that the nucleation of rupture is located at 14 km on an east-west oriented fault plane. Their result for the estimated centroid
using waveform inversion indicates a relatively shallow depth (6±1) km. Larger seismic moment estimations are also obtained by the Iranian Seismological Center (6.70 x 10^{18} \text{N.m}) and global Centroid Moment Tensor (CMT) solution (6.04 x 10^{18} \text{N.m}) equivalent to an Mw=6.5, or Mw=6.45 (Yadav et al., 2016). On the other hand, seismic inversions by Taghizadeh-Farahmand et al., (2010) and Copley et al., (2014) show smaller seismic moments of the order of 3.6 x 10^{18} \text{N.m} (Mw=6.3). In another approach, Ghods et al. (2015) re-analyze the aftershocks hypocentral locations and then relying on the achieved spatial distribution together with field observations. They assess a two-segment fault plane for the first shock with Mw= 6.4 and an average slip of 70 cm. In the case of the second large shock, Donner et al. (2015) estimate an M_0 = 2.58 x 10^{18} \text{N.m}, which better agrees with an Mw=6.2. In the same study, the location of the centroid is obtained for depths of 12±1 km. However, some larger estimations for seismic moment (e.g.; 3.82 x 10^{18} \text{N.m} by IRSC, Iranian Seismological Center; 4.24 x 10^{18} \text{N.m} by CMT) are also available which result in larger moment magnitudes (Mw 6.3 - 6.4).

The AV-doublet is followed by more than 10 aftershocks with M≥4.5. The largest one occurred after nearly three months on 7 Nov 2012 with an estimated magnitude of Mw=5.6-5.7. This event is also followed by a significant increase in the seismic activity (see Figure 2). As in the case of the first mainshock, the centroid depth 3.9-4.1 km lies significantly above the hypocenter’s depth estimations (10 km by IRSC and 16 km by Ghods et al. (2015)), suggesting that rupture starts down-dip propagating upward (Donner et al., 2015).

Another important feature caused by AV-doublet is an east-west-oriented surface rupture, which is mapped in the epicentral area along 8 km using optical satellite images cross-correlation analysis (Copley et al., 2014). Field studies also reveal a longer rupture distance
up to 13 km (Donner et al., 2015; early reports by GSI, Geological Survey of Iran, 2012). The east-west right-lateral strike slip solutions for both events’ focal mechanism, potentially associates the rupture with the first, second or both shocks of AV-doublet. An almost vertically dipping fault plane for the first shock might be more consistent with the trace of the upper edge on the surface and the focal mechanism solutions with a steady dipping east-west fault plane (e.g.; Copley et al., 2014; Donner et al., 2015; IRSC; USGS, U.S. Geological Survey; CMT). For the second shock, previous studies propose different geometries for the fault that generated this event. One possibility is assuming an east-west fault plane solution similar to the first shock fault direction (Zafarani et al., 2015; Ahsari, 2016). However, Donner et al. (2015) suggest that the north-south oriented fault plane would be more reasonable from a rock mechanics perspective.

In the first part of this study, we carry out a statistical characterization of the 2012 Ahar-Varzeghan seismic sequence in time, in order to understand better the earthquake generating processes.

Then, we associate the surface rupture with the first shock of the AV-doublet and discuss two different scenarios explaining the relationship between both events from the view point of Coulomb stress transfer. We then study the impact of stress transfer related to both main shocks on optimally oriented fault planes and its possible control on the location of the largest aftershock on 7 Nov 2012.

2 Data Analysis
Initially, we explore an extended period containing the Ahar-Varzeghan series using the public catalog of the Iranian Seismological Center (IRSC) to identify changes in the seismic
behavior before, during, and after the main seismic series. We employ the IRSC data
(http://irsc.ut.ac.ir) between 1st Jun 2012 and 31st Jul 2014 (26 months), within a radius of 50
km around the doublet epicentral locations (Figure 1a). This database includes near 5000
events (M$_{blg}$ ≥0.7) where their epicentral distribution shows a primarily east-west alignment.
An additional cluster of small magnitude earthquakes (M <2.5) can also be observed showing
a north-south alignment and North of the main series group (Figure 1b).

**Figure 1:** a) Epicentral location of the 2012 Ahar-Varzeghan seismic sequence in
Northwestern Iran. Yellow circles show the locations of the cities of Ahar (right) and
Varzeghan (left), the yellow line indicates North Tabriz fault. b) Zoom to the area enclosed
by a white circle in a; including all earthquakes in the IRSC catalog since first June 2012 to
the end of July 2014 shown by white circles sized by their magnitude. Red line shows the
observed surface rupture.

To study the temporal variations and statistical seismic parameters of the series, we first
extract from the original catalog, those events within the highest seismic activity period and
inside the area shown in Figure 1b. Hence, we study a one-year seismic catalog, shown by an
arrow in Figure 2 as ‘AV-1213’, covering a period from 1st Aug 2012 to the end of Jul 2013
and including 4558 events (M≥0.7).

**Figure 2:** Daily number of events during 26 months since first of June 2012 and magnitude
distribution versus time. Grey stars represent M$_{blg}$ magnitude (Nuttli Scale) by IRSC and gold
stars represent moment magnitude Mw given by Donner et al. (2015) for the doublet and the
third largest event on 7 Nov 2012.
2.1 Frequency-Magnitude Distribution

For an adequate analysis of the series we first perform a completeness assessment for the catalog. An incomplete population of small events usually results from the limited sensitivity of the seismic instruments and ambient noise in the area especially right after large events. Such missing parts in earthquake population may bias the statistical analysis. The best cut-off magnitude (Mc) in the AV-1213 catalog is calculated using Wiemer and Wyss (2000) method of modeling the magnitude frequency law of Gutenberg and Richter (1956). Earthquake magnitudes are assumed to follow the Gutenberg-Richter law (GR) which describes the number of earthquakes with magnitude equal or greater than M as:

\[ N_{cum}(M) = 10^{a-bM} \]  

(1)

Where a and b are constants obtained by regression analysis. Figure 3 shows the time variation of Mc obtained from 200 bootstrapped samples for both 90% and 95% goodness of fit for modeling AV-1213 catalog with the GR power law. The fluctuations could be related to sudden jumps in the activity rate that lead to the overlapping of seismic records of lower magnitude events occurring immediately after higher magnitude events (Hainzl, 2016). After the analysis, an average value of Mc=1.9 calculated for 95% probability of fit with GR law, results as a reasonable cut-off magnitude for the entire AV-1213 catalog. The resultant AV-1213 catalog includes 2247 events with M ≥ 1.9.

**Figure 3;** Solid black lines show the calculated cut-off magnitude versus time for a sample of 500 events with 10% overlap and 90% and 95% goodness of fit for modeling the GR law. Grey lines represent mean ±σ curves obtained from 200 bootstrapped samples.
Accordingly, we estimate the b-value which specify the slope of the GR fit. The time variation of the obtained b-value is shown in Figure 4. As it can be seen in Figure 4, the b-value during the AV-1213 series remains in between the values b=0.8 and b=0.9 with σ~0.2 before February 2013, after which a more stable b-value of 0.9±0.1 is observed. For the whole sequence fitting the entire catalog with GR law using the maximum likelihood estimation results a smaller b-value=0.75 with Mc=1.9±0.15 (Grey box in Figure 4), which can be associated with higher level of confining stress (Schorlemmer et al., 2005; Scholz, 2015) that increases the number of larger size earthquakes.

Figure 4: Solid black line represents the calculated b-value versus time for a sample size of 500 events with 10% overlap and 95% goodness of fit. Dashed grey lines represent the mean ±σ obtained from 200 bootstrapped samples. The grey box shows the maximum likelihood estimation for the time-independent b-value and the cut-off magnitude by 95% goodness of fit for modelling the GR law.

2.2 Aftershock Activity

The aftershock rate due to a single earthquake is usually well-described by the Omori-Utsu law (Utsu et al., 1995). In such relation, all the subsequent seismic activity after a given mainshock is associated with the stress changes produced by that event in the area. Equation 2 shows the relation that states the aftershock decay rate $\dot{N}_{\text{aftershock}}$ with time:

$$
\dot{N}_{\text{aftershock}} \propto \frac{K}{(t+c)^p}
$$

where K, c, and p are real positive constants and t is the elapsed time since the mainshock (for a review, see Utsu et al., 1995). The exponent p is typically in the interval 0.8–1.2 and is
independent of the mainshock magnitude, on the other hand, the term K is exponentially
dependent on the mainshock magnitude (Utsu et al., 1995; Hainzl and Marsan, 2008) and
refers to the capability of the mainshock for triggering earthquakes. The Omori-Utsu law
should only be fit for a period where the records in a given magnitude interval are complete
(Zhuang et al., 2012). Therefore, events before 2012.08.12 at 02:03:16.9 (t=0.567 days) where
the first event with M≤ Mc occurs (M=1.5), might be excluded for maximizing the likelihood
function. Table 1 presents the obtained K, c and p parameters applying the maximum
likelihood method (Ogata, 2006), which estimates these parameters regardless to the
magnitude of the mainshock. The decay of the modeled aftershock rate is shown in Figure 5a.

If we would consider only the first shock of the AV-doublet (Mw=6.4) as the "parent" for the
whole AV-1213 population, the estimated parameter K would reflect the aftershock
productivity of this magnitude. Indeed, the size of the second shock of the doublet highlights
its capacity to trigger its own aftershocks sequence, whose "descendants" would immediately
superimpose with those of the first shock (Ogata, 1988). At the same time, the empirical
Bath’s law states that in average, the largest aftershock magnitude is around 1.2 times lower
than the mainshock magnitude (Bath, 1965). However, different studies validate Bath’s law
only for some values of seismicity parameters and discuss the importance of the selection of
data (Vere-Jones, 1969; Helmstetter and Sornette, 2003). Instead, it can be assumed that the
AV-1213 represents aftershock decay of an event with Mw=6.5 because such event
equivalently releases the energy of two events with Mw=6.4 and 6.2. Then will model the
observed aftershock productivity.

Table 1; Values of K, c and p parameters of the Omori-Utsu law for the AV-1213 aftershock
sequence, including 2247 events with M≥1.9.


2.3 ETAS Analysis

A common statistical approach for analyzing the source process inducing seismic series is the Epidemic Type Aftershock Sequence (ETAS) model, which is a stochastic point process model introduced by Ogata (1988), which incorporates each event with magnitude \( M_i \) occurred at time \( t_i \) (prior to the present time \( t \)) as a potential earthquake triggering event.

According to a modification of the ETAS model (Equation 3) by Hainzl and Ogata (2005), the total seismic rate \( \lambda(t) \) is divided into an external aseismic (or background) rate \( \mu(t) \) and an internal aftershock rate \( \nu(t) \), giving:

\[
\lambda(t) = \mu(t) + \nu(t) = \mu(t) + \sum_{t_1 < t} \frac{K_0 e^{\alpha(M_j-M_{\text{Mr}})}}{(t-t_1+c)^p}
\]

(3)

Here, the parameters \( c \) and \( p \), appear from the Omori-Utsu law and parameters \( K_0 \) and \( \alpha \) are related to the magnitude-dependent aftershock productivity. \( M_{\text{Mr}} \) is the minimum magnitude used to optimize the ETAS parameters.

The aseismic, or background, rate \( \mu(t) \) describes the temporal variation in the aseismic forcing mechanism such as tectonic loading, fluid or magma intrusions or another aseismic transient like slow slip earthquakes (Marsan et al., 2013). The earthquakes induced by the aseismic forcing usually produce local stress field changes accompanied by seismic stress triggering (Stein, 1999; Hainzl and Ogata, 2005). In this sense, the mechanism that triggers the aftershock rate \( \nu(t) \) is the elastic loading by stress transfer from previous earthquakes.

In this study, we use the algorithm developed by Marsan et al. (2013) and then tested by
Hainzl et al. (2013) to analyze the temporal behavior of the AV-1213 series through the estimation of ETAS parameters. The applied algorithm, iteratively estimates the four parameters $K_0$, $\alpha$, $c$, and $p$ of the ETAS model, by maximizing the log-likelihood value for events with $M \geq M_r$, inside a time interval. Then estimates the time-dependent background rate $\mu(t)$ using the mean probability of belonging to the background population, for each event in a chosen window of the $\pm n$-nearest neighbors. The optimal value of the smoothing window is determined by the Akaike information criterion, $AIC = 2k - 2\ln(L)$ where $k$ is the number of free model parameters and $L$ is the maximum likelihood value.

Here we model the AV-1213 ($M \geq 1.9$) by optimizing the ETAS parameters for $M_r = 2.0$, 2.5 and 3.0, in order to account for a probable incompleteness of the catalog and check the consistency of changes in the ETAS parameters. The AIC yields smoothing windows of $n = \pm 19$, $\pm 21$ and $\pm 22$ neighbors respectively. Figure 5 shows how the obtained ETAS parameters in Table 2 model the seismic activity for different reference magnitude $M_r$.

**Figure 5; a)** The observed daily number of the events for AV-1213 sequence and with different $M_{\text{min}}$ is shown by circles in logarithmic scale. The black solid curve shows the result of modeling the AV-1213 sequence with the Omori-Utsu law for $M_{\text{min}} = 1.9$. Colored curves in grey, green and blue are the background rate obtained by the ETAS approach and for maximum likelihood estimation for reference magnitude of 2.0, 2.5 and 3.0 respectively and colored circles are observed daily rate for minimum magnitudes (1.9, 2.0, 2.5 and 3.0). **b)** The cumulative number of background events (dashed lines) obtained by ETAS modeling within different magnitude ranges in (a). Solid lines represent the cumulative number of all events modeled by ETAS and diamond symbols stands for the observed cumulative number of events.
Table 2; The obtained ETAS parameters for the AV-1213 sequence considering different magnitudes ranges for maximum likelihood estimation.

2.4 Spatial Distribution of seismicity

An improvement of the hypocentral location is essential for the spatio-temporal analysis of the AV-1213 series as well as for the stress-transfer modeling. Notwithstanding the method for relocating, the quality of the phase-catalog, which includes the arrivals of seismic phases, is effectively important. The IRSC public database only includes errors for horizontal coordinates of events with $M \geq 2.5$ and the depth errors are not given. The averages of horizontal errors in IRSC public database are 2.03 and 2.26 km in NS and EW components, respectively. Thus, we implement the Double Difference earthquake relocation method (Waldhauser and Ellsworth, 2000) on the IRSC phase catalog including 826 events ($\geq 2.5$) inside an area of about 2500 Km$^2$ and for the AV-1213 catalog (Figure 6). The velocity model by Rezaeifar et al. (2016) with a mean $V_p/V_s = 1.76$ (Taghizadeh-Farahmand et al., 2010) is applied here. This is a 1D model constrained by data of almost 1600 records of local events. The authors of the model tested it using several initial models, and showing fast convergence to the final velocity model. It is adequately resolved for upper crustal layers, down to about 23 km. The initial condition for generating event-pairs usually modifies the precision of the relocation process and the percentage of relocated events gets smaller under a strongly confined coupling condition. A minimum requirement of having 8 double-difference equations for pairing earthquakes leads to 376 remaining events registered in 16 stations in a radial distance less than 200 km. Relocation errors for individual events are not enhanced for this study. However, the absolute centroid location shifts in x, y and z direction are -19.6, 39.8 and 419.1 meters, respectively.
Figure 6; Relocated hypocenters \((M \geq 2.5)\) are shown with blue dots. The blue square, triangle, and circle respectively mark events with \(Mw=6.4, 6.2\) (Aug.11) and 5.6 (Nov.7). Same symbols in red represent the calibrated hypocenters given by Ghods et al. (2015), whereas the ellipse errors are shown in yellow.

Figure 6 shows how the sequence is concentrated in two depth ranges, especially on the Western side. Although the accuracy of the velocity model together with the depth error on the original catalog have an influence on the spatial clustering in depth, the observed gap of seismicity can be also seen on previous hypocentral estimations from other studies (e.g. Ghods et al., 2015; Rezapour, 2016). Results of our study show that the main activity occurs along two depth intervals: 3-14 and 14-23 km (Figure 6).

3 Source Characterization

It is commonly accepted by different authors that the first shock of AV-doublet has an almost pure strike-slip focal mechanism with a nearly vertical east-west striking. A small pitch from vertical dipping (up to ±10°) results from the CMT, USGS and IRSC solutions (Figure 1a). However, there is no such consensus for the allocation of the second large shock, and the association of a nodal plane to the actual faulting plane. The difficulty of this analysis increases due to the superposition of the arrival of the coda waves due to the first event with the waveforms produced by the second shock of the AV-doublet.

In this work, we introduce a simple slip model of faulting geometry that fits best with the field measurements. Then we calculate the ∆CFS due to the first large event and propose a consistent source structure for the second large event as well. The features which are
explicitly evidenced on previous studies (mentioned in section 1) and that we use in our study are listed in the following and shown in Figure 7.

1) A surface rupture of about 13.5 km–long with a main EW alignment is observed and mapped (Faridi and Sartibi, 2012; Copley et al., 2014) which agrees with active faulting mapped by Ghods et al. (2015).

2) Field measurements show maximum horizontal and vertical displacements of ~70 cm and ~25 cm, respectively (Copley et al., 2014; Ghods et al., 2015). Right-lateral offsets of the order of 70 to 110 cm are estimated near the fault (<300 m) using optical image correlation by Copley et al. (2014).

3) Isolated rupture occurs at a longitude of 46.65º with reverse fault along ~1.3 km with north-dipping (35º). Also at a longitude of 46.85º with the EW alignment of small length ruptures are mapped (Ghods et al., 2015).

4) The first large shock is dominantly strike-slip with vertical dipping which implies that its epicenter occurs close to the surface rupture. Among many epicenter estimations summarized in Rezapour (2016), the one which adopts this simple condition is given by Ghods et al. (2015) at 38.399º, 46.842º.

5) The relocated events (see section 2.4) in the shallower cluster are distributed mostly in an east-west direction, along ~20 km and on a depth range ~3-14 km. At higher depths, the north-south distribution of the events is wider (~12 km) than at shallower depths.

**Figure 7;** The most important observed evidence about the rupture area right after AV-doublet. The red line shows the selected trace of the rupture plane for the first shock.
3.1 Source Model for the First Shock

Figure 7 shows the active faults map from Ghods et al. (2015) together with the rupture alignments, and the faulting strike that we take into account for the first large shock analysis in this study. The east-west alignment is divided into five vertical segments along almost 19 km to emphasize the strike change and a more detailed geometry. All five segments are prolonged vertically from the surface down to a depth of 14 km, as shown in Figures 9. This geometry is consistent with the observed magnitude as deduced from several empirical relations. Thus, for the continental tectonic setting and a strike slip fault, a surface rupture of size 19.08 km is empirically relevant for Mw=6.41 using Johnston (1996) formula \( M_w = 1.36 \times \log(L) + 4.67 \) (Stirling et al., 2013). Likewise, another empirical relationship (Anderson et al., 1996) based on slip rate estimates Mw=6.39 for a slip rate of 11.2 mm/year (Djamour et al., 2011) and a surface rupture length of 19.08 km in this study.

For weighting the net-slip distribution, we introduce a cushion-shape model, which implies a maximum value for net-slip in the central area of the fault. The assumed weighting function is the probability density function of a circle-arc with angle \( \theta \) (\( \theta \leq 180^\circ \)). This function gives a simple curve for constructing weights along the length and the width of the fault. The hypocentral location of the first rupture results to be located very close to the east-end of the fault (Donner et al. 2015; IRSC), and here it is assumed that the maximum slip, or centroid is more concentrated at the half-width close to depth of 7 km (Donner et al., 2015). Thus, along two vertical segments No.1 and 2, the circle-arc angle is chosen to be less than 180° (140° and 160° respectively), which implies a bit sharper weight-value at the center. In addition, for consistency with the observed surface rupture on top, a gradual cut-off is made for circle-arcs along the upper edge of segments No. 2, 3, 4 and 5 (Figure 8). The resulting set of weight-values for the net-slip distribution along depth is shown in Figure 9. For the net-slip weighting
along fault’s strike, the circle-arc is flattened in the middle section regarding lack of evidence of a centered slip along specific longitude (Zafarani et al., 2015; Yadav et al., 2016).

**Figure 8;** Grey belts; net-slip weights along each vertical segment as pdf of a circle-arc with angle $\theta \leq 180^\circ$ and center offset. Grey lines; net-slip weights along strike as pdf of a flattened circle-arc with angle of $180^\circ$ (same for all depths).

Figure 9 shows the way vertical segments are tapped along strike and dip constructing a net of 17x14 cells (area ~ 1km$^2$) with normalized net-slip weights driven from the product of weights along strike and dip directions. Considering the measured oblique slip at the western parts, a gradual change in rake (from $180^\circ$ in segment No.1 to $160^\circ$ in segment No.5) is assumed. Finally, multiplying all weight-values by a constant factor we model the measured displacements at the surface with maximum strike-slip of 73 cm.

**Figure 9;** The source model for total net slip (left-hand side) assumed in this study, with right lateral (center) and reverse slip components distribution (right-hand side).

The proposed source model for the first main shock results with a total seismic moment of $4.73 \times 10^{25}$ Dyne.cm obtained by the Aki’s (1966) formula $M_0 = \sum \mu_s \cdot dA \cdot dS$, using a shear modulus of $\mu_s = 32$ GPa. This energy is consistent with an $M_w = 6.44$ applying the empirical relation by Stirling et al. (2013) for a stable continental tectonic regime.

### 3.2 Source Model for the Second Shock

There is no common agreement from previous results on the orientation of the rupture plane for the second shock in the AV-doublet. However, some important features indicated in
previous studies are: I) The seismic moment associated with this event comprises about half of the total seismic moment of the first shock (e.g.; Rezapour 2016; Donner et al. 2015; Mirdamadi and Rezapour 2015; USGS; CMT). II) It took place at about 6 km west from the first shock (e.g.; Ghods et al. 2015; Donner et al. 2015; Rezapour 2016; CMT) being uncertain its relative location in the north-south direction. III) The majority of the previous studies indicate a deeper location for this event with respect to the first shock (e.g.; Ghods et al. 2015; Donner et al. 2015; Mirdamadi and Rezapour 2015; CMT).

In this section, the analysis of changes in Coulomb failure stress ($\Delta$CFS) is employed to shed light on the preferred possible orientations for this second rupture. For each assumed fault plane, the Coulomb failure stress $\sigma_C$ or CFS is defined as the difference between the absolute value of tectonic shear stress $\tau$ on the plane and the frictional stress $\mu^*\sigma_n$ that resists against rupture (Equation 4):

$$\sigma_c = |\tau| - \mu^*\sigma_n \tag{4}$$

where $\mu^*$ is the effective coefficient of friction and $\sigma_n$ is the normal stress to the plane. The failure occurs when $\sigma_C$ exceeds a special positive value which depends on internal characteristics of the rock (Stacey and Davis, 1977).

Regarding the AV-doublet, one reasonable possibility is that the second large shock results from an elastic rebound which response to the abrupt change of CFS arrangements close to the first shock fault. In this study, the $\Delta$CFS resulting after the first shock is calculated for the nodal planes extracted from the CMT focal mechanism solutions for the second shock. Results are illustrated in figure 10 for a depth interval of 10-14 km for $\Delta$CFS estimations and
on cross-sections that include the epicentral location of the second main shock. The area located to the northwest of the first mainshock lies within a high positive ΔCFS for left-lateral strike-slip faulting along NS direction and a negative ΔCFS for right-lateral strike-slip faulting along EW direction. This result strengthens the north-south orientation assumption of the fault plane as the actual rupture plane for the second shock.

**Figure 10:** CFS changes due to the first event on vertical and horizontal sections for EW plane (left) and for NS plane (right) of CMT solution for the second events of the AV-doublet. Red circles (left) and black circles (right) have a diameter of 3 km centered on the hypocentral location of the second event by Ghods et al. (2015).

Hereafter, in order to introduce a source model for the second mainshock on the North-South CMT solution, we take into account the spatial distribution of relocated hypocenters and define a 12.0 km x 10.0 km rupture area, consistent with the observed magnitude Mw=6.2 (e.g. Wells and Coppersmith, 1994). Such fault plane dips down with an angle of 50º, up to a depth of about 20 km (figure 11). A simple uniform model composed by superposition of six concentric planes with constant slip used to smooth the slip at the fault edges. The smallest surface is set to have a total slip of 30 cm on a central patch of 42 km² that gradually drops to 5 cm on the larger fault plane. In this way, the maximum slip at the central area reaches 105 cm, which results in a total seismic moment of $2.2 \times 10^{25}$ Dyne. cm and Mw=6.22 (e.g. Aki, 1966; Stirling et al., 2013).

**Figure 11:** Geometry for the AV-doublet proposed in this study.

4 Optimally Oriented Failure
A given tectonic stress that addresses a given medium at depth produces different shear stresses along different orientations. The Coulomb Failure equation (equation 5) gives the condition for failure (Stein et al., 1992).

\[ \tau_f = \mu^* \sigma_n + S_{\text{int}} \]  

(5)

Where \( \mu^* = \mu \left(1 - \frac{p}{\sigma_n}\right) \) represents the effective coefficient of friction and \( p \) is the fluid pore pressure. The term \( \tau_f \) is the minimum shear stress that is necessary to overcome the internal strength \( S_{\text{int}} \) and the friction that prevents failure on a plane subjected to a normal stress \( \sigma_n \).

Assuming that the material is mechanically isotropic, and considering a rock subjected to principal tectonic compressive stresses \( \bar{\sigma}_1, \bar{\sigma}_2 \) and \( \bar{\sigma}_3 \) (where \( \sigma_1 > \sigma_2 > \sigma_3 \)), it can be shown that the maximum CFS lies on a plane parallel to stress \( \bar{\sigma}_2 \) direction. This plane makes an angle of \( \pm \theta \) with the greatest principal stress \( \bar{\sigma}_1 \) (King et al., 1994) where the angle \( \theta \) directly depends on the effective coefficient of friction \( \mu^* \) (Equation 6).

\[ \theta = \frac{1}{2} \tan^{-1} \frac{1}{\mu^*} \]  

(6)

For \( \mu^* = 0.4 \), we have an angle of \( \theta = \pm 34.1^\circ \) with \( \bar{\sigma}_1 \): whereas the shear stress along \( \theta = +34.1^\circ \) will induce a right lateral slip while this stress along \( \theta = -34.1^\circ \) will induce a left-lateral slip.

If we take the present day \( \sigma_1 \) direction of N128.5E (see Introduction), two scenarios can be considered: first, if \( \bar{\sigma}_3 \) is horizontal and \( \bar{\sigma}_2 \) vertical (\( \bar{\sigma}_1 \) and \( \bar{\sigma}_3 \) have no plunge), then CFS gets larger on vertical planes striking \( \sim 128.5^\circ \pm 34.1^\circ \) (applying \( \mu^* = 0.4 \) for pure strike-slip).
Accordingly, the north-south and east-west–oriented fault planes would be the principal reactivated faults with strike-slip mechanism. This orientation coincides with the nodal planes of focal mechanism determined for the AV-1213 sequence (e.g.; CMT; Donner et al. 2015; Ghods et al. 2015). Second, if in turn \( \sigma^* \) is vertical, then the planes with maximum CFS have a strike along \( \sigma_2 \) or \( \sim 128.5^\circ \pm 90^\circ \) with dip of 29.5° representing oblique-slip (applying zero plunges for \( \sigma_1 \) and \( \sigma_2 \) nd \( \mu^* = 0.6 \) for oblique-slip events).

In the following section, we discuss the \( \Delta \text{CFS} \) distribution related with the AV-doublet along optimally oriented fault planes and analyze if the positively charged areas are consistent with the AV-1213 hypocentral distribution.

5 \( \Delta \text{CFS on Optimally Oriented Planes and Largest Aftershock Source} \)

The change in the Coulomb stress transfer may be calculated for optimally oriented planes for the identification of area with positive stress load where the aftershocks might be excepted to occur (Stein et al., 1994). In most cases, we are facing with existing faults and not future failures. Evidently, when an area is under tectonic loading, the slip might occur on pre-existing faults even if the stress arrangement changed. However, Ghods et al. (2015) remarking the consistency of independently determined stress field, suggest that all the quaternary faults in the area are potentially active and may remain aseismic for long time.

Table3; The results of fault kinematic inversion by Ghods et al. (2015) for sites 25.1 which is located at the east of the ruptured area with highest number of fault slip pairs (9 pairs) for stress calculation.
Here, adopting the principal stress set of Table 3 (based on high-quality measurements with non-zero plunges for principal horizontal stresses according to Ghods et al., 2015), we evaluate ∆CFS for optimally oriented faults. The result is shown in figure 12 together with the epicentral location of all re-located events (see section 2.4).

**Figure 12:** The mean value of ∆CFS for optimally oriented strike-slip (a and b) and thrust faults (c and d) in shallow (a and c, 3 to 10 km) and deep (b and d, 15 to 22 km) depth ranges. All re-located events are overlaid for both depth ranges.

Bar graphs in Figure 12 show that more than 70% of the AV-1213 relocated events are contained in positively charged areas for optimum orientations at higher depth intervals (Figure 12).

By contrast, a relation between the hypocentral distribution and positively charged areas is not clearly observed for shallow depth events. This result supports the assumption of a stress triggering mechanism more active in deeper zones of the upper crust.

The western cluster within this depth interval (also shown in Figure 6) can be attributed to the largest aftershock of the AV-doublet of 7 Nov 2012. The occurrence of this event significantly increased the surrounding seismic activity (Figure 2), especially along NS direction (as it is shown in Figure 13a during the subsequent month). Rezapour (2016) studied the cross-section along this north-south epicentral alignment and showed that this cluster is distributed in a depth range of 5-16 km.
Hence, this time we calculate $\Delta$CFS for an intermediate depth interval 10-16 km applying the CMT solution $183^\circ$-$83^\circ$-$7^\circ$ for the focal mechanism of this event, which is actually close to the optimally oriented strike-slip faulting (left-lateral). The mean value of $\Delta$CFS across seven layers with 1 km vertical increment supports that this large aftershock is located in an area with positive $\Delta$CFS due to AV-doublet (Figure 13b).

**Figure 13; a)** Hypocentral location of 98 events of AV-1213 series during one month since 7 Nov 2012. **b)** The mean value of $\Delta$CFS (depth range 10 to 16 km) for north-south mechanism solution by CMT for the largest aftershock of the AV-1213 series on 7 Nov 2012 with $M_w=5.6$.

### 6 Discussion and Conclusions

The AV-1213 sequence occurred in an area where previous seismic activity was relatively scarce. It started with two relatively large mainshocks constituting a seismic doublet, and the subsequent seismic sequence lasted for several months. The first mainshock is followed by changes in the Coulomb failure stress, which loads positively the hypocentral area of the second mainshock promoting a left-lateral oblique failure along the NS-striking plane. This result can appropriately attribute the surface rupture to the first main shock.

The subsequent earthquake population may consist of events triggered by elastic loading due to stress transfer from previous earthquakes and may also be caused by aseismic stress build-up on the rupturing faults. Statistical characterization allows us to help understand the underlying earthquake generating processes. The slight temporal variation of $b$-values in this study does not suggest a significant change in the process of inducing earthquakes since the start of the sequence. However, the $b$-value constantly remains less than 1.0 (around $0.8\pm0.1$)
indicating a significant contribution of larger magnitudes (inside the completeness magnitude range). Nevertheless, for a classical mainshock-aftershock sequence, a rapid drop in the stress level usually results in a larger b-value (e.g.; Scholz, 1968; Wyss, 1973).

The Omori-Utsu modeling gives an aftershock decay rate of 0.94 (p < 1) which is affected by sudden jumps that due to large magnitude aftershocks.

Furthermore, the ETAS modeling is applied to address sudden rises in the activity rate. The result is highly in conformance with the AV-1213 daily rate of seismicity. A time-varying background activity with a descending rate over time is also verified. Taking into account larger events (M≥3.0) as potential parents, is shown that over 72% of them have much more participation in the aftershock population caused by elastic loading due to stress transfer. However, this contribution decreases when we consider a wider range of magnitudes. Thus, the aftershock contribution drops to 52% and 30% within magnitudes M≥2.5 and M≥2.0 respectively. This implies that the energy released by the AV-1213 sequence follows a two-fold pattern: a more energetic (higher magnitudes) group of aftershock events, and a less energetic group of small-magnitude events that implies a high background rate and a transient loading force after the AV-doublet.

Our analysis shows that the AV-1213 sequence is not solely explainable by earthquake-earthquake triggering and, therefore, an additional aseismic process must have taken place (e.g.; Yazdi et al., 2017). The source of such loading process acting together with the build-up tectonic stress on faults remains unknown. However, the exhibited hypocenter migration studied by Rezapour (2015) might invoke fluid movement or pore pressure diffusion (Shapiro et al., 1997; Hainzl et al., 2012).
Regarding to the small percentage of relocated events (45% of the events with M≥2.5) and uncertainties in the depth determination we calculate the changes in the CFS after the doublet for two (shallow crust and deep crust) depth range of 5 km width. The changes calculated for optimally oriented planes show that the positively loaded area only corroborate the hypocentral distribution of the relocated population for higher depth range (16-21 km) where the superposition reaches to more than 70% (Figures 12b and 12d). However, the positive ΔCFS areas comply well with the largest aftershock (7 Nov 2012) estimated hypocenter interval (10-16 km) and its focal mechanism which is in accordance with optimally strike-slip rupture (north-south left-lateral strike slip). The significant difference between ΔCFS maps in the two deep ranges (Figure 12) appears in consequence of doublet geometry setting which changes from EW to NS orientation at higher depths.

In Figure 12 it is excluded more than 50% of the events with M≥2.5 and an almost 48% contribution is of background seismicity, which together with systematic uncertainties in the re-locating process limit our interpretation from the superposition of ΔCFS results and aftershock distribution. An ideal-case scenario for analyzing the triggering effects on the aftershock seismicity due to stress changes would be to compute the CFS resolved on the specific slip direction of each aftershock and then define its possible positive or negative influence due to a previous earthquake. This analysis, in fact, would require knowing the focal mechanism of each aftershock, which in most cases is unknown. In this work, it is assumed that the aftershocks focal mechanisms share similar rupture slip directions and focal parameters with respect to the main events. However, several works have shown that this is not necessarily the common situation for inslab earthquakes, where a significant number of aftershocks may result with dissimilar mechanisms (e.g.; Steacy et al 2005; Santoyo, et al.,
This might be the case for the shallow aftershock activity of the series analyzed here, where after the analysis there are obtained inconclusive evidence for specific correlations with respect to the positive stress change zones due to the AV-doublet mainshocks. Given this, a more detailed analysis on the focal parameters of the aftershock seismic series would be needed.

Acknowledgements:

S. Hainzl is thanked for his advice with the use of the ETAS code. A. Razmyar is thanked for his support in catalog processing. Some of the tasks and figures contained in this paper are developed using the following software tools: ZMAP (Wiemer, 2001), GMT (Wessel et al. 2013), Coulomb 3.3 (Toda et al., 2011) and SAPP (Ogata, 2006). This work is part of the PhD Project of P.Y. that is carried out in the Earthquake Engineering Research Group of UPM, which it is also acknowledged.

References


### Table 1

<table>
<thead>
<tr>
<th>$MLE$ method</th>
<th>$K$</th>
<th>$c$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>303.0</td>
<td>0.485</td>
<td>0.940</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>$M_r$</th>
<th>Smoothing window</th>
<th>$K_0$</th>
<th>$c$</th>
<th>$p$</th>
<th>$a$</th>
<th>$N_{arr}(M_r)$</th>
<th>$N = \int \sigma(t),,dt$</th>
<th>$N_{arr} = \int \mu(t),,dt$</th>
<th>$N_{arr}/N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>19</td>
<td>0.007</td>
<td>0.020</td>
<td>1.213</td>
<td>1.487</td>
<td>1961</td>
<td>1941</td>
<td>1372</td>
<td>0.70</td>
</tr>
<tr>
<td>2.5</td>
<td>21</td>
<td>0.009</td>
<td>0.027</td>
<td>1.190</td>
<td>1.671</td>
<td>828</td>
<td>811</td>
<td>392</td>
<td>0.48</td>
</tr>
<tr>
<td>3.0</td>
<td>22</td>
<td>0.009</td>
<td>0.020</td>
<td>1.163</td>
<td>1.885</td>
<td>333</td>
<td>327</td>
<td>91</td>
<td>0.28</td>
</tr>
</tbody>
</table>

### Table 3

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>$\sigma_1$</th>
<th>$\sigma_2$</th>
<th>$\sigma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.1</td>
<td>38.375</td>
<td>46.857</td>
<td>136/-4</td>
<td>44.5/-21</td>
<td>56.5/69.3</td>
</tr>
</tbody>
</table>
Fig12a (in color)

Fig12b (in color)

Fig12c (in color)
Acknowledgements:

S. Hainzl is thanked for his advice with the use of the ETAS code. A. Razmyar is thanked for his support in catalog processing. Two anonymous reviewers provided insightful comments to this paper and they are gratefully thanked. Some of the tasks and figures contained in this paper are developed using the following software tools: ZMAP (Wiemer, 2001), GMT (Wessel et al. 2013), Coulomb 3.3 (Toda et al., 2011) and SAPP (Ogata, 2006). This work is part of the PhD Project of P.Y. that is carried out in the Earthquake Engineering Research Group of UPM, which it is also acknowledged.
Highlights

- The ΔCFS analysis verifies a NS strike for the rupture plane of the second shock.
- At higher depths (16-21 km) events highly conform with optimally oriented ruptures.
- The stress drop is not as fast to indicate a simple mainshock-aftershock sequence.
- An aseismic transient loading force acts above the tectonic stress in the area.
Figure 1
Figure 2
Figure 5